Anticipatory Life Cycle Assessment of Phosphorus Recovery from Human Urine and Application in Agricultural Food Systems

by

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ABSTRACT

The escalating global demand for food production underscores the urgent need for sustainable agricultural innovations. This research contributes new insights into the environmental benefits of using urine-derived phosphorus (P) fertilizers by closing the nutrient loop and applying the technology to agricultural food systems. Anticipatory life cycle assessment was used to quantify the environmental impacts of replacing conventionally mined P fertilizer with recovered urine-derived P fertilizer within the production of beef and plant-based burgers. Results shows that implementing recovered P fertilizer provides greater environmental benefits for all environmental impact categories, with global warming, eutrophication, and water consumption being the main impact categories examined in this study. Urine-derived P fertilizer use in beef burger production led to a 4% reduction in global warming impacts (3% for plant-based), 15% reduction in eutrophication (2% for plant-based), and 42% reduction in water consumption (46% for plant-based). Uncertainty in the results was accounted for using Monte Carlo simulation with 10,000 runs to rank the four burger production scenarios (e.g., conventional and urine-derived beef burger and conventional and urine-derived plant-based burger) based on their environmental impact on global warming, eutrophication, and water use under conditions of baseline, realistic, and maximum uncertainty. Under conditions of realistic uncertainty, implementing urine-derived P fertilizer for beef burger production was considered beneficial for global warming, eutrophication, and water consumption, with 78%, 99%, and 89% of the runs showing environmental benefits, respectively. Due to the lower P fertilizer requirements in plant-based burger production, uncertainty assessment under realistic conditions showed that a reduction in water use was the only expected benefit of implementing recovered P fertilizer, with 71% of the runs providing water use benefits. These results show that closing the nutrient loop by implementing urine-derived P fertilizers can be beneficial when applied to the correct agricultural food system (e.g., beef burger production) and is expected to have the most pronounced benefits with regard to water savings.

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CHAPTER 1

INTRODUCTION

To meet the increasing global demand for food, estimated to rise by 70-100% by 2050, food production in developing countries will need to nearly double (USDA, n.d.-a). As the global population continues to expand, ensuring an adequate food supply becomes paramount, particularly in regions where food scarcity is already a pressing issue. Thus, there is a growing need for innovations in sustainable agricultural techniques to address this challenge. However, the trend towards industrial agriculture and globalization, while aimed at boosting food production, also brings about potentially grave social, environmental, and economic consequences (Altieri, 2009). For instance, the chemicals used in agricultural operations can run off into streams or enter groundwater, posing risks to aquatic life, wildlife dependent on fish, and drinking water supplies (US EPA, 2015). Furthermore, the agricultural sector contributes greatly to climate change through greenhouse gas emissions. Accounting for nearly 10% of total greenhouse gas emissions in 2022, agriculture has emerged as a major driver of the Earth system exceeding its planetary boundaries (Campbell et al., 2017; EPA, 2024).

An important and continuously growing area of interest within sustainable agriculture is the production and use of phosphorus (P) fertilizers. Phosphorus is necessary for plant growth, maintenance, DNA and RNA production, photosynthesis, and more (Mount Sinai, n.d.; Prasad & Chakraborty, 2019). Phosphorus is indispensable for the agricultural sector and lacks substitutes in food production (Johnston, 2000). Presently, over 95% of phosphate rock mined in the US is converted into various P fertilizers, contributing to the more than 85% of global P that is processed to fertilizer

(USGS, 2015, 2024). Additionally, the global consumption of P fertilizers (P_2O_5) witnessed a 4.3% increase in 2023, with projections indicating a further rise of 9.4% by 2027 (USGS, 2024). Given the substantial reliance on mined P for fertilizer production and the escalating fertilizer demand, it becomes imperative to assess the environmental impacts and sustainability of P extraction and fertilizer production processes.

It is known that human development and well-being rely heavily on the agricultural sector, yet we continue to deplete the finite global P supply, a crucial component in plant growth (USGS, 2024; Withers, 2019). While there is debate within the scientific community about when global P reserves will be depleted (most models suggest peak P production between 2025 and 2084), it is widely accepted that the resource is finite and decreasing in availability (Cordell & White, 2011, 2014; Scholz & Wellmer, 2019). The geochemical cycling of P is unlike many of the other essential elements of life (C, H, N, O, etc.) because it lacks a gas phase (Prasad & Chakraborty, 2019). Limited mobility and accessibility underscore the importance of sustainable management and conservation practices of this non-renewable resource. Continuous P mining not only depletes natural reserves, but diminishes ore quality, increases extraction costs, and generates more waste products over time (Steen, 1998). Moreover, global P reserves are disproportionately held, with Morocco controlling over 67%, raising concerns about monopolistic tendencies and geopolitical risks causing supply disruptions (Ridder et al., 2012; USGS, 2024). Addressing the linear nature of the P economy can help mitigate the aforementioned issues associated with P fertilizer production.

The current P fertilizer industrial model is primarily linear (open), consisting of exploration, extraction, beneficiation, processing to fertilizer, and application for crop growth. The linear model has resulted in a human-driven alteration in global P cycling by mobilizing four times the natural level of P from phosphate rock into the environment (Cordell & White, 2014; Lavelle et al., 2005). These unprecedented level of nutrients in the environment has led to eutrophication, which promotes the breakdown of aquatic ecosystems and the gradual degeneration of their functions (Yang et al., 2008). Eutrophication also has economic implications, causing an estimated $2.2 billion annually in the US (Dodds et al., 2009; McDowell & Hamilton, 2013). In contrast to the linear extractive model, circular principles intend to close loops through reuse and recycling along the supply chain to reduce negative environmental and social impacts (De Angelis, 2018). With respect to P cycling, circular principles could entail recovering P from waste streams and reprocessing it for agricultural purposes. There are numerous P-recovery techniques, however they are not widely used currently (Cordell et al., 2011).

One promising technology intended to close the P loop is source-separated human urine diversion. Source separation refers to diverting urine from conventional wastewater flow to avoid the dilution of nutrients or contamination with pathogens (Johansson, 2000). Source-separated urine is known as the “liquid gold” of wastewater due to its substantial amounts of P, nitrogen (N), and potassium (K) (Desmidt et al., 2015; Randall et al., 2016; Volpin et al., 2019). The high P concentrations found in human urine (0.4 – 1.07 g P/L) indicate that it could be influential in closing the P loop. Compared to synthetic fertilizers, urine-derived fertilizers can recover important nutrients, contain lower amounts of heavy metals, and still be effective in stimulating plant growth (Johnston & Richards, 2003; Jönsson et al., 1997). Struvite production as a P fertilizer has been one of the main focuses of urine-derived fertilizers due to its P content and potential as a slow release fertilizer (Hao et al., 2013). However struvite extraction from human waste can be a difficult and costly process, that has not shown to be superior to other P compounds in terms of fertilizer application efficiency (Hao et al., 2013; Johnston & Richards, 2003). Therefore, it is of interest to diversify P precipitation technologies and P end products. Calcium phosphates are a group of alternative P compounds that have shown to be viable fertilizers (Johnston & Richards, 2003). The accessibility and cost of calcium salts compared to magnesium salts make calcium phosphate a worthwhile alternative to struvite for recovered P fertilizer. Additionally, because recovered calcium phosphate has the same effective composition of phosphate rock, it can be directly applied to other industrial applications (Driver et al., 1999). The recovery of high-quality calcium phosphates from source-separated urine also has implication on water use. The use of waterless urinals and source-separated toilets reduces the need for tap water to be used for flushing, subsequently reducing the volumetric load at the wastewater treatment plant. Using source-separation for more sustainable P fertilizer production provides an opportunity to close the P loop and reduce harmful environmental impacts like global warming, eutrophication, and water consumption.

While there is great potential in nutrient recovery from source-separated urine, it is important to understand the impact of implementing this technology to optimize its use and minimize environmental burdens. Anticipatory life cycle assessment (LCA) serves as a tool to provide environmental guidance to researchers and decision-makers, supplementing technical and economic measures when assessing technology readiness. Anticipatory LCA has the potential to actively pinpoint environmental opportunities and redirect research paths before substantial investments are made (Wender et al., 2014).

Previous studies have conducted LCA on P recovery from human urine, however, none of them have fully closed the P loop by relating the impacts to an agricultural output (Hilton et al., 2021; Ishii & Boyer, 2015; Landry & Boyer, 2016). There exists a need to fully bridge this gap and quantify the environmental benefits of implementing urine-diversion for agricultural food production. The production of beef and plant-based burgers were selected as case-studies in which urine-derived fertilizers could be applied. Within the context of this study, beef burgers are considered a traditional agricultural production method with a well-known environmental impact. Moreover, cattle farming is the most important agricultural industry in the US, occurring in a nation where meat consumption exceeds the global average by threefold (*Meat Consumption*, n.d.; USDA, 2023). In contrast, previous studies have shown that a dietary shift away from meat consumption and towards plant-based alternatives is essential for achieving P sustainability (MacDonald et al., 2012; Metson et al., 2016). Additionally, plant-based meat alternatives have shown to be competitive with traditional meat products, as IFIC (2021) found via survey that 65% of Americans consumed plant-based meat alternatives in 2021. For these reasons, the environmental impacts of urine-derived P fertilizers for plant-based burger production were analyzed alongside beef burger production.

The goal of this research was to contribute new insights into the environmental impacts of using urine-derived P fertilizers by closing the nutrient loop and applying the technology to agricultural food systems. The agricultural food systems were divided into two categories: (1) beef burger production and (2) plant-based burger production. The specific objectives expanded on the two main categories of agricultural production by evaluating the environmental impacts of: (1a) beef burger production utilizing conventionally mined P fertilizer, (1b) beef burger production utilizing urine-derived P fertilizer, (2a) plant-based burger production utilizing conventionally mined P fertilizer, and (2b) plant-based burger production utilizing urine-derived P fertilizer. Nitrogen and K were input as conventional fertilizers for all objectives when necessary. The LCA followed the standard methodology of goal and scope definition, inventory analysis, impact assessment, and interpretation.

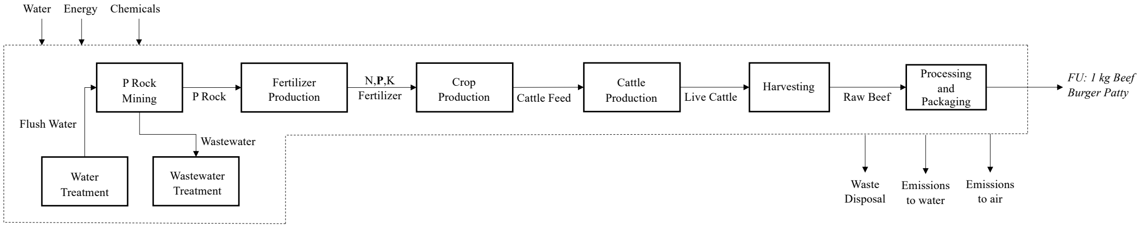
CHAPTER 2

METHODS

2.1 Goal, Scope, and Functional Unit

This study used anticipatory LCA to compare the environmental impacts of producing beef and plant-based burgers using P fertilizer produced from urine diversion and conventional mining processes. The system boundary was defined as cradle-to-gate, meaning the analysis began with raw materials extraction and ended at the burger manufacturer's gate. The system boundary for beef burger production with conventional and recovered P fertilizer is shown in Figure 1. The system boundary for plant-based burger production with conventional and recovered P fertilizer is shown in Figure 2. The distribution, use, and end-of-life phases were left out of this analysis because they were assumed to be the same for both burger products. Similarly, foreground transportation was not explicitly accounted for in this study as variability in transport distances is high and transport has been found to have relatively low environmental impacts within the US beef production system previously (Rotz et al., 2015). The chosen functional unit was 1 kg of uncooked packaged burger patty (beef or plant-based).

Scenario 1: Beef Burger with Conventional P Fertilizer



Scenario 2: Beef Burger with Urine-Derived P Fertilizer

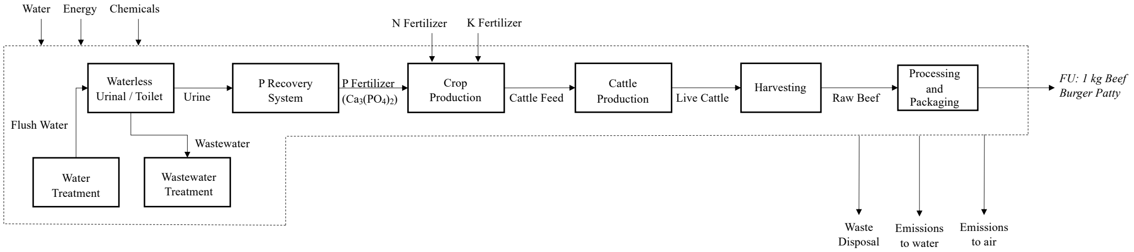
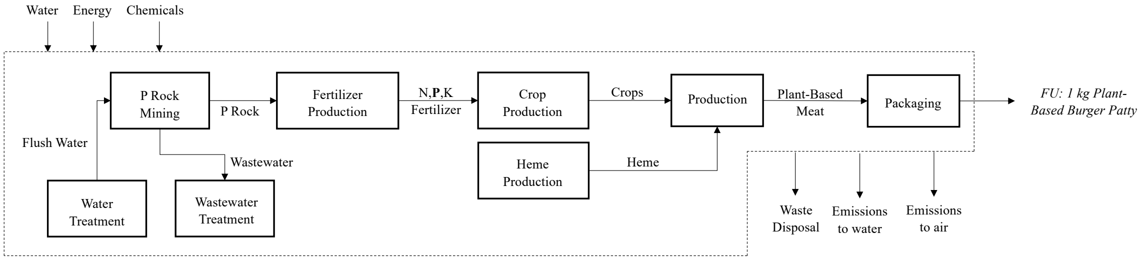


Figure 1. System boundaries for beef burger production with conventional P fertilizer (scenario 1) and urine-derived P fertilizer (scenario 2).

Scenario 3: Plant-Based Burger with Conventional P Fertilizer



Scenario 4: Plant-Based Burger with Urine-Derived P Fertilizer

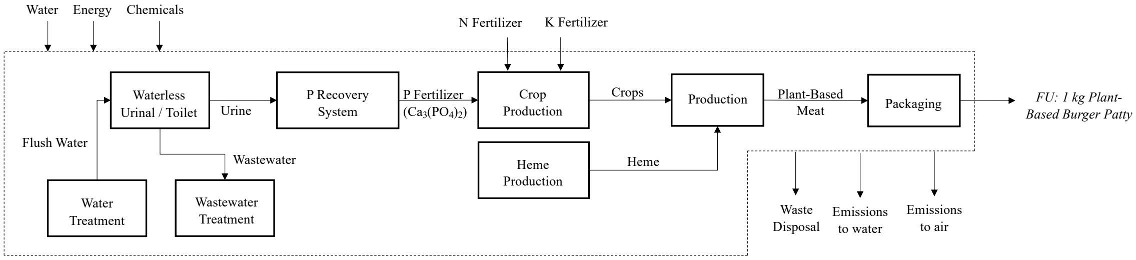


Figure 2. System boundaries for plant-based burger production with conventional P fertilizer (scenario 3) and urine-derived P fertilizer (scenario 4).

2.2 Beef Burger Inventory Data

Inventory data for beef burger production was sourced from recent and relevant literature. A literature review of beef production LCAs can be found in Table S1. The United States Department of Agriculture (USDA) collaborated with the National Cattlemen's Beef Association to assess the environmental footprint of beef cattle production in various regions of the US. Using surveys, farm visits, and other data sources, the USDA collected data on 150 representative cattle production systems throughout the country, then modeled the production using the Integrated Farm System Model (IFSM) to create an inventory of farm inputs and emissions (Rotz et al., 2019). The IFSM's accuracy and applicability have been studied in the past. Comparing feed production and intake, energy use, and production costs, the IFSM displayed less than a 1% difference between predicted values and observed values at the US Meat Animal Research Center and is considered a reliable source of inventory data (Rotz et al., 2013). The provided inventory accounted for cattle feed, energy and water use, and emissions from the cattle production process (Table S2).

In a recent follow-up study, the USDA considered both the harvesting and ground beef production processes that occur after cattle production (Putman et al., 2023). Data collection via a survey of 6 harvesting facilities processing 5.2 million cattle over the data collection period provided the inputs for the harvesting of live cattle. The outputs of the harvesting process were considered to be edible beef, rendered products, and hides. The authors used economic allocation to properly distribute environmental impact to respective processes. The three products' percent of live weight and corresponding economic allocation factors are presented in Table 1. The inventory used in this study accounted for allocation and is presented in Table S2.

Table 1. Revenue allocation factors used in the harvesting phase with associated coproducts as a percent of live weight.

Harvesting Product	**Percent of Live Weight**	**Revenue Allocation**
Edible meat	43.9	89.3%
Rendered products	18.7	8.0%
Hides	4.9	2.7%

Along with the harvesting phase inventory, Putman et al. (2023) provided an inventory for the processing of edible meat into ground beef. It was assumed that the ground beef produced from the processing phase was ready to be packaged as beef burger patties. The processing phase was comprised of grinding and packaging of ground beef. Since the present analysis was focused on the production methods, the packaging step for both beef and plant-based burgers was assumed to be the same. The packaging inventory was sourced from Khan et al. (2019), who made the same assumption while conducting a comparative LCA between a beef burger and Impossible Food burger. Processing and packaging inventory data can be found in Table S2.

2.3 Plant-Based Burger Inventory Data

Inventory data for plant-based burger production were sourced from relevant literature. A literature review of beef production LCAs can be found in Table S3. Due to the proprietary nature of plant-based meat alternatives, precise and recent inventory data were not readily available for analysis. However, in 2017, Impossible Foods funded a publicly available LCA on shifting dietary patterns by implementing their plant-based burger (Goldstein et al., 2017). For this study, Impossible Foods provided the researchers with primary bulk data from a pilot plant producing hundreds of kilos of plant-based burgers per day (Goldstein et al., 2017). Impossible Foods uses heme to replicate the flavors and aroma that make meat unique (Brown, 2018). The heme production process consists of fermenting genetically modified yeast that produces soybean leghemoglobin (heme; Eisen, 2018). The inventory from the pilot plant included heme production, and was chosen to represent the plant-based burger scenario in this research due to its creation from a detailed and reputable data source. The data uncertainty arising from pilot scale processes was addressed via uncertainty assessment. The inventory for this plant-based burger is provided in Table S4.

2.4 Urine-Derived Phosphorus Fertilizer Production Inventory Data

This study assumed that source separation for urine diversion was implemented at the city scale, and any capital requirements necessary for source separation implementation were omitted from the analysis. Neglecting the environmental impact of capital goods is typical of LCA research (Goedkoop et al., 2016). Source separation involves the diversion of urine from standard wastewater streams to prevent nutrient dilution or pathogen contamination (Johansson, 2000). Without flush water to send the urine through pipes, there can be stagnation and subsequent scaling within pipes. To address scaling, acid dosing schemes at the point of use have been developed, suggesting a cleaning vinegar dose of 0.05 L per L urine is sufficient to prevent scaling within pipes (L. Crane, personal communication, November 20, 2023).

To isolate the effects of P recovery in agriculture, the recovered fertilizer was chosen to be one containing only P as the active fertilizing element. Zhang et al. (2022) recently determined a method for precisely recovering high-purity calcium phosphate from human urine, which was used as the recovery process in this study. The kinetics and precipitation of calcium phosphate can be complex, so it was assumed for this analysis that the final product is the basic tricalcium phosphate ($Ca_3(PO_4)_2$). It was found that 100% P recovery via precipitation occurred at an initial pH of 4 while dosing with calcium hydroxide $Ca(OH)_2$ in a 1.67 Ca/P molar ratio (Zhang et al., 2022). While a pH of 4 is optimal for P precipitation, stored urine without stabilization results in the hydrolysis of urea to ammoniacal nitrogen, usually happening within a few days, which raises the pH around 9 (Martin et al., 2022; Udert et al., 2003, 2006). At a pH of 9, P precipitation via $Ca(OH)_2$ will be hindered by the presence of carbonate (CO_3^{2-}) ions, forming the unwanted calcium carbonate ($CaCO_{3(s)}$). To prevent $CaCO_{3(s)}$ formation during P recovery, the stored urine must be dosed with acid, keeping the pH low until used in the precipitation reaction. Hellström et al. (1999) found that the one-time dosage of 60 meq/L sulfuric acid (H_2SO_4) was enough to maintain a pH of 3 for 200 days of storage. It was assumed that the recovery of P precipitate from human urine will occur within the 200-day period in which the urine is stabilized with respect to pH. Due to the novel nature of P precipitation from human urine, there is little data on process energy inputs. Therefore, it was assumed that calcium phosphate precipitation was similar in energy demand to struvite precipitation. Maurer et al. (2003) estimated the energy requirements for struvite production from urine to be 16 MJ/kg P, and the energy input was assumed to represent the mixing and drying stages of P recovery. The system boundary for P recovery is displayed in Figure 5. The full inventory for the recovered P fertilizer process is presented in Table S5.

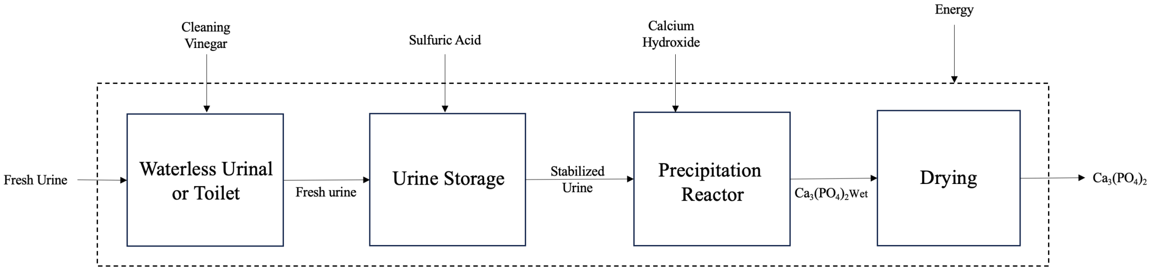


Figure 3. System boundary for urine-derived P fertilizer ($Ca_3(PO_4)_2$) production.

2.5 Co-Benefits Inventory Data

The adoption of urine diversion for P fertilizer recovery offers direct advantages in reducing the need for conventional P fertilizer production, as well as indirect co-benefits such as water conservation. Urine-diversion via source separation does not use water to flush urine to be treated, therefore reducing the need for treated flush water. Similarly, the wastewater treatment plant will receive a reduced volumetric load from the avoided flushing. Due to the lack of US-based water and wastewater treatment plant processes existing in Ecoinvent, two processes representing these treatment operations were created. The water treatment inventory was sourced from Hilton et al. (2021), who used a similar technique to conduct a LCA on urine diversion previously. A basic wastewater treatment inventory was sourced from EPA (2021), representing a conventional plug-flow activated sludge wastewater treatment configuration. The inventories and associated emissions for water and wastewater treatment are presented in Tables S6 and S7, respectively.

Precipitating P fertilizer from urine streams also reduces the P load that needs to be treated at the wastewater treatment plant. It was assumed that aluminum sulfate was used as a coagulant at the wastewater treatment plant, and a molar ratio of 2 Al:P was sufficient to reduce P levels to below regulatory limits (Neethling, 2013). For every 1 kg burger being produced using recovered P fertilizer, there is an associated reduction in coagulant use at the wastewater treatment plant from not having to remove P from the wastewater. The coagulant reduction co-benefit was taken into account and described more in Table S5.

2.6 Urine-Derived Beef and Plant-Based Burger Inventories

Burger inventories for the urine-derived P fertilizer scenarios were the exact same as the conventional scenarios, however all P terms were replaced with the recovered P process described previously. P replacements were required for inputs like corn, grass, alfalfa, potato protein, coconut oil, etc., which require upstream P fertilizer as an input to grow the crops. The replacement was conducted on a P basis. For example, to change an input of P_2O_5 fertilizer to the recovered $Ca_3(PO_4)_2$, the amount of P contained in the P_2O_5 was calculated, then an equivalent amount of P was entered as $Ca_3(PO_4)_2$. For P-containing inputs that also had N and K components (NPK fertilizers and diammonium phosphate), each compound was split up based on their N, P, and K content and then converted to urea (H_2NCONH_2), $Ca_3(PO_4)_2$, and potassium oxide (K_2O) respectively. Urea and potassium oxide were assumed to be appropriate fertilizers to agricultural food production, and we're often present alongside NPK and P fertilizers in existing Ecoinvent processes. Fertilizer substitution ensured that the nutrient inputs to crops remained constant but allowed recovered P fertilizer to be used instead of conventional P fertilizer.

2.7 Environmental Impact Metrics

The Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI 2.1) was used to quantify the environmental impact of switching P fertilizer sources (J. Bare, 2012). TRACI was the preferred environmental impact method due to its development and applicability within the United States (US EPA, 2024a). The impact assessment methodology translates input processes and emissions into measurable environmental effects along the cause-and-effect pathway of environmental degradation (J. C. Bare, 2010). TRACI, formulated by the U.S. EPA, incorporates location-specific characteristics tailored for the United States and North America. It employs midpoint impact categories better aligned with U.S. environmental regulations and priorities (J. C. Bare, 2011). TRACI uses ten midpoint impact categories: ozone depletion (kg CFC-11 eq), global warming (kg CO_2 eq), smog (kg O_3 eq), acidification (kg SO_2 eq), eutrophication (kg N eq), carcinogens (CTUh), non-carcinogens (CTUh), respiratory effects (kg PM2.5 eq), ecotoxicity (CTUe), and fossil fuel depletion (MJ surplus). TRACI does not have the capacity to calculate water consumption at the time of this study, so ReCiPe 2016 (H) was used to assess water usage (m^3). ReCiPe 2016 is considered representative of the global scale, instead of the European scale as it was done in ReCiPe 2008. The hierarchist (H) perspective was assumed for this analysis because it is based on the most common policy principles concerning time frame and other issues (Pré Sustainability, 2023).

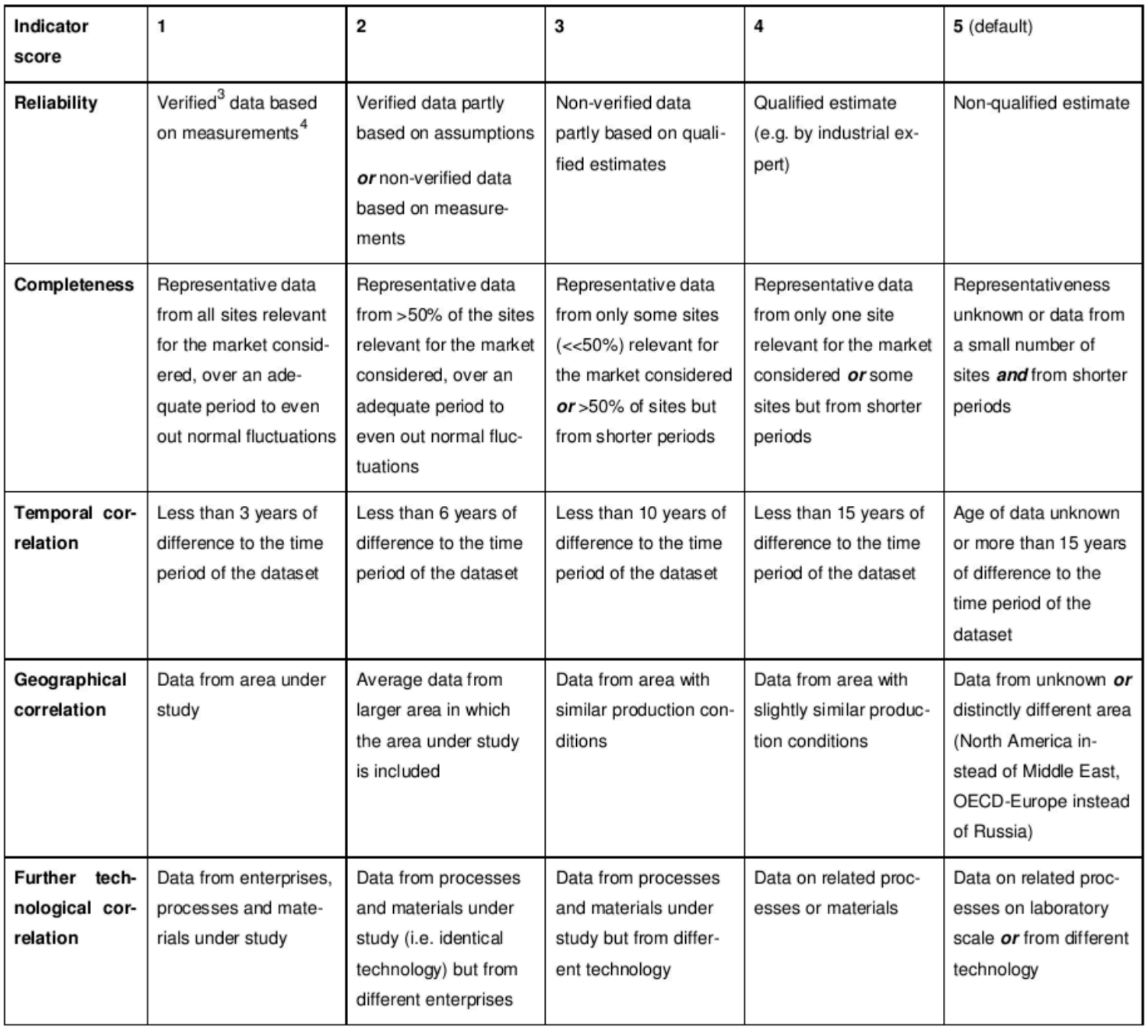
The environmental impact results are presented as scaled characterization values, meaning the scenario or process with the highest environmental impact for a specific category was set to 100% and the other scenarios or processes were scaled accordingly. Because this research is focused on the role of P in agriculture, impact categories of relevance include global warming, eutrophication, and water use.

2.8 Uncertainty Assessment

A Monte Carlo simulation was used to account for uncertainty within the inventory data. The Ecoinvent pedigree matrix was used as a semi-quantitative approach to address uncertainty within input data. The pedigree matrix ranks all process inputs on a scale from 1-5 depending on their reliability, completeness, temporal correlation, geographic correlation, and technical correlation, where 1 has the least uncertainty, and 5 has the highest (Table 2). These rankings were used to define log-normal distributions for all process inputs, instead of relying on one value. Each of the four burger production scenarios were assessed under conditions of baseline, realistic, and maximum uncertainty. Baseline uncertainty did not use the pedigree matrix and relied on the uncertainty of the upstream distributions to determine results, making it the scenario with the least uncertainty. Maximum uncertainty required all processes created for this study (burger inventory, P fertilizer precipitation, water and wastewater treatment, etc.) to be set at level 5 in the Ecoinvent pedigree matrix. Realistic uncertainty required that all input processes be assigned pedigree matrix values that best represented the data source from which they were sourced. Assigned values and reasoning for realistic uncertainty can be found in process inventory tables within the supplementary tables (Tables S2, S4, S5, S6, and S7). While realistic uncertainty provides a general understanding of data quality and confidence in outcomes, this approach is semi-quantitative and relies on some subjectivity. Therefore, baseline and maximum uncertainty were assessed along with realistic uncertainty to understand the range of possible environmental outcomes based on uncertainty in input data.

Under each condition of baseline, realistic, and maximum uncertainty, TRACI was used to determine the distribution of each environmental impact category for all burger production scenarios. The uncertainty assessment focused on global warming, eutrophication, and water consumption, as these impact categories were the focus of this study. The mean and standard deviation for each environmental impact category calculated by TRACI and ReCiPe were assumed to represent a log-normal distribution. The generated distribution parameters were then used to run a Monte Carlo assessment in Microsoft Excel with 10,000 runs to rank each scenario's environmental impact based on impact category. For example, 4 distributions (conventional and recovered beef burger, and conventional and recovered plant-based burger) of 10,000 observations of global warming impact (kg CO_2 eq) were generated using the log-normal distribution parameters provided by TRACI and ReCiPe. For each observation, the 4 scenarios were ranked from highest global warming impact to lowest, in order to understand which burger production scenario was most environmentally beneficial, and which was worst. The results were compiled and visualized graphically. Distribution creation, environmental ranking, and graphic visualization was repeated for eutrophication and water use impacts to understand how data uncertainty affects the environmental impact outputs.

Table 2. Ecoinvent 3.0 pedigree matrix used for semi-quantitative uncertainty assessment.



Indicator score	**1**	**2**	**3**	**4**	**5** (default)
Reliability	Verified[3] data based on measurements[4]	Verified data partly based on assumptions ***or*** non-verified data based on measurements	Non-verified data partly based on qualified estimates	Qualified estimate (e.g. by industrial expert)	Non-qualified estimate
Completeness	Representative data from all sites relevant for the market considered, over an adequate period to even out normal fluctuations	Representative data from >50% of the sites relevant for the market considered, over an adequate period to even out normal fluctuations	Representative data from only some sites (<<50%) relevant for the market considered ***or*** >50% of sites but from shorter periods	Representative data from only one site relevant for the market considered ***or*** some sites but from shorter periods	Representativeness unknown or data from a small number of sites ***and*** from shorter periods
Temporal correlation	Less than 3 years of difference to the time period of the dataset	Less than 6 years of difference to the time period of the dataset	Less than 10 years of difference to the time period of the dataset	Less than 15 years of difference to the time period of the dataset	Age of data unknown or more than 15 years of difference to the time period of the dataset
Geographical correlation	Data from area under study	Average data from larger area in which the area under study is included	Data from area with similar production conditions	Data from area with slightly similar production conditions	Data from unknown ***or*** distinctly different area (North America instead of Middle East, OECD-Europe instead of Russia)
Further technological correlation	Data from enterprises, processes and materials under study	Data from processes and materials under study (i.e. identical technology) but from different enterprises	Data from processes and materials under study but from different technology	Data on related processes or materials	Data on related processes on laboratory scale ***or*** from different technology

CHAPTER 3

RESULTS AND DISCUSSION

3.1 Environmental Impact of Urine Diversion on Burger Production

The environmental impact of implementing urine-derived P fertilizer for burger production is displayed in Figure 4. The results for every environmental impact category are represented as scaled characterization values, with the scenario exhibiting the highest impact set at 100%. Given that the eleven impact categories utilize diverse units of measurement (e.g., kg CO_2 eq for global warming and m^3 for water consumption), using scaled characterization values allows for a comparable assessment of all burger production scenarios across different environmental impact categories.

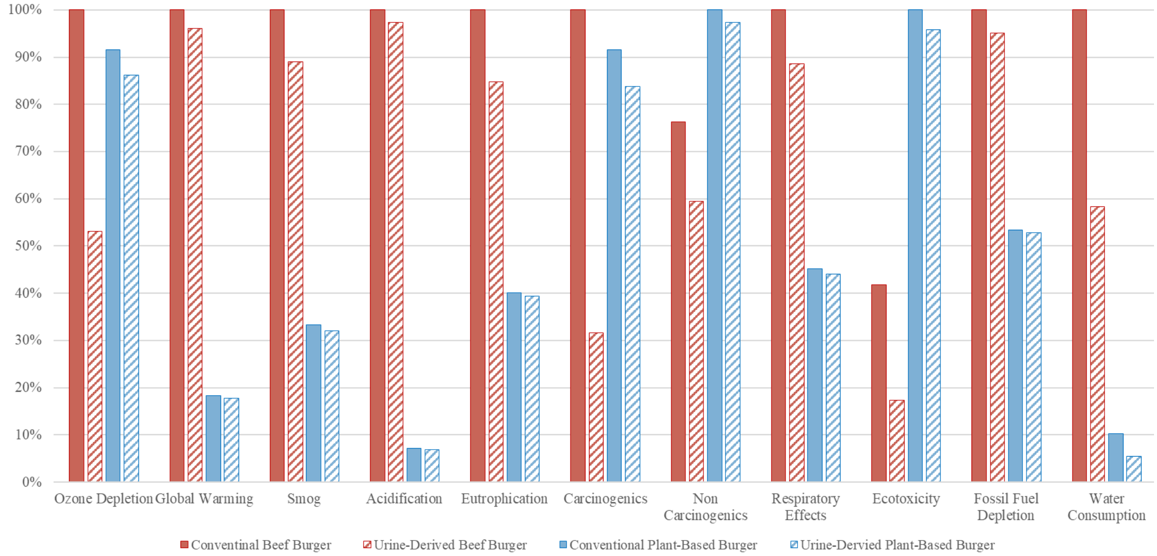


Figure 4. Environmental impact assessment results for conventional beef burger, urine-derived beef burger, conventional plant-based burger, and urine-derived plant-based burger (values normalized to 1 kg of burger patty).

As seen in Figure 4, nine of eleven impact categories show the conventional beef burger has a larger environmental impact than the conventional plant-based burger. The comparison of beef and plant-based burgers has been studied previously, typically with a focus on global warming and water consumption impact categories. Figure 4 shows a >80% decrease in global warming and >90% decrease in water usage when comparing beef to plant-based burgers, which is consistent with previous study's findings (Dettling, 2016; Heller & Keoleian, n.d.; Khan et al., 2019; Mazac et al., 2023; Smetana et al., 2021).

For all burger production scenarios and all considered environmental impact categories, the implementation of urine-derived P fertilizers provided environmental benefits. However, the environmental benefits were more pronounced when applied to beef burger production due to the increased P fertilizer requirement. As modeled, beef burger production required approximately 8 times the amount of P to make the same mass of burger, with alfalfa hay, grass hay, and distiller's grains being the most P-intensive inputs. The difference in P requirements is largely because of the difference in crop inputs for both systems. Plant-based burger production did not require the continued feed inputs necessary to raise cattle, thereby reducing its P requirements. The increased P fertilizer requirements for beef burger production required more urine to be diverted when using recovered P fertilizer, increasing the environmental benefits generated from offsetting water use, water and wastewater treatment, and conventional P fertilizer production.

The ozone depletion impact category saw a 47% decrease after conventional P fertilizer was replaced with recovered P fertilizer in beef burger production, which was driven primarily by offsets in chemical use during water and wastewater treatment. Preventing water usage at the toilet or urinal reduces the need for water and wastewater treatment. Sodium hydroxide and chlorine gas, chemicals are often used in water and wastewater treatment for pH adjustment, precipitation processes, coagulation, and disinfection, provided the most offsets to ozone depletion. It is important to note that the scaled characterized values give insight into relative environmental impacts between burger production scenarios and do not show the relative impacts between impact categories.

Noncarcinogens and ecotoxicity stood out as environmental impact categories in which conventional plant-based burgers had an unfavorable impact when compared to beef burgers. The major driver of noncarcinogenic and ecotoxicity impacts within plant-based burger production came from crop production that was not used in the production of beef burgers. For example, wheat grain (insecticide emissions) and coconut oil (wood preservative process) were the greatest contributors to noncarcinogenic and ecotoxicity impacts for plant-based burger production, but were not inputs for beef burger production, causing the difference in impact. Additionally, mine tailings (e.g., sulfidic tailings) were a significant contributor to ecotoxicity within plant-based burger production. Mine tailing pollution stems from the use of chemicals such as sulfuric acid, copper sulfate, and iron sulfate as ingredients within the plant-based burger production line, which require mining of natural sulfate minerals.

The largest reduction in environmental impacts after implementing recovered P fertilizer came in the carcinogens impact category for beef burger production, receiving 68% reduction. The reduction in carcinogen impact was driven almost entirely by the avoided process of disposing of redmud which was a byproduct of bauxite digestion. The bauxite digestion process is required in the manufacturing of aluminum hydroxide, which is a key ingredient in producing aluminum sulfate. Precipitating P from diverted human urine reduces the P load at the wastewater treatment plant, and reduces the coagulant (aluminum sulfate) dosing, subsequently reducing environmental impact with regards to carcinogens. It is important to note that the uncertainty associated with the inputs and methods used to calculate carcinogen and noncarcinogen environmental impact was by far the greatest for any impact category.

While implementing recovered P fertilizer in burger production provided environmental benefits, it is expected that the environmental benefits of resource recovery from human urine could be markedly enhanced through simultaneous N recovery. Considering N is the primary nutrient in human urine and a crucial macronutrient for plant growth, it presents an opportunity to further offset traditional fertilizer production, reduce environmental impacts, and close the nutrient loop.

3.2 Input Contribution of Beef Burger Production

The environmental impact of beef burger production with conventional fertilizer can be seen in Figure 5. All values are represented as a percentage of the total environmental impact for that category. ReCiPe 2016 (H) was used to obtain water consumption impacts, while all other environmental impact categories were calculated using TRACI 2.1. Each impact category was split into process contributions that represent the four main stages of beef burger production: Feed production, cattle raising, harvesting, and processing (Asem-Hiablie et al., 2019; Putman et al., 2023; Rotz et al., 2019).

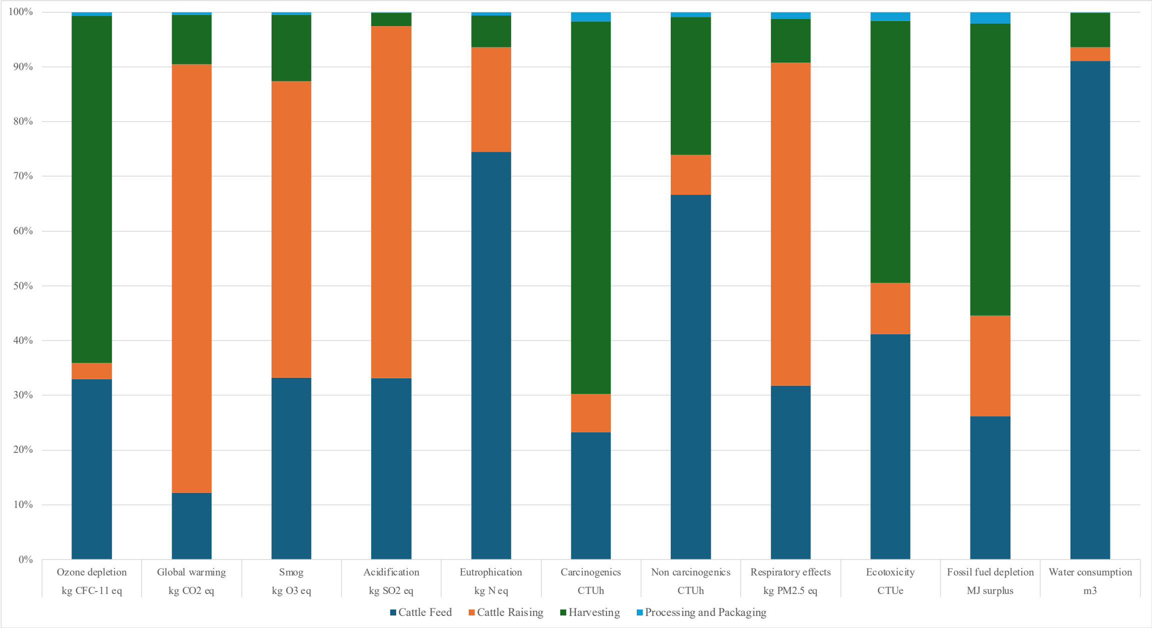


Figure 5. Scaled characterization environmental impact results for the production of 1 kg beef burger with conventional P fertilizer. Process contribution was divided into the four main production stages: Cattle feed, cattle raising, harvesting, and processing and packaging.

Figure 5 provides insight into which stages of production drive environmental impact categories. The cattle-raising phase was the primary contributor to many impact categories, including global warming (78%), smog (54%), acidification (64%), and respiratory effects (60%). The negative environmental impact of raising cattle, particularly on global warming, has been well researched, with the first half of cattle's lives, the cow-calf phase, contributing most to global warming impacts (Asem-Hiablie et al., 2019). Feed production was found to be the primary contributor to eutrophication (75%) and water consumption (91%) due to fertilizer runoff and irrigation needs, respectively. The processing and packaging phase was found to have a negligible environmental impact, contributing ≤ 2% for all impact categories. The relative unimportance of processing and packaging to environmental impacts in the beef production line has been found in previous research (Asem-Hiablie et al., 2019; Putman et al., 2023). In contrast, the harvesting phase had a substantial environmental impact in categories like ozone depletion (63%) and carcinogenics (68%) due to its use of refrigerants and other chemicals. Figure 5 serves as verification of the model's results, as previous studies have produced similar results for impact categories like ozone depletion, global warming, water consumption, and eutrophication (Asem-Hiablie et al., 2019; Putman et al., 2023).

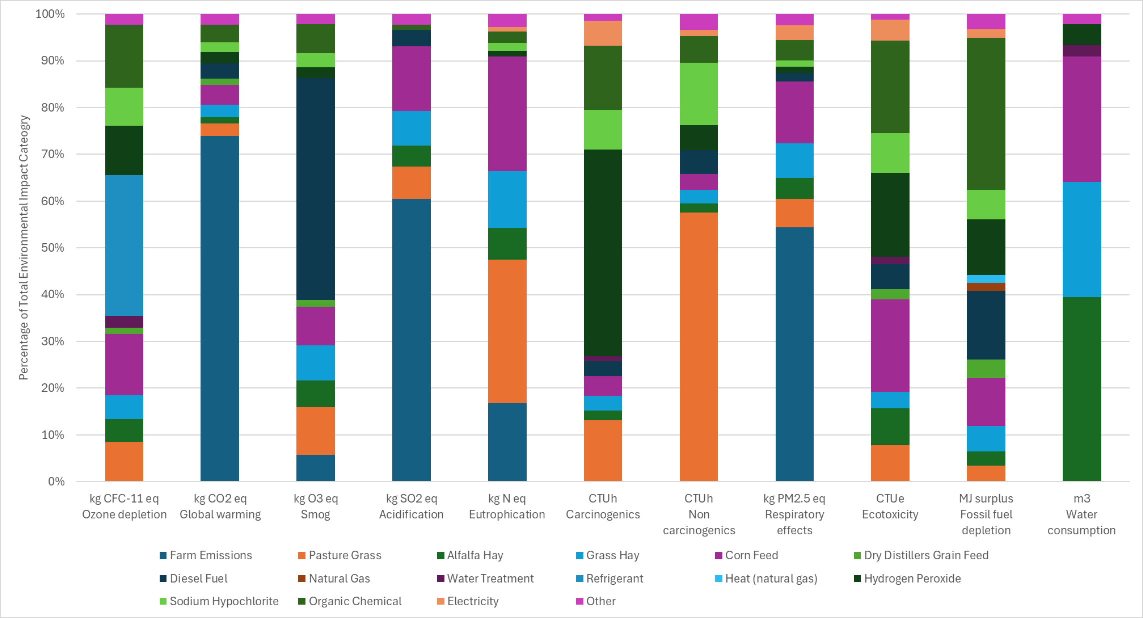


Figure 6. Scaled characterization environmental impact results for the production of 1 kg beef burger with conventional P fertilizer. Process contribution is divided into main process inputs, with inputs contribution <1% classified as “Other”.

Figure 6 provides a more detailed look at the specific inputs that drive environmental impact during beef burger production with conventional P fertilizer. Processes that contributed <1% to an impact category were grouped into “other” for that impact category. On-farm emissions to air were found to be responsible for 74% of the global warming potential in the beef production process. Enteric fermentation is primarily responsible for the large amounts of methane released during cattle production, while the nitrification and denitrification processes that occur in soil and stored manure are responsible for nitrous oxide emissions (Rotz et al., 2019). Methane and nitrous oxide are the most important chemical species contributing to global warming during the cattle production phase, with global warming potentials of around 28 and 273 times that of CO_2 (US EPA, 2024c).

Feed production was the most important impact driver of eutrophication, with 31% of impacts coming from pasture grass, 25% from corn feed, and 19% from grass and alfalfa hay. Eutrophication impacts from these crop processes are primarily due to N and P emissions to water bodies via leaching or runoff from the application of manure or chemical fertilizer (US EPA, 2023b). Approximately 16% of eutrophication impacts also came from on-farm activities. This was primarily due to ammonia that is released from animal waste, which can form ammonium when in contact with water and contribute to eutrophication impacts (USGS, 1996).

Of the 91% of water consumed during the feed production phase, 39% was used for alfalfa hay, 25% for grass hay, and 27% for corn feed. Water consumption during the feed production phase was due to irrigation needs for crop growth. Notably, the pasture grass had a smaller water footprint compared to the farmed and processed feed inputs because it was modeled as reliant on rainfall for water consumption. Drinking water needed to support cattle during the cattle-raising process only accounted for 3% of the overall water usage to produce a beef burger.

Figure 7 provides a detailed look at the inputs that drive environmental impacts during beef burger production with urine-derived P fertilizer. Processes that contributed

<1% to an impact category were grouped into “other” for that impact category. A negative value indicates that replacing conventional P fertilizer with recovered P fertilizer for that input made it have a net environmental benefit. Although an input marked by a negative value continued to bear negative environmental impacts from its production and application, the environmental offsets generated through its utilization were sufficient to overcome those negative impacts. Offsets are only present within inputs that contain P fertilizer.

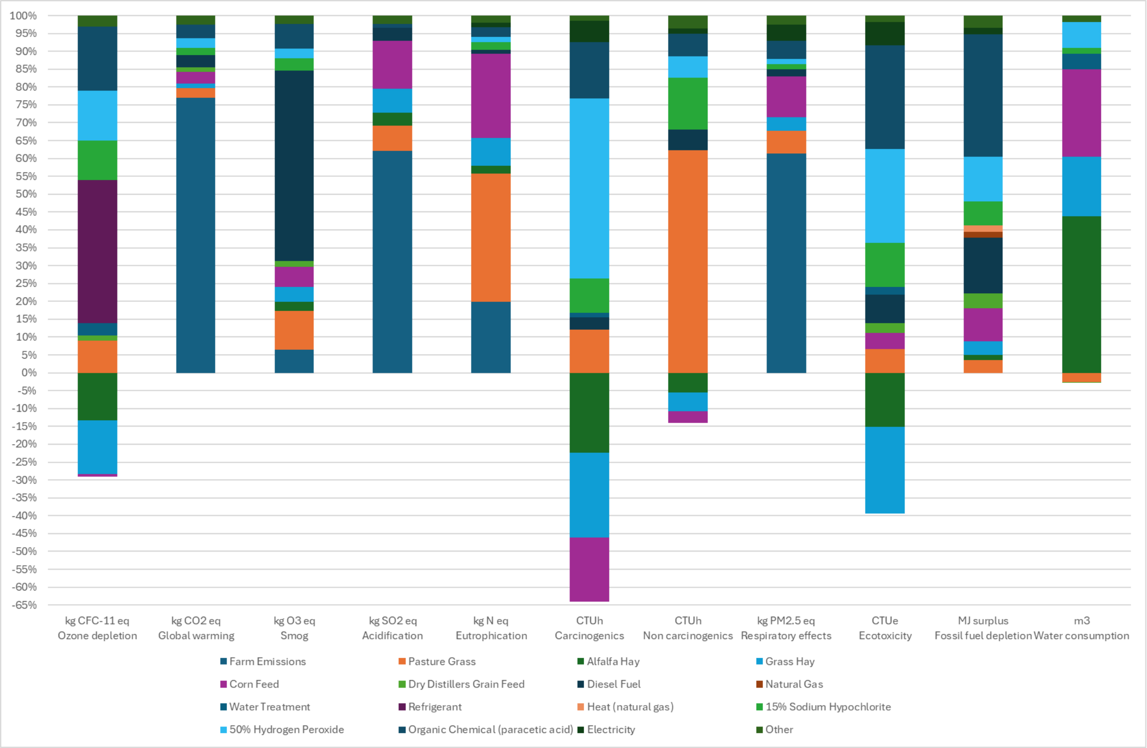


Figure 7. Scaled characterization environmental impact results for the production of 1 kg beef burger with urine-derived P fertilizer. Process contribution is divided into main process inputs, with inputs contribution <1% classified as “Other”.

The difference between Figures 6 and 7 is the substitution of conventionally mined P fertilizer with recovered P fertilizer from urine diversion. P fertilizer substitution only affected inputs with P fertilizer, including pasture grass, corn feed, dry distillers grain, and grass and alfalfa hay. For alfalfa hay, grass hay, and corn feed, the environmental benefits from using recovered P fertilizer (e.g., offsetting traditional P fertilizer production, reducing water demand, and reducing wastewater treatment) resulted in larger benefits than harmful impacts in some categories. Net positive environmental impacts for certain inputs was seen in impact categories like ozone depletion, carcinogens, noncarcinogens, ecotoxicity, and water consumption. As mentioned previously, decreases in ozone depletion were primarily due to reduced usage of sodium hydroxide and chlorine gas from offsetting water and wastewater treatment, while avoiding the production and use of aluminum sulfate at the wastewater treatment plant reduced the impact in categories like carcinogens, noncarcinogens, and ecotoxicity.

Many macroscale trends remained after substituting conventional P fertilizer with recovered P fertilizer. For example, farm emissions still dominated global warming impact, while feed production contributed greatly to eutrophication impacts and water consumption. Since Figure 7 presents environmental impacts as a percentage of the total impact, the importance of P substitution can be lost if most processes are reduced by similar amounts. The true effect of P fertilizer substitution within these notable impact categories such as global warming, eutrophication, and water consumption, can be seen by comparing the magnitudes of important inputs within their respective impact category. Figure 8 provides a comparison of the magnitudes of select impact categories for beef burger production with conventional and recovered P fertilizer. Pasture grass, alfalfa hay, grass gay, corn feed, and dry distillers grain are displayed because they are the inputs that received P fertilizer substitution.

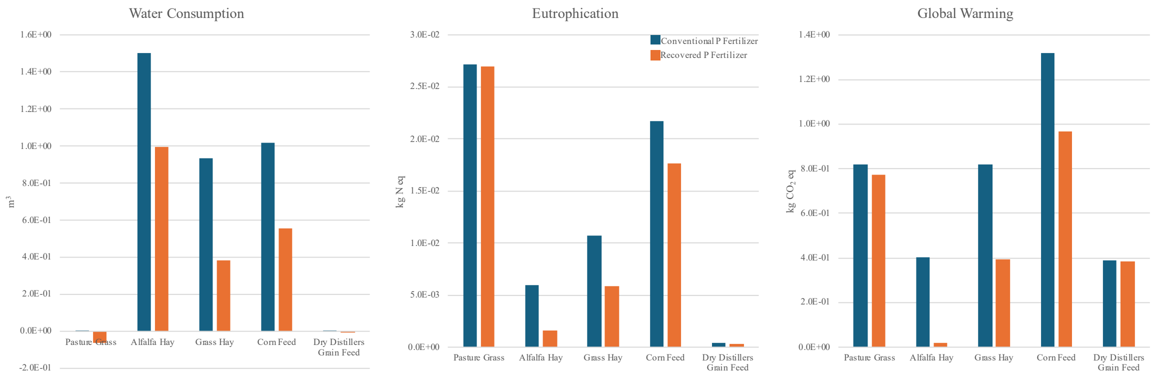


Figure 8. Comparison of water consumption, eutrophication, and global warming impact magnitudes for beef burger production with conventional and recovered P fertilizer.

The extent to which environmental impacts were lessened by the use of recovered P in beef burger production was dependent on the amount of P required to produce the feed. Pasture grass required approximately 1.7 g P/kg beef burger, alfalfa hay required 14 g P/ kg beef burger, grass hay required 16 g P/ kg beef burger, corn feed required 13 g P/ kg beef burger, and dry distillers grain required 0.2 g P/ kg beef burger. The increased P inputs for grass hay, alfalfa hay, and corn feed corresponded with the largest drop in environmental burden after substituting fertilizer with recovered P. In contrast, inputs like pasture grass and dry distillers grain showed much smaller benefits after substitution due to their low P fertilizer requirements. The difference in environmental benefits depending on P fertilizer requirements emphasizes the importance of applying recovered P to the proper agricultural system in order to maximize environmental benefits.

While water consumption was slightly reduced by avoiding the mining and production of conventional P fertilizers, the main driver (85%) of water savings after P fertilizer substitution was the offsetting of water use for toilet flushing. Approximately 60 L of diverted urine is needed to produce enough recovered P fertilizer to produce 1 kg beef burger. With no water sent to the toilet, approximately 1300 L (1.3 m^3) of water is saved per kg of beef burger produced. Pasture grass showed a negative water consumption (Figure 8) because the avoided water consumption from reduced toilet flushing was greater than the water used to maintain the pasture (assumed to be primarily from rain).

Eutrophication impacts are generally attributed to leaching and runoff that occurs from fertilizer application on agricultural fields. The replacement of conventional P fertilizer with recovered P fertilizer does not directly address the issue of runoff and was assumed to have the same behavior when applied to agricultural fields, which is why the reduction in eutrophication was not as large as water consumption (Figure 4). The eutrophication benefits seen in Figure 8 were mainly driven by the avoided production of conventional P fertilizers. Mining phosphate rock and processing it to P fertilizer has associated P losses, and it has been found that waterways in P mining areas have elevated P levels when compared to areas without phosphate mining (Duan et al., 2021). Another conventional source of eutrophication is wastewater treatment effluent (US EPA, 2023c). It was assumed in both scenarios (conventional and urine-derived P production), that the wastewater treatment facility was meeting effluent standards and not greatly contributing to eutrophication. Reduced P load to the wastewater treatment plant was accounted for in this study by offsetting chemical coagulant (aluminum sulfate) use but had no additional benefits with regard to eutrophication reduction.

The reduction in global warming impacts was primarily attributed to the avoided wastewater treatment that results from not flushing toilets, as well as avoided electricity use from various avoided processes such as conventional P fertilizer production and water treatment. Wastewater treatment plants are recognized as considerable sources of atmospheric greenhouse gases, responsible for the emission of high-potency greenhouse gases like methane and nitrous oxide (Mannina et al., 2018). The wastewater treatment plant modeled in this study accounted for methane and nitrous oxide emissions, as well as emissions from biogas flaring. Reducing the volumetric load sent to the wastewater treatment plant consequently reduced the greenhouse gas emissions and lowers the process' global warming impacts. Reduction in global warming impacts was more pronounced in cattle feed inputs with higher P fertilizer requirements because they required more diverted urine and prevented higher amounts of flush water from being sent to the treatment facility.

3.3 Input Contribution of Plant-Based Burger Production

The environmental impact of plant-based burger production with conventional fertilizer can be seen in Figure 9. All values are represented as a percentage of the total environmental impact for that category. ReCiPe 2016 (H) was used to obtain water consumption impacts, while all other environmental impact categories were calculated using TRACI 2.1. Each impact category was split into process contributions that represent the main stages of plant-based burger production: Ingredients (crops and additives), burger production, and packaging (Goldstein et al., 2017; Khan et al., 2019).

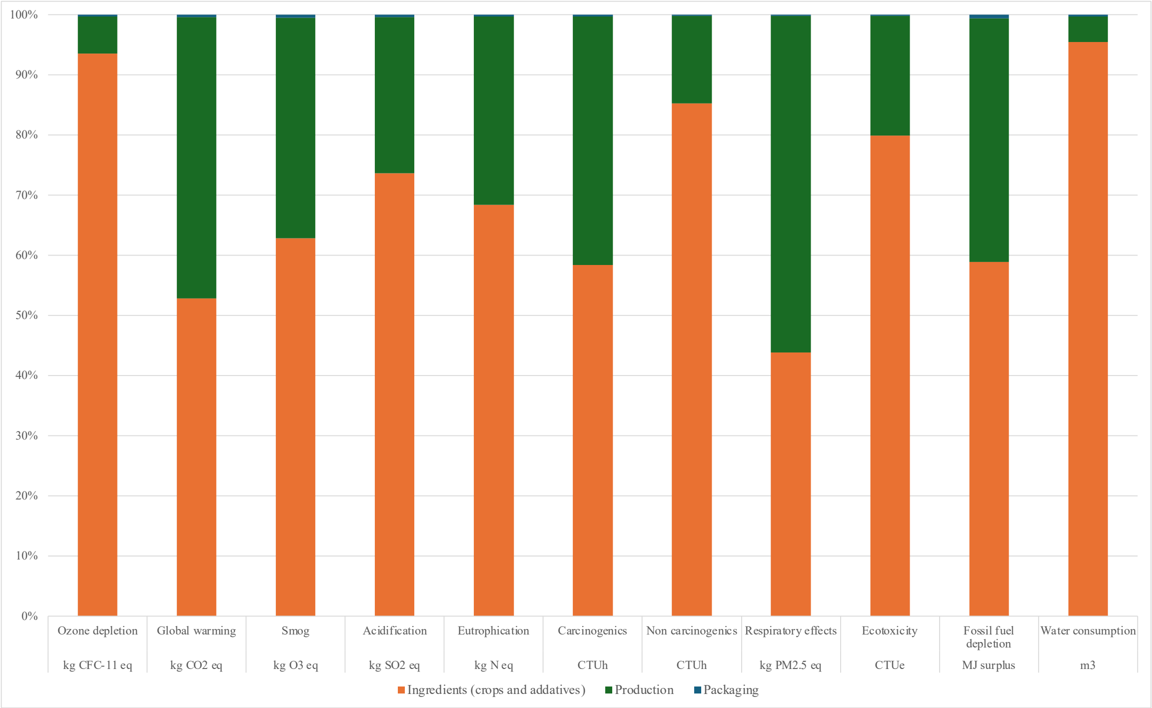


Figure 9. Scaled characterization environmental impact results for the production of 1 kg plant-based burger with conventional P fertilizer. Process contribution was divided into the three main production stages: Ingredients (crops and additives), production, and packaging.

Figure 9 provides insight into which stages of production drive environmental impact categories. Environmental impacts from ingredients (crop production and additives) were the primary contributors to nearly all environmental impact categories, responsible for 70% of impacts on average. Specifically, the plant-based burger ingredients contributed 53% to global warming, 68% to eutrophication, and 95% to water consumption. The production phase had minimal inputs but contributes the second most to environmental impacts in nearly all categories. The packaging phase had negligible environmental impact, contributing <1% for all impact categories. Figure 9 serves as verification of the model's results, as previous studies have produced similar results for impact categories like global warming potential, eutrophication, and water consumption (Khan et al., 2019).

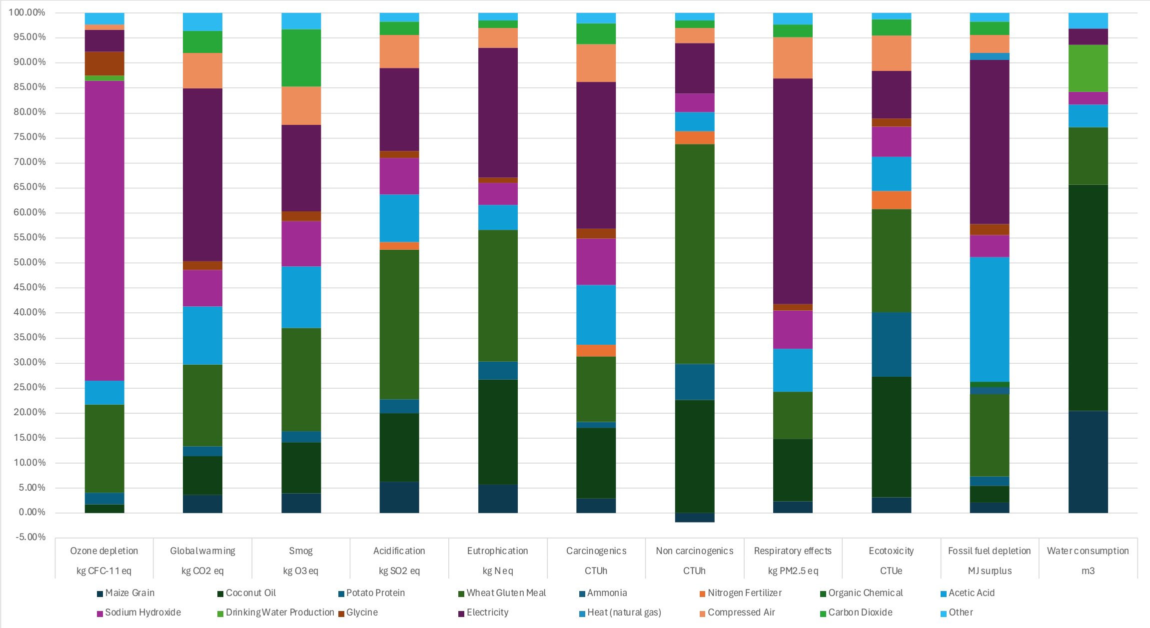


Figure 10. Scaled characterization environmental impact results for the production of 1 kg plant-based burger with conventional P fertilizer. Process contribution is divided into main process inputs, with inputs contribution <1% classified as “Other”.

Figure 10 provides a more detailed look at the inputs that drive environmental impact during plant-based burger production with conventional P fertilizer. Processes that contributed <1% to an impact category were grouped into “other” for that impact category. In contrast to beef burger production, electricity consumption was the primary contributor to global warming in the production of plant-based burgers using conventional P fertilizer, accounting for 35% of the impact. Electricity was mainly used for the processing of the plant-based burger and showed the largest contribution to global warming impacts due to a lack of on-farm processes required in the beef burger production scenario. Additionally, agricultural inputs such as wheat gluten meal (16%)

and coconut oil (8%), along with chemicals like acetic acid (12%) and sodium hydroxide (7%) contributed to global warming due to the electricity and energy inputs required in their production.

Crop production was shown to be the main contributor to eutrophication impacts (55%), with wheat gluten meal (26%) and coconut oil (21%) as the largest contributors. Crop production dominating eutrophication impacts was an expected result, as runoff and leaching of N and P from agricultural processes are known to be a major contributor to eutrophication (US EPA, 2023b). Electricity contributed 26% to eutrophication effects, which was primarily due to spoils from lignite and coal mining which contain a heterogenous mix of pollutants, including P and N. As the average US electrical grid continues to decarbonize, the environmental impact of electricity production will consequently decrease, making global warming and eutrophication impacts less prominent in future food production (US EIA, 2023).

Within the water consumption impact category, crop inputs such as coconut oil (45%), maize grain (20%), and wheat gluten meal (11%) were primarily responsible for consumption during their growth. Water needed during the processing stage also contributed 9% to the overall water consumption. Potato protein was the only crop input without a significant water requirement compared to the others, because its production was modeled using both rainwater and irrigation water. Additionally, potato protein wass one of the multiple outputs of potato processing and was modeled to take on approximately 10% of the environmental burdens on a mass allocation basis, making its water consumption even smaller. Notably, maize grain had a small, -2%, environmental benefit with regard to noncarcinogenic environmental impacts. Maize grain was modeled in Ecoinvent such that some metal compounds (zinc, cadmium, copper, etc.) were taken up by the plant and removed from the environment, resulting in a small environmental benefit for the crop.

Figure 11 provides a more detailed look at the inputs that drive environmental impact during plant-based burger production with urine-derived P fertilizer. Processes that contributed <1% to an impact category were grouped into "other" for that impact category. A negative value indicates that replacing conventional P fertilizer with recovered P fertilizer for that input made it have a net environmental benefit. Although an input marked by a negative value continued to bear negative environmental impacts from its production and application, the environmental offsets generated through its utilization were sufficient to overcome those negative impacts. Offsets are only present within inputs that contain P fertilizer.

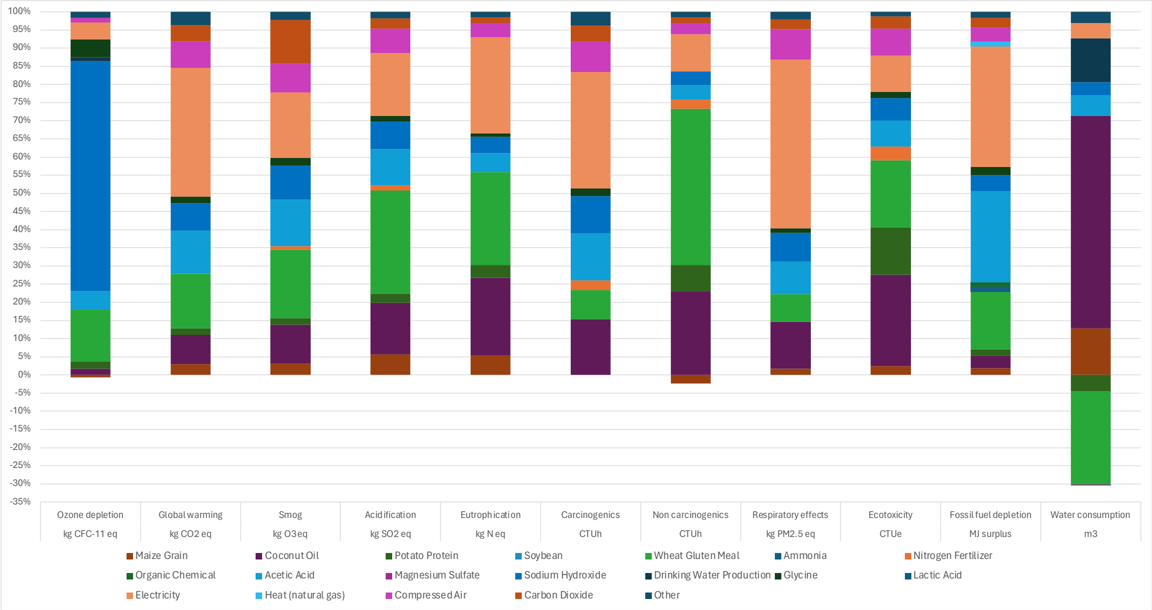


Figure 11. Scaled characterization environmental impact results for the production of 1 kg plant-based burger with urine-derived P fertilizer. Process contribution is divided into main process inputs, with inputs contribution <1% classified as "Other".

The difference between Figures 10 and 11 is the substitution of conventionally mined P fertilizer with recovered P fertilizer from urine diversion. P fertilizer substitution only affected inputs with P fertilizer, including soybean, potato protein, wheat gluten meal, maize grain, and coconut oil. For maize grain, potato protein, and wheat gluten meal, the environmental benefits from using recovered P fertilizer (e.g., offsetting traditional P fertilizer production, reducing water demand, and reducing wastewater treatment) resulted in larger benefits than harmful impacts in some categories. Net positive environmental impacts for certain inputs were seen in impact categories like ozone depletion, noncarcinogens, and water consumption. The slight reversal in impacts related to ozone depletion were primarily due to reduced usage of sodium hydroxide and chlorine gas from offsetting water and wastewater treatment, while avoiding the production and use of aluminum sulfate use at the wastewater treatment plant reduced the impact in categories like carcinogens, noncarcinogens, and ecotoxicity.

Many macroscale trends remained after substituting conventional P fertilizer with recovered P fertilizer. For example, electricity use still contributed the most to global warming impacts, crop production (e.g., coconut oil, wheat gluten meal, and maize grain) contributed most to eutrophication impacts, and water consumption was mainly driven by the production of coconut oil and maize grain. The true effect of P fertilizer substitution with respect to global warming, eutrophication, and water consumption impacts can be seen by comparing the magnitudes of important inputs within their respective impact category. Figure 12 provides a comparison of the magnitudes of select impact categories for beef burger production with conventional and recovered P fertilizer. Soybean, potato protein, wheat gluten meal, maize grain, and coconut oil are shown because they are the inputs that received P fertilizer substitution.

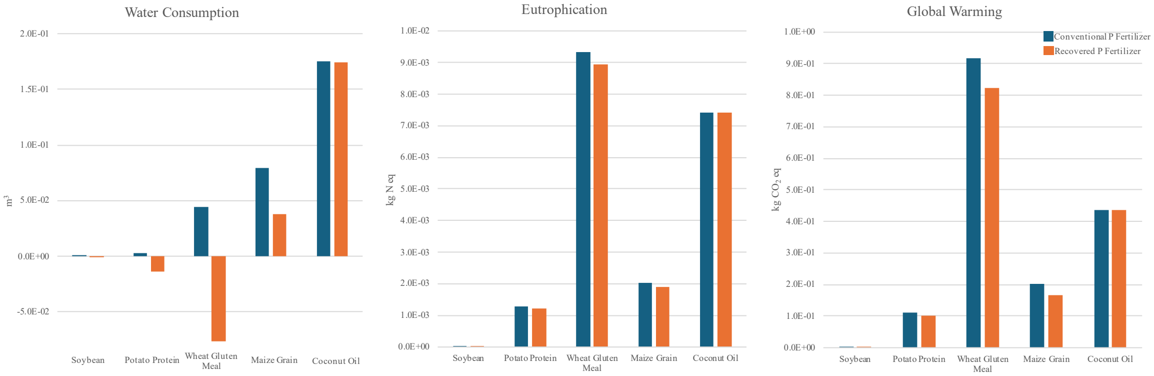


Figure 12. Comparison of water consumption, eutrophication, and global warming impact magnitudes for plant-based burger production with conventional and recovered P fertilizer.

The extent to which environmental impacts were lessened by the use of recovered P in plant-based burger production was dependent on the amount of P required to produce the feed. Soybean required approximately 0.01 g P/kg plant-based burger, potato protein required 0.5 g P/ kg plant-based burger, wheat gluten meal required 3.45 g P/ kg plant-based burger, maize grain required 1.2 g P/ kg plant-based burger, and coconut oil required 0.04 kg P/ kg plant-based burger. The increased P inputs for wheat gluten meal and maize grain corresponded with the largest drop in environmental burden after substituting fertilizer with recovered P. In contrast, inputs such as soybean, potato protein, and coconut oil showed smaller benefits after substitution due to their low P fertilizer requirements.

While water consumption was slightly reduced by avoiding the mining and production of conventional P fertilizers, the main driver (85%) of water savings after P fertilizer substitution was the offsetting of water use for toilet flushing. Approximately 7 L of diverted urine is needed to produce enough recovered P fertilizer to produce 1 kg beef burger. With no water sent to the toilet, approximately 150 L (0.15 m^3) of water is saved per kg of plant-based burger produced. Soybean water consumption and P fertilizer usage were substantially lower than other crop inputs, causing it to appear negligible in Figure 12. Potato protein and wheat gluten meal showed a negative water consumption because the avoided water consumption from reduced toilet flushing was greater than the water used to grow these crops. Wheat gluten meal, due to its large P fertilizer requirement, received the largest water use benefits, reducing water consumption by 0.12 m^3, approximately 80% of the total water savings.

Similar to the case of beef burger production, eutrophication impacts are generally attributed to leaching and runoff that occurs from fertilizer application on agricultural fields, and this issue is not directly addressed by substituting P fertilizers. The eutrophication benefits seen in Figure 12 were mainly driven by the avoided production of conventional P fertilizers. Phosphate rock mining and processing for P fertilizer production has associated P losses, and it known that these processes can contribute to higher nutrient loads entering waterways (Duan et al., 2021). By reducing the demand for conventional P fertilizers, the nutrient load entering waterways from P mining is reduced. Because of the elevated P fertilizer use in maize grain and wheat gluten meal, they accounted for the largest eutrophication savings, with 0.4 and 0.1 g N eq saved per kg plant-based burger produced, respectively.

The reduction in global warming impacts is primarily attributed to the avoided wastewater treatment that results from not flushing toilets, as well as avoided electricity use from various avoided processes such as conventional P fertilizer production and water treatment. Methane and nitrous oxide are two important greenhouse gasses known to be emitted from wastewater treatment plants (Mannina et al., 2018). Reducing the volumetric load sent to the wastewater treatment plant consequently reduces the greenhouse gas emissions and lowers the process' global warming impacts. Because of the elevated P fertilizer use in maize grain and wheat gluten meal, they accounted for the largest global warming savings, with 40 and 100 g CO_2 eq saved per kg plant-based burger produced, respectively.

CHAPTER 4

UNCERTAINTY ASSESSMENT

4.1 Overview

Uncertainty propagation within the model was evaluated via Monte Carlo simulations across baseline, realistic, and maximal uncertainty conditions. The simulation offers insights into the dependency of environmental impacts on input uncertainties. While a global sensitivity analysis would be required to pinpoint the specific sources of uncertainty, the present analysis broadly delineates the variability of environmental impacts under conditions of baseline and maximum uncertainty and gives an estimate of realistic uncertainty. Given that the majority of input processes modeled in Ecoinvent are represented by log-normal distributions, this study utilized log-normal distributions for Monte Carlo simulations. Distribution parameters, sourced from TRACI and ReCiPe environmental impact results, were used to generate log-normal distributions of 10,000 runs each, representing the global warming, eutrophication, and water consumption impacts across all four burger production scenarios. For every run in the simulation, the four burger production scenarios were ranked as best for the environment (1) and worst for the environment (4) with respect to a specific impact category.

4.2 Global Warming

Figure 13 exhibits the outcomes of the global warming uncertainty assessment for baseline, realistic, and maximum uncertainty. The x-axis denotes the comparative ranking of each burger production scenario against the others with respect to their global warming impacts. A rank of 4 represents the highest impact (worst for the environment), while a rank of 1 represents the least impact (best for the environment). The y-axis displays the burger production scenarios, and the z-axis indicates the percent (out of 10,000 simulations) a scenario attained a particular rank.

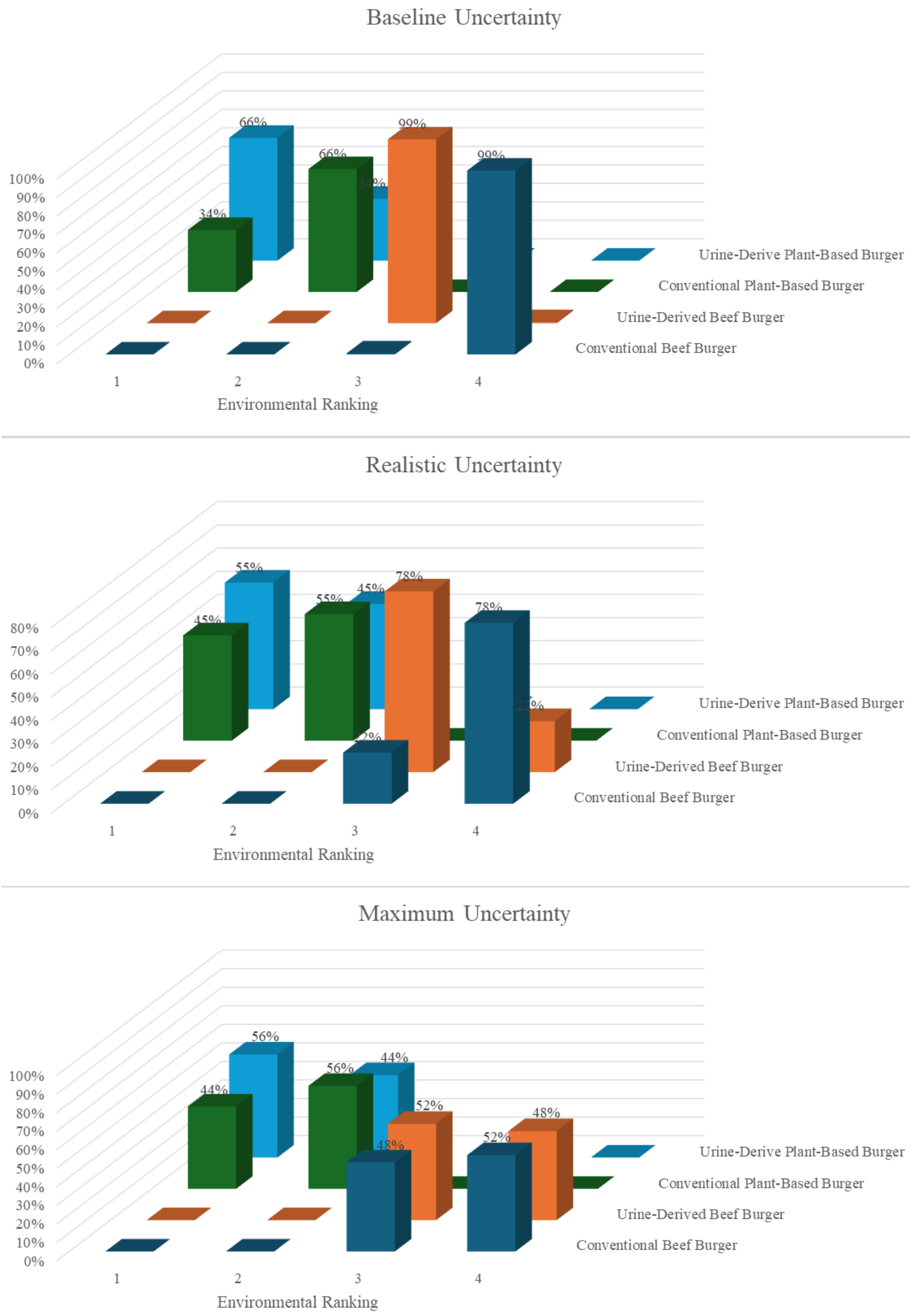


Figure 13. Results of global warming uncertainty assessment, showing percentage of Monte Carlo runs (10,000 total) in which a burger production scenario received a particular environmental ranking for baseline, realistic, and maximum uncertainty. Environmental ranking of 1 signifies most environmental benefit.

Under all conditions of uncertainty, plant-based burgers had less global warming impact than beef burgers 100% of the time. The substantially lower global warming impact of plant-based burgers can be attributed to the omission of the cattle-raising phase, responsible for approximately 78% of the total global warming impacts in beef burger production (Figure 5). For 99% of the runs under baseline uncertainty, the global warming impact of beef burgers with recovered P fertilizer was lower than beef burgers with conventional P fertilizer. However, at maximum uncertainty, only 52% of the runs showed a climate benefit after implementing recovered P fertilizer. Baseline and maximum uncertainty set the boundaries of global warming results and suggest that global warming impacts are sensitive to uncertainty in the data inputs, with high data uncertainty able to nullify environmental benefits. Under conditions of realistic uncertainty, 78% of the runs displayed a positive global warming impact when implementing recovered P fertilizer. Realistic uncertainty provided a strong result in favor of recovered P fertilizer use and was primarily due to the relatively low uncertainty attributed to the beef burger production dataset. Therefore, accounting for uncertainty, the substitution of recovered P fertilizer for conventional P fertilizer in beef burger production was considered to reduce global warming impacts.

The global warming benefits from implementing recovered P in plant-based burger production were less pronounced when compared to beef burger production. Under conditions of baseline uncertainty, 66% of runs resulted in reduced global warming impact when implementing recovered P fertilizer. However, in conditions of both realistic and maximum uncertainty, only 55% and 56% of runs displayed this benefit, respectively. Therefore, accounting for uncertainty, it cannot be said with confidence that implementing recovered P in plant-based burger production was beneficial with respect to global warming impacts. The difference in uncertainty of global warming impacts between recovered P use in plant-based and beef burger production was primarily due to the difference in P fertilizer requirements of each process, with beef burgers requiring 8 times more P fertilizer. This results in larger offsets of conventional fertilizer production, water use, wastewater treatment, etc. in beef burger production, which decreases the uncertainty in the result. Additionally, the proprietary nature of plant-based burger production and pilot scale from which its inventory data was sourced increased the uncertainty associated with its inputs, leading to higher uncertainty in the output, and a more difficult task to prove recovered P fertilizer provides environmental benefits.

4.3 Eutrophication

Figure 14 exhibits the outcomes of the eutrophication uncertainty assessment for baseline, realistic, and maximum uncertainty. The x-axis denotes the comparative ranking of each burger production scenario against the others with respect to their eutrophication impacts. A rank of 4 represents the highest impact (worst for the environment), while a rank of 1 represents the least impact (best for the environment). The y-axis displays the burger production scenarios, and the z-axis indicates the percent (out of 10,000 simulations) a scenario attained a particular rank.

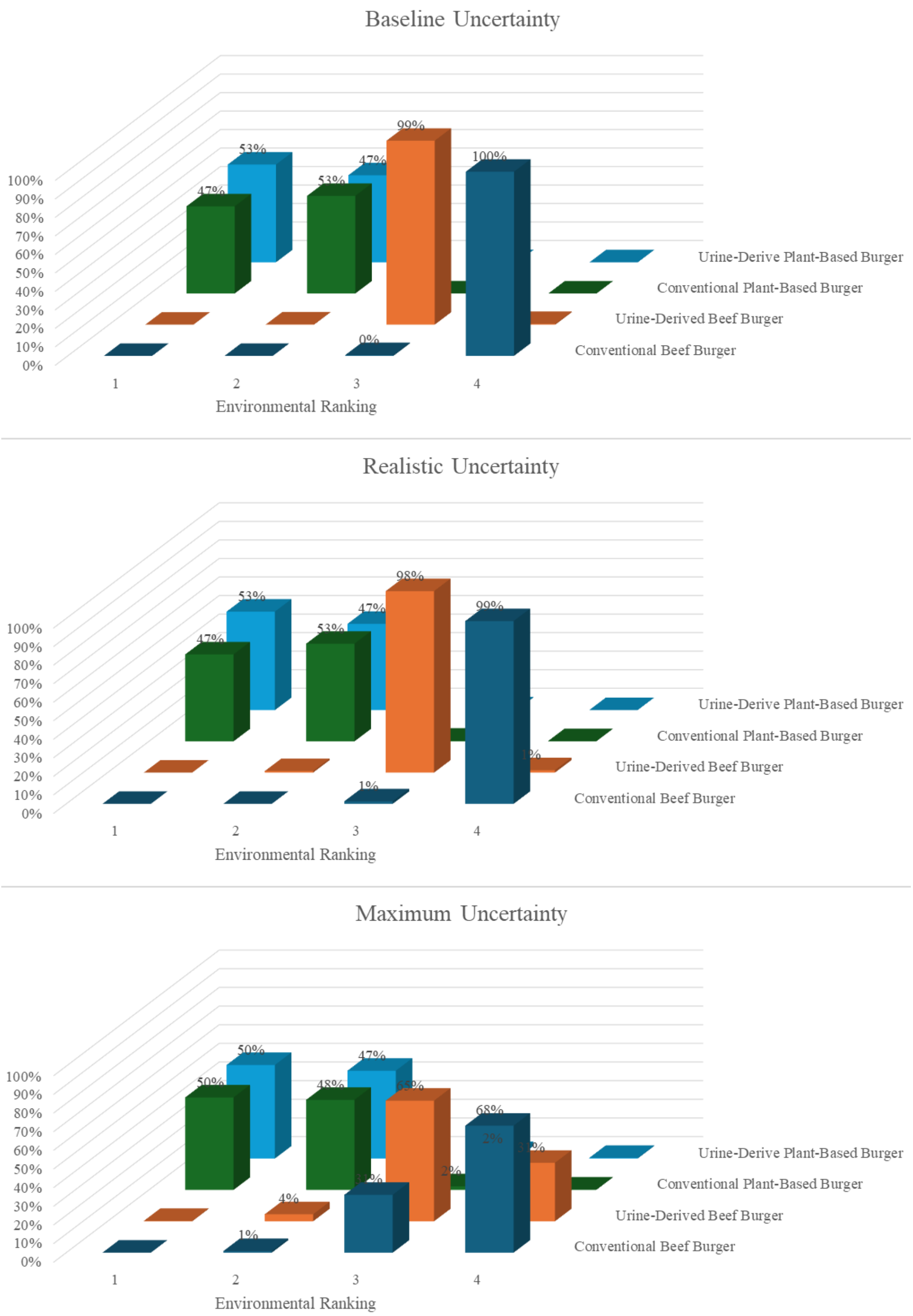


Figure 14. Results of eutrophication uncertainty assessment, showing percentage of Monte Carlo runs (10,000 total) in which a burger production scenario received a particular environmental ranking for baseline, realistic, and maximum uncertainty. Environmental ranking of 1 signifies most environmental benefit.

Under conditions of baseline, realistic, and maximum uncertainty, plant-based burgers had fewer eutrophication impacts than beef burgers 100%, 100%, and 95% of the time, respectively. The lower eutrophication impact of plant-based burgers can be attributed to the reduced crop inputs for plant-based burger production, as crop production and agricultural fertilizer use are the main contributors to eutrophication (Tables S2 and S4). For 99% of the runs under baseline uncertainty, the eutrophication impact of beef burgers with recovered P fertilizer was lower than beef burgers with conventional P fertilizer. However, at maximum uncertainty, only 65% of the runs showed a climate benefit after implementing recovered P fertilizer. Baseline and maximum uncertainty set the boundaries of eutrophication results and suggest that eutrophication impacts are slightly sensitive to uncertainty in the data inputs. Under conditions of realistic uncertainty, 99% of the runs displayed a positive eutrophication impact when implementing recovered P fertilizer. Realistic uncertainty provided a very strong result, which was primarily due to the relatively low uncertainty attributed to the beef burger production dataset, as well as the elevated P fertilizer requirements during production. Therefore, accounting for uncertainty, the substitution of recovered P fertilizer for conventional P fertilizer in beef burger production was be considered to reduce eutrophication impacts.

The eutrophication benefits from implementing recovered P in plant-based burger production were much less pronounced when compared to beef burger production. Under conditions of baseline, and maximum uncertainty, 53% and 50% of runs resulted in reduced eutrophication impact when implementing recovered P fertilizer, respectively.

Baseline and maximum uncertainty set the boundaries of eutrophication results and suggest that eutrophication impacts are not sensitive to uncertainty in the data inputs. Unsurprisingly, the realistic uncertainty scenario showed eutrophication benefits 53% of the runs when substituting recovered P fertilizer. Therefore, accounting for uncertainty, it cannot be said with confidence that implementing recovered P in plant-based burger production was beneficial with respect to eutrophication impacts. The difference in uncertainty of eutrophication impacts between recovered P use in plant-based and beef burger production was primarily due to the difference in P fertilizer requirements of each process, with plant-based burgers requiring 8 times less P fertilizer. As a result, there were less offsets of conventional fertilizer production, water use, wastewater treatment, etc. in beef burger production, which increases the uncertainty in the result. Additionally, the proprietary nature of plant-based burger production and pilot scale from which its inventory data was sourced increase the uncertainty associated with its inputs, leading to higher uncertainty in the output.

4.4 Water Use

Figure 15 exhibits the outcomes of the water consumption uncertainty assessment for baseline, realistic, and maximum uncertainty. The x-axis denotes the comparative ranking of each burger production scenario against the others with respect to their water consumption impacts. A rank of 4 represents the highest impact (worst for the environment), while a rank of 1 represents the least impact (best for the environment). The y-axis displays the burger production scenarios, and the z-axis indicates the percent (out of 10,000 simulations) a scenario attained a particular rank.

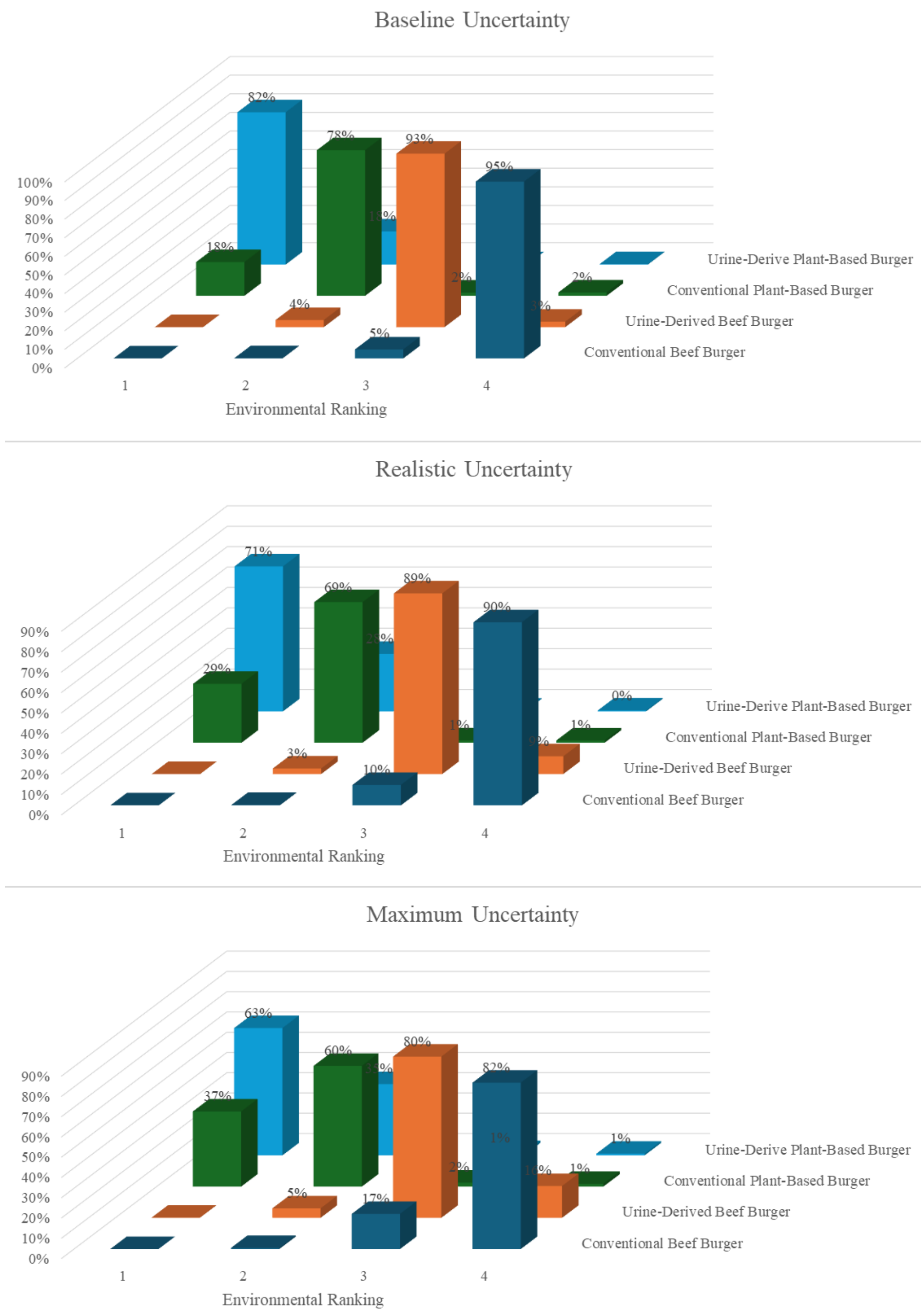


Figure 15. Results of water consumption uncertainty assessment, showing percentage of Monte Carlo runs (10,000 total) in which a burger production scenario received a particular environmental ranking for baseline, realistic, and maximum uncertainty. Environmental ranking of 1 signifies most environmental benefit.

Under conditions of baseline, realistic, and maximum uncertainty, plant-based burgers had fewer eutrophication impacts than beef burgers 96%, 97%, and 95% of the time, respectively. The lower water consumption impact of plant-based burgers can be attributed to the reduced crop inputs for plant-based burger production, as crop production is the main contributor to water consumption in both burger production scenarios (Figure 5 and 9). For 93% of the simulation runs under baseline uncertainty, and 80% of the simulation runs under maximum uncertainty, the water consumption impact of beef burgers with recovered P fertilizer was lower than beef burgers with conventional P fertilizer. Baseline and maximum uncertainty set the boundaries of water consumption results and suggest that water consumption is not very sensitive to uncertainty in the data inputs. Under conditions of realistic uncertainty, 89% of the runs displayed a positive water consumption impact when implementing recovered P fertilizer. Realistic uncertainty provided a very strong result, which was primarily due to the relatively low uncertainty attributed to the beef burger production dataset, as well as the elevated P fertilizer requirements during production. Therefore, accounting for uncertainty, the substitution of recovered P fertilizer for conventional P fertilizer in beef burger production was be considered to reduce water consumption impacts.

The water consumption benefits from implementing recovered P in plant-based burger production were slightly less pronounced when compared to beef burger production. Under conditions of baseline, and maximum uncertainty, 82% and 63% of runs resulted in reduced water consumption impact when implementing recovered P fertilizer, respectively. Baseline and maximum uncertainty set the boundaries of eutrophication results and suggest that eutrophication impacts are slightly sensitive to uncertainty in the data inputs. The realistic uncertainty scenario showed water consumption benefits 71% of the time when substituting recovered P fertilizer. Therefore, accounting for uncertainty, it can be said that implementing recovered P in plant-based burger production reduced water consumption. The difference in uncertainty of eutrophication impacts between recovered P use in plant-based and beef burger production is primarily due to the difference in P fertilizer requirements of each process, with plant-based burgers requiring 8 times less P fertilizer. As a result, there were less offsets of conventional fertilizer production, water use, wastewater treatment, etc. in beef burger production, which increases the uncertainty in the result. Additionally, the proprietary nature of plant-based burger production and pilot scale from which its inventory data was sourced increase the uncertainty associated with its inputs, leading to higher uncertainty in the output.

CHAPTER 5

LIMITATIONS

This project assumes that urine diversion is done at the city scale and disregards capital investments. The exclusion of capital investments is a common and generally accepted assumption in LCA studies, however, the environmental impacts of widescale adoption of urine diversion would be nontrivial in reality. The cost of adopting source separation infrastructure has been explored previously, however, the environmental impacts have not been looked at and could be the basis for future research (Landry & Boyer, 2016).

The data inventory used to model plant-based burgers was sourced from an Impossible Foods pilot plant in 2016 (Goldstein et al., 2017). It should be noted that efficiencies, inputs, and emissions from plant-burger production have likely changed since the data was provided. Additionally, due to proprietary concerns about the manufacturing process, Impossible Foods provided the inventory data in bulk, making it difficult to know what inputs are used for what processes, and what part of the production process is most environmentally impactful. With this in mind, the data provided gives a good baseline indication of the plant-based burger production process and the results of the environmental impact assessment reflect those of more recent LCAs on the product.

Lastly, the phosphate precipitation process to produce P fertilizer makes some simplifying assumptions for the sake of modeling that may not be reflective of true conditions. One of those being that tricalcium phosphate ($Ca_3(PO_4)_2$) is the main product formed from the process. Zhang et al. (2019) write that the precipitation process produces some hydroxyapatite along with calcium phosphate, showing that 100% recovery of pure tricalcium phosphate is unlikely under current conditions. Nevertheless, assuming $Ca_3(PO_4)_2$ was the only precipitation product allowed for a good preliminary analysis that indicated the potential environmental benefits of applying recovered P fertilizers to agricultural food systems.

CHAPTER 6

FUTURE WORK AND CONCLUSIONS

6.1 Future Work

The following steps will be taken prior to submitting this research for publication to add to the analysis and increase the robustness of the research results:

- Conduct global sensitivity analysis for all scenarios to understand drivers of uncertainty and how it can be reduced
- Use an alternative functional unit, 1 L of diverted urine, to understand the system from a different perspective, focusing on water savings and the urine diversion process instead of the agricultural food system
- Apply the model to crops with maximized P fertilizer intensities to understand what agricultural food systems would benefit most from utilizing recovered P fertilizer

The present research was meant to provide a framework from which more extensive and novel research on the application of nutrient recovery in agriculture could be built. Future continuations of this project could focus on the following:

- Quantify the environmental impacts of recovering the more influential N fertilizer, along with P fertilizer, by urine diversion and their application in agricultural food systems
- Explore a novel functional unit for the analysis, such as 1 kg of essential amino acids or a nutrient density index of 1, to better reflect the function of the system to provide nutrition

- Apply the LCA framework developed in this project to future food systems such as CO_2 capture as a source of carbon for food and novel fermentation technologies

6.2 Conclusions

This research contributes a critical perspective to the ongoing dialogue on sustainable P management by applying urine-derived P fertilizer to agricultural food systems, a previous gap in the literature. It was demonstrated that recovering P from human urine and applying it as a fertilizer in agricultural food systems such as beef and plant-based burger production provided environmental benefits to all environmental impact categories. Accounting for realistic uncertainty within input data, it was determined that using recovered P in beef burger production was likely to reduce global warming, eutrophication, and water consumption impacts due to its higher P fertilizer requirements, while recovered P fertilizer application for plant-based burgers was primarily beneficial for water savings. The reduction in water use for beef and plant-based burger production following recovered P fertilizer application was the most significant environmental benefit, highlighting the importance of co-benefits and offsets when assessing new technologies. The results emphasize the importance of applying resource recovery to the appropriate system in order to maximize environmental benefits. The utilization of urine-derived P fertilizer, as investigated in this research, stands as a testament to the potential of resource recovery technologies to mitigate some of the most pressing environmental challenges faced today.

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APPENDIX A

SUPPLEMENTARY TABLES

Table S1. Literature review for beef burger production inventory.

Title	Qualitative Inventory Data?	Quantitative Inventory Data?	Location	General Processing Steps	System Boundaries	Functional Unit	Data Collection Period	Primary or Secondary Data?
Red Meat Production in Australia: Life Cycle Assessment and Comparison with Overseas Studies	No	No	Australia	Feed Production, Animal Raising, Processing	Cradle-to-Processing Gate	1 kg hot standard carcass weight	2002-2004	Primary
Comparative life cycle assessment of plant and beef-based patties, including carbon opportunity costs	Yes	Yes	Brazil, Ireland	Beef Production and Transport, Burger Production, Packaging, Distribution, Storage and Cooking	Cradle-to-Fork	113 g burger patty, NDU	N/A	Secondary
Mitigation of greenhouse gas emissions from beef production in western Canada – Evaluation using farm-based life cycle assessment	Yes	Yes	Canada	Backgrounding and Finishing Cattle	Cradle-to-Farm Gate	1 kg beef carcass	N/A	Secondary (farm simulator)
Greenhouse gas emissions from the Canadian dairy industry in 2001	Yes	Yes	Canada	Feed Production, Dairy Cow Raising and Milking	Cradle-to-Farm Gate	1 kg Milk	N/A	Secondary
Greenhouse gas emissions from beef production systems in Denmark and Sweden	Yes	Yes	Denmark, Sweden	Feed Production, Animal Raising and Fattening	Cradle-to-Farm Gate	1 kg meat (carcass weight)	N/A	Secondary
Environmental consequences of different beef production systems in the EU	Yes	Yes	EU	Feed Production, Animal Raising and Fattening	Cradle-to-Farm Gate	1 kg meat slaughter weight delivered from farms	N/A	Secondary
Greenhouse Gas Emissions from Conventional, Agri-Environmental Scheme, and Organic Irish Suckler-Beef Units	No	No	Ireland	Feed Production, Livestock Raising, Nutrient Recycling (Manure)	Cradle-to-Farm Gate	1 kg live weight during 1 year	<2006	Primary
Quantification of GHG emissions from sucker-beef production in Ireland	Yes	Yes	Ireland	Feed Production, Livestock Raising, Nutrient Recycling (Manure)	Cradle-to-Farm Gate	1 kg live weight during 1 year	<2005	Primary
Environmental effects of protein-rich food products in the Netherlands Consequences of animal protein substitutes	No	No	Netherlands	Feed Production, Animal Husbandry System, Slaughterhouse, Food Assembly, Retail	Cradle-to-consumer	N/A	N/A	Both
Life Cycle Inventory of 23 Dairy Farms in South-Western Sweden	Yes	Yes	Sweden	Feed Production, Cattle Rearing and Milking	Cradle-to-Farm Gate	1 kg of energy corrected milk	2000-2003	Primary
Carbon footprinting of lamb and beef production systems: insights from an empirical analysis of farms in Wales, UK	Yes	Yes	UK	Feed Production, Animal Raising	Cradle-to-Farm Gate	1 kg live weight beef	2005-2006	Primary
A life cycle assessment of the environmental impacts of a beef system in the USA	Yes	Yes	USA	Feed Production, Cattle Production, Packing, Case-Ready, Retail, Consumer, Restaurant, Recycling and Waste	Cradle-to-grave	1 kg consumed, boneless, edible beef in the USA	2011-2013	Both
BASF U.S. Beef – Phase 2 Eco-efficiency Analysis	Yes	No	USA	Feed, Cow-Calf, Feedlot, Harvesting, Case-Ready, Reatil, Consumer, Restaurant	Cradle-to-grave	1 lb consumed, boneless, edible beef	2011-2013	Both
Is the Grass Always Greener? Comparing the Environmental Impact of Conventional, Natural and Grass-Fed Beef Production Systems	No	No	USA	Cow-calf, Stocker, Feedlot, Slaughter	Cradle-to-Farm Gate	1x10^9 kg beef (hot carcass weight)		
A Comparative LCA of Plant Based Foods and Meat Foods	Yes	Yes	USA	Feed Production, Animals Raising, Slaughtering and Processing, Packaging, Retail and Distribution, Waste Management	Cradle-to-Grave	60 g meat patty or alternative at their home	<2016	Both
Beyond Meat's Beyond Burger Life Cycle Assessment: A detailed comparison between a plant-based and an animal-based protein source	No	No	USA	Feed Production, Cow-Calf, Feedlot, Harvesting, Case-Ready	Cradle-to-Distribution	113 g uncooked burger patty delivered to retail outlets	N/A	Secondary
Comparative Environmental LCA of the Impossible Burger with Conventional Ground Beef Burger	Yes	Yes	USA	Feed Production, Cattle Raising and Fattening, Slaughtering and Processing, Manufacturing, Packaging	Cradle-to-Manufacturers Gate	1 kg uncooked burger patty	<2019	Primary
Life-Cycle Assessment of the Beef Cattle Production System for the Northern Great Plains, USA	Yes	Yes	USA	Feed Production, Facility Operations, Transportation	Cradle-to-Gate	1 kg standard carcass weight	<2014	Both

Table S1 Continued. Literature review for beef burger production inventory.

Title	Qualitative Inventory Data?	Quantitative Inventory Data?	Location	General Processing Steps	System Boundaries	Functional Unit	Data Collection Period	Primary or Secondary Data?
Comparative life cycle environmental impacts of three beef production strategies in the Upper Midwestern United States	Yes	Yes	USA	Fodder Production, Calf-Cow, Backgrounding, Finishing System (Feedlot)	Cradle-to-Farm Gate	1 kg live weight beef	<2010	Primary
A comprehensive environmental assessment of beef production and consumption in the United States	Yes	Yes	USA	Feed Production, Beef Cattle Operations, Harvesting, Processing, Retail, Consumption	Cradle-to-Grave	1 kg beef cooked and consumed in the US	N/A	Secondary (farm simulator)
A simulation-based approach for evaluating and comparing the environmental footprints of beef production systems	Yes	Yes	USA	Crop-Farm, Spring-Calving Cow-Calf Operation, Fall-Calving Cow-Calf Operation, and Feedlot	N/A	N/A	2011 MARC	Secondary
The carbon footprint of dairy production systems through partial life cycle assessment	Yes	Yes	USA	Feed Production, Animal Production, Manure Handling	N/A	N/A	N/A	N/A
Sustainability Assessment of U.S. Beef Production Systems	No	No	USA	Feed, Cattle Production, Harvesting, Case-Ready, Retail and Customer	Cradle-to-Grave	1 lb consumed, boneless, edible beef	N/A	Secondary
Carbon footprint and ammonia emissions of California beef production systems1	No	No	USA (CA)	Feed Production, Animal Production (Cow-Calf, Stocker, and Feedlot), Manure Handling	Cradle-to-Farm Gate	1 kg animal (beef)	N/A	Secondary (farm simulator)
Environmental footprints of beef cattle production in the United States	Yes	Yes	USA (SW)	Cow-Calf, Stocker or Background, Finishing	Cradle-to-Farm Gate	1 kg carcass weight	2015-2018	Primary
Nexus on animal proteins and the climate change: The plant-based proteins are part of the solution?	Yes	Yes	USA, Brazil, Argentina, New Zealand	Pre-production, Feed Production, Animal Production	Cradle-to-Factory Gate	113 g burger	N/A	Secondary
Greenhouse Gas Emissions from the Dairy Sector A Life Cycle Assessment	No	No	USA, Global	Feed Production, Animal Raising, Processing, Distribution	Cradle-to-Retail	1 kg FPCM, 1 kg carcass weight	N/A	Secondary
Greenhouse gas emissions from ruminant supply chains – a global life cycle assessment	Yes	Yes	USA, Global	Feed Production, Animal Raising, Processing, Distribution	Cradle-to-Retail	1 kg carcass weight, 1 kg FPCM	N/A	Secondary

S2. Inventory used to model 1 kg beef burger production in the US.

Phase	Input Given by Source	Ecoinvent Input Used in this Study	Value	unit	Assumptions/Notes	Ecoinvent Pedigree Matrix Values and Reasoning for Realistic Uncertainty
Cattle feed and raising (Rotz et al., 2019)	Grazed Forage	Grass, at farm {US} Economic, U	1.67E+01	kg	Assumed grazed forage is grass	Reliability (2) – Data was partially sourced via survey and partially through site visits for data collection. Data was input into a model to determine average cattle feed and raising phase inputs, so it is taken to be non-verified data but based on actual measurements Completeness (3) – Data was taken from nearly 2300 cattle operations across the US. This is a large sample size, but still represents <<50% of US beef production Temporal Correlation (3) – Data was sourced from 2015-2018, less than a 10 year difference to the time period of this study Geographical Correlation (1) – Data was sourced from cattle processes in the US and modeled using a US based tool. This study is focused on beef production in the US. Technological Correlation (1) – Data was focused on inputs needed during the cattle raising phase of beef production. This is the exact system represented in this study.
	Harvested Forage	Grass hay, region 4, at farm/US U	3.22E+00	kg	Assume that harvested forage means it was harvested, dried, and fed to them at a later date. This could be hay or silage. Assume 50% alfalfa hay and 50% grass hay (USDA, n.d.-b).	
		Alfalfa hay, region 4, at farm/US U	3.22E+00	kg	Region 4 is used for feed inputs because it represents 4 out of the 5 highest cattle producing states in the US (Data Pandas, n.d.)	
	Grain Concentrate	Corn grain, region 4, at field/US U	3.29E+00	kg	Primarily corn, but may include other grains fed to cattle (Rotz et al., 2019). Assume this is all corn	
	Other Feed	DDGS, wet, at farm/US U - economic value allocation	1.90E+00	kg	"Distillers grain, other byproduct feeds (corn gluten feed, soybean meal, cottonseed, etc.) and waste (bakery, potato, almond hulls, etc.) unsuitable for human consumption." (Asem-Hiablie et al., 2019). Assume that this is dry distillers grains with solubles (DDGS). This is used extensively in the cattle feeding industry (Ponce et al., 2019), and was one of the main feeding components in a well known USA beef LCA (Asem-Hiablie et al., 2019).	
	Fuel	Diesel, combusted in industrial equipment/US	3.16E-01	L	Gasoline and diesel usually used on a farm. Previous beef LCAs have shown diesel to be the major fuel source (Asem-Hiablie et al., 2019). Considering diesel fuel powers the majority of farm equipment (Energy Technology Forum, n.d.), assume that this is all diesel.	
	Natural Gas	Natural gas, combusted in industrial boiler/US	3.79E-02	m3		
	Electricity	Electricity, high voltage {US}| market group for electricity, high voltage | Cut-off, U	5.18E-01	kWh	1 kWh of this process produced 0.462 kg CO2eq, which is higher than the 2022 average grid value of 0.376 kg CO2/kWh (US EIA, 2023). To more accurately represent the US electrical grid, the process inputs were scaled down by a factor of 81.4% so that the CO_2 emissions from 1 kWh were 0.376 kg.	
	Drinking Water	Drinking Water Production {US}	8.12E+01	kg	Assume 1 L = 1 kg. This process was created based on a previous LCA on urine diversion (Hilton et al., 2021)	
Cattle Harvesting (Putman et al., 2023)	Refrigerant	Refrigerant R134a, at plant/US-US-EI U	1.26E-05	kg	This refrigerant is currently being phased out in the US, but it is assumed to still be representative for this study.	Reliability (3) – Data was sourced via survey of 6 harvesting facilities. It is considered to be non-verified data based on qualified estimates from the facilities. Completeness (3) – Data was taken from 6 harvesting operations in the US. This represents <<50% of US harvesting operations. Temporal Correlation (3) – Data was sourced from a 2017 survey, less than a 10 year difference to the time period of this study Geographical Correlation (1) – Data was sourced from harvesting operations in the US. This study is focused on beef production in the US. Technological Correlation (1) – Data was focused on inputs needed during the cattle harvesting phase of beef production. This is the exact system represented in this study.
	Carbon dioxide	Carbon dioxide, liquid {RoW}| market for carbon dioxide, liquid | Cut-off, U	1.19E-02	kg	CO_2 can be used to keep meat cold via dry ice, and can also be used for stunning, but not typically for cows (Goldstein et al., 2017). Assume that the mass represents liquid CO_2 (Goldstein et al., 2017).4/25/24 2:08:00 PM	
	Electricity	Electricity, high voltage {US}| market group for electricity, high voltage | Cut-off, U	8.38E-01	MJ	1 kWh of this process produced 0.462 kg CO2eq, which is higher than the 2022 average grid value of 0.376 kg CO2/kWh (US EIA, 2023). To more accurately represent the US electrical grid, the process inputs were scaled down by a factor of 81.4% so that the CO_2 emissions from 1 kWh were 0.376 kg.	
	Heat	Heat, natural gas, at industrial furnace >100kW/US- US-EI U	1.27E+00	MJ	Assume heat is sourced from natural gas	
	Chemicals	-	1.58E-03	m^3	Typical chemicals used during meat packing phase are chlorine (sodium hypochlorite), hydrogen peroxide, and peracetic acid, and CO_2 (OSHA, n.d.). CO_2 not included here because it has its own inputs line, and ammonia not included bc it is a gas (conversion with density is negligible). Chemical volume split evenly between the three inputs, and respective densities used to determine mass	
		Sodium hypochlorite, 15% in H2O, at plant/US- US-EI U	6.37E-01	kg	Density = 1210 kg/m^3	
		Hydrogen peroxide, 50% in H2O, at plant/US- US-EI U	6.30E-01	kg	Density = 1197 kg/m^3	
		Chemical, organic {GLO}| chemical production, organic | Cut-off, U	5.90E-01	kg	Density = 1120 kg/m^3 ; Meant to represent paracetic acid, but no existing database process exists so this is a proxy	
	Lubricating Oil	Lubricating oil, at plant/US-US-EI U	1.64E-04	kg		

Table S2 Continued. Inventory used to model 1 kg beef burger production in the US.

Cattle Harvesting (Putman et al., 2023)	Water	Drinking Water Production {US}	1.22E+01	kg	Assume 1 L = 1 kg. This process was created based on a previous LCA on urine diversion (Hilton et al., 2021)	
	Metal	Iron and steel, production mix/US	2.53E-05	kg		
	Rubber	Synthetic rubber, at plant/US-US-EI U	1.26E-05	kg		
	Wastewater	Wastewater Treatment	5.62E-03	m^3	This process was created based on a conventional activated sludge WWTP (EPA, 2021)	
Ground Beef Production (Putman et al., 2023)	Electricity	Electricity, high voltage {US}| market group for electricity, high voltage | Cut-off, U	2.69E-01	kWh	1 kWh of this process produced 0.462 kg CO2eq, which is higher than the 2022 average grid value of 0.376 kg CO2/kWh (US EIA, 2023). To more accurately represent the US electrical grid, the process inputs were scaled down by a factor of 81.4% so that the CO_2 emissions from 1 kWh were 0.376 kg.	Reliability (3) – Primary data was sourced from 2 processing facilities. It is considered non-verified data based on qualified estimates from the facilities Completeness (3) – Data was taken from 2 processing facilities in the US. This represents <<50% of US processing operations Temporal Correlation (3) – Data was sourced in 2017, less than a 10 year difference to the time period of this study Geographical Correlation (1) – Data was sourced from processing facilities in the US. This study is focused on beef production in the US. Technological Correlation (1) – Data was focused on inputs needed to produce ground beef from raw beef. This is the exact system represented in this study.
	Heat	Heat, natural gas, at industrial furnace >100kW/US- US-EI U	6.08E-01	MJ	Assume heat is sourced from natural gas	
	Waste	Non-hazardous waste, landfill	2.13E-02	kg		
	Water Use	Drinking Water Production {US}	1.84E+00	kg	Assume 1 L = 1 kg. This process was created based on a previous LCA on urine diversion (Hilton et al., 2021)	
	Wastewater	Wastewater Treatment	1.27E-03	m3	This process was created based on a conventional activated sludge wastewater treatment process (EPA, 2021)	
Packaging (Khan et al., 2019)	Patty Paper	Paper, woodfree, coated {RoW}| market for paper, woodfree, coated | Cut-off, U	1.60E-03	kg	Assume all packaging data is the same between beef and plant-based burger, as has been done in previous LCA studies (Khan et al., 2019)	Reliability (3) – Data was provided by impossible foods. Considered non-verified based on qualified estimates. Completeness (4) – Since only 1 source (impossible foods) provided the data, it is considered representative of only one site. Temporal Correlation (3) – Data provided by Impossible Foods was published in 2019, assumed to be given to authors within 10-year period. Geographical Correlation (1) – Impossible Foods is a US based company; data is considered to be from the US. Technological Correlation (2) – Packaging data is representative of the same technology (burger packaging), but sourced from its application for plant-based burger packaging (different enterprise)
	Plastic Film	Packaging film, low density polyethylene {GLO}| market for packaging film, low density polyethylene | Cut-off, U	2.30E-03	kg		
	Corrugated Cardboard	Corrugated board, fresh fibre, single wall, at plant/US- US-EI U	1.0E-02	kg		
Emissions from farm processes (Rotz et al., 2019)	Ammonia	Ammonia	1.26E+02	g	Primarily from cow waste (urine)	Same as cattle feed and raising
	Methane	Methane	6.09E+02	g	Primarily from cow belching from enteric fermentation	
	Nitrous Oxide	Dinitrogen monoxide	2.52E+01	g	Primarily from microbial activity in soil and manure	
	VOCs	VOC, volatile organic compounds, unspecified origin	1.23E+01	g		

Table S3. Literature review for plant-based burger production inventory.

Title	Qualitative Inventory Data?	Quantitative Inventory Data?	Location	Primary Crop	General Processing Steps	System Boundaries	Functional Unit	Data Collection Period	Primary or Secondary Data?
Comparative life cycle assessment of plant and beef-based patties, including carbon opportunity costs	Yes	Yes	UK	Legume and Cereal Proteins	Crop Cultivation, Processing , Burger Production, Packaging, Distribution, Storage, Consumption	Cradle-to-Fork	113 g uncooked burger patty, 1 NDU		Primary (proprietary)
Life cycle assessment of animal-based foods and plant-based protein-rich alternatives: an environmental perspective	Yes	Yes	EU	Lupin, Faba-bean	Crop Cultivation, Processing and Packaging	Cradle-to-Factory Gate	100 g product, 30 g protein, 54 kcal energy content		Both
Plant based meat alternative, from cradle to company-gate: A case study uncovering the environmental impact of the Swedish pea protein value chain	Yes	Yes	Sweden	Pea	Crop Cultivation, Pea Protein Processing, Dough Processing, Sausage Production	Cradle-to-Factory Gate	1 kg pea protein concentrate, 1 kg pea protein sausage	N/A	Secondary
Protein Chains and Environmental Pressures: A Comparison of Pork and Novel Protein Foods	Yes	Yes	?	Pea	Pea Agriculture, Processing, Consuming		1000 kg protein content for consumption		
Environmental impact of four meals with different protein sources: Case studies in Spain and Sweden	Yes	Yes	Spain, Sweden	Soy and Pea	Crop Cultivation, Processing and Packaging	Cradle-to-Fork	1 meal served at the table in a household		
Beyond Meat's Beyond Burger Life Cycle Assessment: A detailed comparison between a plant-based and an animal-based protein source	Yes	Some	USA	Pea, Oil	Upstream Processes, Agricultural Production, Processing, Packaging, Distribution	Cradle-to-Distribution	113 g uncooked burger patty delivered to retail outlets		Primary (Beyond Meat)
Meat alternatives: life cycle assessment of most known meat substitutes	Yes	Yes	?	Soy	Raw Material Acquisition, Processing, Distribution, Consumption	Cradle-to-Plate	1 kg product ready for consumption	N/A	Secondary
Meat substitution in burgers: nutritional scoring, sensorial testing, and Life Cycle Assessment	Yes	Yes	Germany	Soy	Crop Cultivation, Texturizing and Cutting, Mixing and Forming	Cradle-to-Gate	113 g burger patty	N/A	Secondary
Comparison of life cycle assessments and nutritional contents of soy protein and wheat protein (seitan) based vegan bacon products for human and environmental health	Yes	Yes	Database	Soy	Soy Protein Manufacturing, Bacon	Cradle-to-Fork	60 g food		
Comparative Environmental LCA of the Impossible Burger with Conventional Ground Beef Burger	Yes	Some	USA	Soy, Potato	Raw Materials Manufacturing, Heme Production, Burger Production, Packaging	Cradle-to-Manufacturers Gate	1 kg uncooked burger patty		Primary (Impossible Foods)
Life cycle assessment of burger patties produced with extruded meat substitutes	Yes	Some	Europe	Soy, Pumpkin	Raw Material Acquisition, Material Treatment, Processing, Distribution, Consumption	Cradle-to-Gate	1 kg fresh, ready to pack burger patties		
Soybean and maize cultivation in South America: Environmental comparison of different cropping systems	Yes	Yes	Paraguay	Soybean	Crop Cultivation	Cradle-to-Farm Gate	1 t grain with 14% moisture content	2013-2018	Primary
Environmental assessment of organic soybean (Glycine max.) imported from China to Denmark: a case study	Yes	Yes	Denmark, China	Soybean	Production of Ag. Inputs, Soybean Cultivation, Sorting and Packaging., Transportation	Cradle-to-Farm Gate	1 t organic soybean produced in China and delivered to Denmark		
Land occupation and transformation impacts of soybean production in Southern Amazonia, Brazil	No	No	Brazil	Soybean			1 t soybean		
Nexus on animal proteins and the climate change: The plant-based proteins are part of the solution?	Yes	Yes	US, Braz, Argentina ,New Zea.	Soybean, Chickpea, Lentil	Pre-Production, Plantation, Grain	Cradle-to-Factory Gate	1 kg plant-based feedstock	N/A	Secondary
Potential to curb the environmental burdens of American beef consumption using a novel plant-based beef substitute	Yes	Yes	USA	Soybean, Potato	PBB ingredients, production (not packaging)	Cradle-to-Processing	Inventory for 1 kg PBB (not packaged)	2015-2016	Both? (Impossible Foods)
Meat Analogs from Different Protein Sources: A Comparison of Their Sustainability and Nutritional Content	No	No		Wheat, Soy, Nuts			100 g product, 20 g protein, 100 kcal energy content		
Environmental and nutritional Life Cycle Assessment of novel foods in meals as transformative food for the future	No	No	Europe			Cradle-to-Consumer			
Life Cycle Assessment of the Production of a Large Variety of Meat Analogs by Three Diverse Factories	No	No				Cradle-to-Factory Gate		2013-2015	Primary (proprietary)

Table S4. Inventory used to model 1 kg plant-based burger production in the US.

Phase	Ecoinvent Input from Goldstein et al. (2017)	Ecoinvent Input for this Project	Value	Unit	Notes and Assumptions	Ecoinvent Pedigree Matrix Values and Reasoning for Realistic Uncertainty
Crop Cultivation and Heme Production (Goldstein et al., 2017)	Ammonia, liquid {RER}| market for | Alloc Rec, U	Ammonia, anhydrous, liquid {RNA}| market for ammonia, anhydrous, liquid | Cut-off, U	1.72E-02	kg		Reliability (3) – Data was provided by impossible foods in bulk. Considered non-verified based, but based on qualified estimates. Completeness (3) – The data is representative of the entire plant-based burger production process, however it is a snapshot in time and data is provided in bulk, so it is not considered complete enough to normal out fluctuations. Temporal Correlation (3) – Authors of this inventory note that data is representative of 2015-2016 processing, so it is considered to be within 10 years of the current project Geographical Correlation (1) – Impossible Foods is a US based company; data is considered to be from the US. Technological Correlation (5) – Data was sourced from early-stage low-volume production of plant-based burgers. Production and scale has likely changed much over the last 10 years, so maximum uncertainty is set.
	Ammonium sulfate, as N {GLO}| market for | Alloc Rec, U	Inorganic nitrogen fertiliser, as N {RoW}| nutrient supply from ammonium sulfate | Cut-off, U	6.02E-03	kg		
	Chemical, organic {GLO}| market for | Alloc Rec, U	Chemical, organic {GLO}| market for chemical, organic | Cut-off, U	5.19E-03	kg	Item shows up multiple times in the inventory, likely because Goldstein et al. had to use proxies for various inputs. Any duplicate inputs are combined into one before being entered into SimaPro	
	Boric acid, anhydrous, powder {GLO}| market for | Alloc Rec, U	Boric acid, anhydrous, powder {GLO}| market for boric acid, anhydrous, powder | Cut-off, U	5.50E-08	kg		
	Calcium Sulfate Dihydrate*	Magnesium sulfate {GLO}| market for magnesium sulfate | Cut-off, U	1.65E-04	kg	Assume magnesium sulfate is a suitable proxy for calcium sulfate due to process gaps in databases	
	Acetic acid, without water, in 98% solution state {GLO}| market for | Alloc Rec, U	Acetic acid, without water, in 98% solution state {GLO}| market for acetic acid, without water, in 98% solution state | Cut-off, U	1.52E-01	kg	Item shows up multiple times in the inventory, likely because Goldstein et al. had to use proxies for various inputs. Any duplicate inputs are combined into one before being entered into SimaPro	
	Cobalt {GLO}| market for | Alloc Rec, U	Cobalt {GLO}| market for cobalt | Cut-off, U	1.19E-06	kg		
	Copper sulfate {GLO}| market for | Alloc Rec, U	Copper sulfate {GLO}| market for copper sulfate | Cut-off, U	1.43E-05	kg		
	Iron sulfate {GLO}| market for | Alloc Rec, U	Iron sulfate {GLO}| market for | Cut-off, U	1.54E-04	kg		
	Magnesium sulfate {GLO}| market for | Alloc Rec, U	Magnesium sulfate {GLO}| market for magnesium sulfate | Cut-off, U	4.49E-03	kg		
	Manganese sulfate {GLO}| market for | Alloc Rec, U	Manganese sulfate {GLO}| market for manganese sulfate | Cut-off, U	7.13E-06	kg		
	Potassium carbonate {GLO}| market for | Alloc Rec, U	Potassium carbonate {GLO}| market for potassium carbonate | Cut-off, U	3.61E-03	kg		
	Sodium hydroxide, without water, in 50% solution state {GLO}| market for | Alloc Rec, U	Sodium hydroxide, without water, in 50% solution state {GLO}| market for sodium hydroxide, without water, in 50% solution state | Cut-off, U	1.63E-01	kg	Item shows up multiple times in the inventory, likely because Goldstein et al. had to use proxies for various inputs. Any duplicate inputs are combined into one before being entered into SimaPro	
	Sodium {GLO}| market for | Alloc Rec, U	Sodium {GLO}| market for sodium | Cut-off, U	6.60E-07	kg		
	Sulfuric acid {GLO}| market for | Alloc Rec, U	Sulfuric acid {GLO}| market for | Cut-off, U	1.19E-05	kg		
	Water, completely softened, from decarbonised water, at user {GLO}| market for | Alloc Rec, U	Drinking Water Production {US}	1.54E+01	kg	Assume that tap water is a suitable replacement for softened water to better represent environmental benefits (water usage) as they apply to the US	
	Zinc {GLO}| market for | Alloc Rec, U	Zinc {GLO}| market for zinc | Cut-off, U	2.83E-05	kg		

Table S4 Continued. Inventory used to model 1 kg plant-based burger production in the US.

Crop Cultivation and Heme Production (Goldstein et al., 2017)	Maize grain {GLO}| market for | Alloc Rec, U	Maize grain {US}| maize grain production | Cut-off, U	4.60E-01	kg		
	Acetic acid, without water, in 98% solution state {GLO}| market for | Alloc Rec, U	Acetic acid, without water, in 98% solution state {GLO}| market for acetic acid, without water, in 98% solution state | Cut-off, U	1.52E-01	kg		
	Glycine {GLO}| market for | Alloc Rec, U	Glycine {GLO}| market for glycine | Cut-off, U	1.86E-02	kg		
	Lactic acid {GLO}| market for | Alloc Rec, U	Lactic acid {GLO}| market for lactic acid | Cut-off, U	9.68E-04	kg		
	Chemical, organic {GLO}| market for | Alloc Rec, U	Chemical, organic {GLO}| market for chemical, organic | Cut-off, U	5.19E-03	kg		
	Sodium hydroxide, without water, in 50% solution state {GLO}| market for | Alloc Rec, U	Sodium hydroxide, without water, in 50% solution state {GLO}| market for sodium hydroxide, without water, in 50% solution state | Cut-off, U	1.63E-01	kg		
	Coconut oil, crude {PH}| production | Alloc Rec, U	Coconut oil, crude {PH}| coconut oil production, crude | Cut-off, U	1.83E-01	kg	Assume that coconut oil is imported from the Philippines. This is how the process has been modeled in the past, and it is well known that the Philippines are a major world exporter of coconuts. Other coconut oil processes do not have explicit P fertilizer terms for substitution, this one does.	
	Acetic acid, without water, in 98% solution state {GLO}| market for | Alloc Rec, U	Acetic acid, without water, in 98% solution state {GLO}| market for acetic acid, without water, in 98% solution state | Cut-off, U	1.52E-01	kg		
	Potato protein	Potato protein, at processing {DE} Economic, U	7.26E-02	kg	Germany used as proxy for potato protein production due to process gaps in databases	
	Soybean {GLO}| market for | Alloc Rec, U	Soybean {US}| soybean production | Cut-off, U	2.30E-03	kg		
	Wheat gluten meal, consumption mix, at feed compound plant/NL Economic	Wheat gluten meal, at processing {US} Economic, U	2.75E-01	kg		
	Water, completely softened, from decarbonised water, at user {GLO}| market for | Alloc Rec, U	Water, completely softened, from decarbonised water, at user {GLO}| market for water, completely softened, from decarbonised water, at user | Cut-off, U	1.54E+01	kg		
Plant-Based Burger Processing (Goldstein et al., 2017)	Electricity, low voltage, US average	Electricity, high voltage {US}| market group for electricity, high voltage | Cut-off, U	5.17E+00	kWh		
	Heat, central or small-scale, natural gas {RoW}| market for heat, central or small-scale, natural gas | Alloc Rec, U	Heat, central or small-scale, natural gas {RoW}| market for heat, central or small-scale, natural gas | Cut-off, U	1.61E-01	kWh		

Table S4 Continued. Inventory used to model 1 kg plant-based burger production in the US.

Plant-Based Burger Processing (Goldstein et al., 2017)	Compressed air, 800 kPa gauge {GLO}| market for | Alloc Rec, U	Compressed air, 700 kPa gauge {RoW} market for compressed air, 700 kPa guage | Cut-off, U	3.22E+00	M3	800 kPa compressed air is an obsolete process in the database	
	Carbon dioxide, liquid {RER}| market for | Alloc Rec, U	Carbon dioxide, liquid {RoW}| market for carbon dioxide, liquid | Cut-off, U	2.97E-01	kg		
Packaging (Khan et al., 2019)	Paper, patty paper	Paper, woodfree, coated {RoW}| market for paper, woodfree, coated | Cut-off, U	1.60E-03	kg	Packaging items assumed to be same for plant-based and beef burger production (Khan et al., 2019)	Reliability (3) – Data was provided by impossible foods. Considered non-verified based on qualified estimates. Completeness (4) – Since only 1 source (impossible foods) provided the data, it is considered representative of only one site. Temporal Correlation (3) – Data provided by Impossible Foods was published in 2019, assumed to be given to authors within 10-year period. Geographical Correlation (1) – Impossible Foods is a US based company; data is considered to be from the US. Technological Correlation (1) – Data described the packaging of plant-based burgers, which is the exact system studied.
	Plastic Film	Packaging film, low density polyethylene {GLO}| market for packaging film, low density polyethylene | Cut-off, U	2.30E-03	kg		
	Corrugated Cardboard	Corrugated board, fresh fibre, single wall, at plant/US- US-EI U	1.00E-02	kg		

Table S5. Inventory used to produce 3.76 g calcium phosphate ($Ca_3(PO_4)_2$) from 1 L of diverted urine.

Phase	Input Name	Ecoinvent Input	Value	Unit	Notes and Assumptions	Ecoinvent Pedigree Matrix Values for Realistic Uncertainty
Urine Collection	Acetic Acid	Acetic acid, without water, in 98% solution state {GLO}| market for acetic acid, without water, in 98% solution state | Cut-off, U	3.00E-03	kg	Urine collection occurs at a waterless urinal or toilet. The process train is based on diverting and treating 1 L of urine, which is assumed to have an average concentration of 0.75 g P/L (cite papers). Acetic acid is necessary to prevent scaling in pipes, dosing scheme (0.05 L cleaning vinegar/ L urine) has been practiced by others investigating urine diversion (L. Crane, personal communication, November 20, 2023). Assume negligible dilution from acetic acid addition.	All values set to maximum uncertainty, as this technology is still at bench scale and is a compilation of various assumptions
Urine Storage	Sulfuric Acid	Sulfuric acid {RoW}| market for sulfuric acid | Cut-off, U	2.94E-03	kg	Stored urine needs to be stabilized using strong acid to prevent urea hydrolysis from raising the pH and forming carbonate, which would interfere with precipitation (Randall et al., 2016). 60 meq/L urine (~ 3 g/L H_2SO_4) sulfuric acid dosing has been shown to stabilize urine past 200 days at pH = 3 (Hellström et al., 1999). Assume negligible dilution from sulfuric acid addition, and P is recovered within 200 days.	
Precipitation	Sodium Hydroxide	Lime, hydrated, packed {RoW}| market for lime, hydrated, packed | Cut-off, U	3.00E-03	kg	At pH = 4, a calcium-to-phosphate molar ratio of 1.67 has been shown to achieve complete P recovery (Zhang et al., 2022). Therefore, its assumed that 3 g $Ca(OH)_2$ is sufficient to achieve complete P recovery. It is assumed that the product of precipitation is 100% amorphous tricalcium phosphate $Ca_3(PO_4)_2$ (Zhang et al., 2022).	
Mixing and Drying	Electricity	Electricity, high voltage {US}| market group for electricity, high voltage | Cut-off, U (Scaled Down)	1.20E-02	MJ	It was assumed that the energy demand of calcium phosphate (16 MJ/kg P) precipitation was similar to struvite precipitation (Maurer et al., 2003)	
Avoided Products	Water Treatment	Drinking Water Production {US}	2.24E+01	kg	Current federal standards require toilets and urinals to use 1.0 and 1.6 gal/flush, so 1.3 gal/flush was assumed (US EPA, 2023a, 2024d). Assuming an average urine volume of 0.22 L, 22.4 L (22.4 kg) of water was avoided per L of urine diverted (Huang Foen Chung & van Mastrigt, 2009). This water does not need to be treated at the water treatment plant and conveyed to the toilet or urinal.	
	Wastewater Treatment	Wastewater Treatment	2.24E+01	kg	The water not needed to flush the toilet or urinal, as shown above, does not need to be treated at the wastewater treatment plant. Therefore, 22.4 L (22.4 kg) of wastewater treatment is avoided.	
	Alum	Aluminium sulfate, powder {RoW}| market for aluminium sulfate, powder | Cut-off, U	8.3E-03	kg	Removing all P from the urine stream before sending it to the wastewater treatment plant decreases the P load at the plant. It is assumed that the chemical removal of P via coagulant is the main removal mechanism for P, alum is the primary coagulant used, and a dosing ratio of 2:1 (Al/P) is needed to reduce P levels to regulatory limits at the treatment plant (Neethling, 2013).	

Table S6. Inventory used to create 1 kg (1 L) of drinking water in the US, adapted from (Hilton et al., 2021)

Phase	Input Name	Ecoinvent Input for this Study	Value	Unit	Notes and Assumptions	Ecoinvent Pedigree Matrix Values and Reasoning for Realistic Uncertainty
Water Intake	River Water	Water, river, US	1.16E+00	kg	Assume 14% water losses during treatment and distribution processes (US EPA, 2024b)	All values are set to maximum uncertainty, as this inventory was taken from Hilton et al. (2021) and is a compilation of many other studies. Difficult to determine uncertainty, so maximum is defaulted.
Surface Water Treatment	Electricity	Electricity, high voltage {US}| market group for electricity, high voltage | Cut-off, U	4.43E-04	kWh	1 kWh of this process produced 0.462 kg CO_2 eq, which is higher than the 2022 average grid value of 0.376 kg CO2/kWh (US EIA, 2023). To more accurately represent the US electrical grid, the process inputs were scaled down by a factor of 81.4% so that the CO_2 emissions from 1 kWh were 0.376 kg.	
	Alum	Aluminium sulfate, powder {RoW}| market for aluminium sulfate, powder | Cut-off, U	4.91E-05	kg	Same term is used for avoided coagulants during wastewater treatment	
	Ferric Chloride	Iron (III) chloride, 40% in H2O, at plant/US* US-EI U	1.59E-05	kg		
	Polymer	Polyacrylamide {GLO}| market for polyacrylamide | Cut-off, U	1.19E-07	kg		
	Lime	Quicklime, at plant/US	4.93E-06	kg		
	Limestone	Limestone, crushed, washed/US* US-EI U	2.03E-05	kg		
	NaOH	Sodium hydroxide, 50% in H2O, production mix, at plant/US- US-EI U	3.32E-05	kg		
	HSF	Chemical, inorganic {GLO}| market for chemical, inorganic | Cut-off, U	1.10E-06	kg		
	Ammonia	Ammonia, liquid, at regional storehouse/US* US-EI U	2.10E-07	kg		
	Phosphoric Acid	Phosphoric acid, fertiliser grade, 70% in H2O, at plant/US US-EI U	4.00E-05	kg		
	CO_2	Carbon dioxide, liquid {RoW}| market for carbon dioxide, liquid | Cut-off, U	1.82E-05	kg		
	Chlorine Gas	Chlorine, gaseous {RoW}| market for chlorine, gaseous | Cut-off, U	1.48E-06	kg		
	Sodium Hypochlorite	Sodium hypochlorite, without water, in 15% solution state {RER}| market for sodium hypochlorite, without water, in 15% solution state | Cut-off, U	8.60E-05	kg		
	Calcium Hydroxide	Lime, hydrated, packed, at plant/US* US-EI U	1.38E-05	kg		
	KMnO4	Potassium permanganate, at plant/US- US-EI U	1.97E-07	kg		
Distribution	Distribution Electricity	Electricity, high voltage {US}| market group for electricity, high voltage | Cut-off, U	2.00E-04	kWh	Scaled down to represent the current US electrical grid as described above.	

Table S7. Inventory used to create 1 m^3 wastewater treatment in conventional plug flow activated sludge system, adapted from (EPA, 2021).

Phase	Input Name	Ecoinvent Input	Value	Unit	Notes and Assumptions	Ecoinvent Pedigree Matrix Values and Reasoning for Realistic Uncertainty
Conveyance	Electricity	Electricity, high voltage {US}| market group for electricity, high voltage | Cut-off, U	9.41E-02	kWh	Small value because most conveyance is via gravity. Value sourced from Hilton et al. (2021)	Reliability (3) – Data was sourced primarily from design wastewater treatment plant design software and literature values. Considered to be non-verified but based on qualified estimates. Completeness (3) – The dataset represents one type of wastewater treatment plant setup, and is not considered to be reflective of the majority of setups. Temporal Correlation (5) – Unsure of how old the data and model used in this inventory are, set as maximum to be cautious. Geographical Correlation (1) – EPA is a US-based agency and the wastewater treatment plant setup is based in the US. Technological Correlation (1) – The dataset describes conventional plug flow activated sludge wastewater treatment, which is the exact system needed for this study.
Screening and Grit Removal	Electricity	Electricity, high voltage {US}| market group for electricity, high voltage | Cut-off, U	3.40E-03	kWh		
Primary Clarifier	Electricity	Electricity, high voltage {US}| market group for electricity, high voltage | Cut-off, U	8.60E-04	kWh		
Plug Flow Activated Sludge	Electricity	Electricity, high voltage {US}| market group for electricity, high voltage | Cut-off, U	1.40E-01	kWh		
Secondary Clarifier	Electricity	Electricity, high voltage {US}| market group for electricity, high voltage | Cut-off, U	1.30E-03	kWh		
Chlorination	Electricity	Electricity, high voltage {US}| market group for electricity, high voltage | Cut-off, U	9.50E-03	kWh		
	Chlorine Gas	Chlorine, gaseous {RoW}| market for chlorine, gaseous | Cut-off, U	1.00E-02	kg		
Dechlorination	Electricity	Electricity, high voltage {US}| market group for electricity, high voltage | Cut-off, U	9.50E-03	kWh		
	Sodium Bisulfite	Sodium hydrogen sulfite {GLO}| market for sodium hydrogen sulfite | Cut-off, U	1.52E-03	kg		
Gravity Thickener	Electricity	Electricity, high voltage {US}| market group for electricity, high voltage | Cut-off, U	7.50E-04	kWh		
Anaerobic Digester	Electricity	Electricity, high voltage {US}| market group for electricity, high voltage | Cut-off, U	2.00E-02	kWh		
	Natural Gas	Natural gas, low pressure {US}| market for natural gas, low pressure | Cut-off, U	4.00E-02	m3		
	Biogas Flaring	Biogas Flaring	1.20E-01	m3	Biogas flaring process taken from Table F-8 (EPA, 2021)	
Centrifuge	Electricity	Electricity, high voltage {US}| market group for electricity, high voltage | Cut-off, U	2.00E-02	kWh		
	Polymer	Polyacrylamide {GLO}| market for polyacrylamide | Cut-off, U	2.10E-03	kg		
Sludge Hauling and Landfill	Avoided Electricity	Electricity, high voltage {US}| market group for electricity, high voltage | Cut-off, U	-2.00E-02	kWh		
Emissions from wastewater treatment	Methane	Methane	5.40E-03	kg		
	Nitrous Oxide	Dinitrogen Monoxide	2.90E-04	kg		