Re-organising Nutrients Flows in Leicestershire

Systemic innovation to transform nutrient flows for environmental and socioeconomic benefits

Agile Initiative | December 2023

1.1 Executive Summary

Current research on mapping nutrient systems has revealed the complexity of the nutrient system and how different sectors and waste streams are interlinked; changes in one stream will impact another. A system's approach is needed for better nutrient management, preferably one that takes the potential for circularity into account.

The overall objectives of this project were as follows. Firstly, to produce quantitative mapping of organic waste and nutrient flows (nitrogen (N) and phosphorus (P) in particular) in the case study region including Leicestershire County (LCC) and Leicester City, to identify significant nutrient losses. Secondly, to identify technical and business opportunities for improving nutrient management in the case study region, for economic and environmental benefits. While the case study is used to focus the research, learnings generated are potentially transferrable to other regions and can inform policy making and implementation at national and local levels. Therefore, this report is also relevant for: government, local planning authorities, wastewater processing consultancies, agriculture, regulators, real estate developers, landscape contractors, energy companies, capital providers, innovative nutrient recovery technology companies, food manufacturers, fertiliser manufacturers, environmental organisations, the water industry and research institutions.

The organic waste system is deeply interconnected and complex. Analysis from this project demonstrates the value of stakeholder-driven food systems mapping, data acquisition and the importance of understanding the business and economic assessment of available technologies. There are multiple avenues for approaching a circular organic waste system requiring the buy-in of stakeholders at multiple levels and scales, and opportunities for environmental and economic benefits across the system identified in this report.

Key findings:

1. **Significant leakages of nutrients in the case study region:** Within processed waste streams, discharged wastewater represents the most significant leakage of N and P, while rejected water from anaerobic digestion (AD) plants is the second most significant nutrient-leaking stream. However, nutrient content in the land application/deposition of slurry and manure appears to overtake all other flows in the region.
2. **Movement of organic waste:** There is clear evidence of sizable transportation of organic wastes between the case study region and other locations and between regions in England. Such haulage burdens have economic and environmental implications.
3. **Business opportunities for re-design:** This project has identified four business opportunity areas to improve regional nutrient management: **(i) Upstream wastewater solutions** - intervening prior to nutrients entering the wastewater system; **(ii) Transformation of digestate** - utilising technology to ensure that the nutrients contained within digestate can be more fully utilised by crops; **(iii) Downstream farming interventions** - farming differently to apply nutrients more sparingly and prevent loss to the wider environment and **(iv) Nutrient co-location** - tackling the challenges associated with moving nutrient-rich materials by situating sources and uses close together.
4. **Stakeholder commitment and regional mechanisms for coordinated actions:** To link local policy with recommended solutions, there is need for commitment from multiple stakeholders, investment and consideration of multiple drivers and income streams to progress considerations such as where nutrients are (and are not) needed, where they are

going to be produced, commitment of local food waste collection to drive a more nutrient focused approach compared to traditional 'collect and dispose' practice. National policies overpower the local motivations and needs. There is a need for a bottom-up approach where the agency and capacity for planning changes and leadership is based on the needs and willingness of the actors at grassroots level.

5. **Regulatory reforms:** Regulations around use of fertilisers derived from organic waste need to be updated to avoid negative impacts of applying recovered nutrient products on the soil health and environment. Current regulations do not give indications of these consequences. For example, green waste is processed into compost according to PAS100 certification, which allows for a certain percentage of plastic in the compost. This plastic can accumulate in the soil over time and create long-term issues.
6. **Household behaviours:** Organic waste contamination is one of the biggest barriers to enhancing the valorisation of AD digestate, which is key for closing the nutrient loop in an agrarian region. How people dispose wastes in bins and mix plastic waste with the organic waste is key in optimising the waste processing systems. If the waste is better managed at the source itself, it can prevent contamination of organic waste and therefore the resources needed to remove contamination.
7. **Robust and consistent data:** There are significant discrepancies between the datasets acquired from multiple sources (e.g., LCC and Environment Agency (EA)). Consistent micro-scale data pertaining to waste streams, recovered nutrients and farmers practices is required to prepare plans for optimising nutrient recycling.

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Section 1: Introduction

1.2 Project background

The 'Nutrients Flow' Sprint project as part of the Agile Initiative, based at the Oxford Martin School, University of Oxford, involved stakeholders from varied backgrounds and explored opportunities and barriers to instigating nutrient circularity by making socio-technical changes in the nutrient flow system. The research team investigated four viable and scalable options for recovering nutrients from organic waste in terms of the feasibility, resources and impact drivers. The assessment was carried out with stakeholders during three stakeholder workshops over 12 months between July 2022 and September 2023. This research focused on Leicestershire as a case study. This document compiles the key findings of the assessment and lists key considerations for implementing the recommended options. This project is pioneering work that involved a systems and interdisciplinary approach and provides a deep dive into the current local organic waste management system and its bottlenecks. This information is most relevant to local policy makers, upcoming technology enterprises and academics who are interested in solving the nutrient circularity challenges highlighted in this report.

For decades, nutrient pollution management has been a key agenda item for Defra with a focus on preparing guidelines for nutrient management at an agriculture farm scale through better practices. However, DEFRA recently announced a 'Nutrient Mitigation Scheme'[i] as part of the Natural England Nutrient Neutrality and has invited local authorities to find innovative solutions for tackling nutrient losses in the organic waste system that is contributing to ecological degradation. Current research on mapping nutrient systems has revealed the complexity of the nutrient system and how different sectors and waste streams are interlinked; changes in one stream will impact another. A system's approach is needed for better nutrient management, preferably one that takes the potential for circularity into account.

The adverse effects on the environment from organic waste ending up in landfills is well known. Systemic socio-technical changes are required in the waste flow system, i.e., waste generation, collection, disposal, transportation, processing and post processing valorisation of recovered products/disposal of unwanted waste products in order to mitigate environmental damage from nutrient surplus. Generating circularity of the nutrients by recovering N and P from the waste and feeding it back to point of source (e.g., as fertiliser for agriculture) can tackle many of given organic waste challenges and this topic has received much attention from researchers in recent years. Several technical solutions for recovering nutrients from waste have been investigated in scientific literature. However, the scale of impact and relevance of the potential solutions varies across geographies depending on a number of drivers, namely source and composition of organic waste, methods for managing waste, support available for adopting new practices (e.g., subsidies, technical assistance), waste management institutional structures, and local interests and motivation. These drivers are inevitably influencing the 'Nutrient flows system' which is comprised of sources and destinations of nutrients as nodes and the processes involved that links these system nodes (Figure 2.2). The systems approach enables stakeholders to explore the interdependencies and sensitivities of different parts of the system and understand where and how the changes will make a significant difference.

1.3 Why Leicestershire

Nutrient flows are key elements in the UK's bio-economy and bear significant environmental, social and economic importance in multiple areas, including securing food supply, restoring the aquatic environment, maintaining biodiversity and meeting Net-Zero. However, the linear and imbalanced nature of current nutrient flows creates significant challenges. For example, urban centres concentrate nutrient elements imported from surrounding catchments, posing a substantial waste management problem for local authorities and municipal operators. Reorganising such nutrient flows requires them to be understood as a resource opportunity and managed differently as part of a circular economy concept. This needs to take place both within cities, through new value-added activities, and along the city-rural links as sustainable agricultural fertiliser solutions. However, concerted, systemic actions in this area are rare. At the regional level, our discussions with Leicestershire County Council (LCC), as a key partner representing local authorities show that there is now an urgent need to explore such opportunities, not least to respond effectively to recent and upcoming policies, particularly in anticipation of the mandatory weekly collection of food wastes (rising from the current 50% level) by 2023, as contained in the Environment Act 2021[i] Considering both food waste and other organic streams arising from a regional economy (e.g., green waste and biosolids) involves the following challenges:

- Primary food production and processing hub which is a source of organic waste and also potential consumers for recovered nutrients
- Inefficiencies in the waste collections strategies due to disjointed institutional structure and lack of knowledge sharing.

Nutrients are a key part of the nature recovery agenda but knowledge around how it can be managed by different actors along the waste value chain in a synergic way is scarce. There are a lot of emerging ideas around land use management for better nutrient circularity at the farm level. But the information on the best practices and challenges in deploying these changes is scattered and do not focus on what is feasible at the local level. An assessment of options can support decision making and help in identifying knowledge gaps for in-depth investigation.

1.4 Overall objectives and structure of work

The overall objectives of this research are (i) to produce quantitative mapping of organic waste and nutrient (N and P in particular) flows in the case study region including Leicestershire County and Leicester City, to identify significant nutrient losses and (ii) to identify technical and business opportunities for improving nutrient management in the case study region, for economic and environmental benefits. While the case study is used to focus the research, the learnings generated from the case study are expected to be transferrable to other regions and to inform the connections of policy making and implementation across national and local levels.

To achieve the above objectives, the project has adopted a structure shown in Figures 1a and 1b.

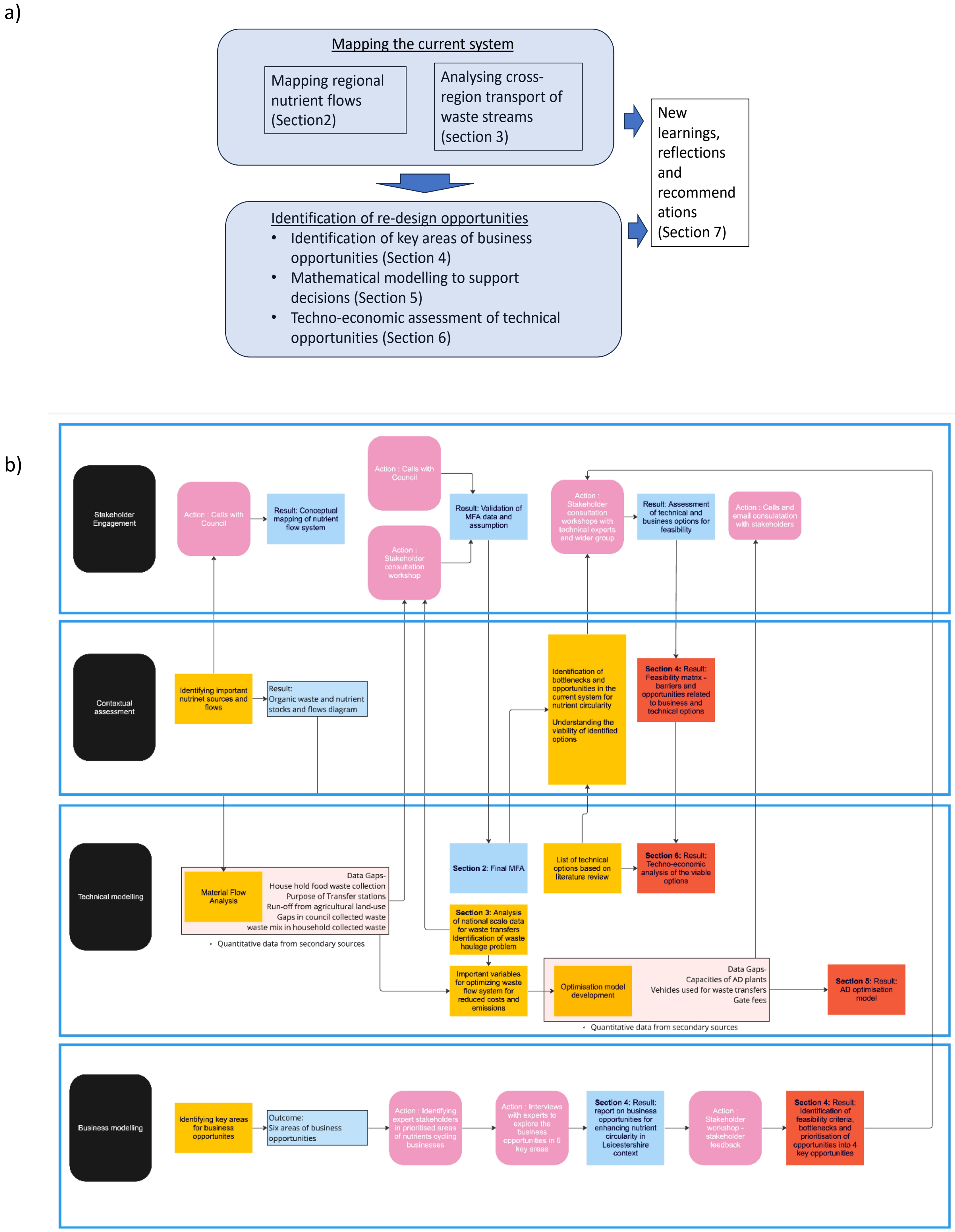


Figure 1: a) structure of the project; b) inter-disciplinarity of the project and work flow

Section 2: Mapping the organic waste flow system

2.1 Approach

The first step to systemic transformation is understanding the current complexities and interactions between organic waste system activities, drivers, trade-offs and key players while assessing the entry-points for techno-economic interventions. Various data resources were explored in order to map the waste flow system in Leicestershire and estimate the amount of nutrients N and P that are leaked into the environment or transformed into by-products along the waste flows from the source to the last destination i.e., waste processing facility. Consultations with the local authorities and waste processing facilities helped in making assumptions for estimations and filling the data gaps resulting in a comprehensive map of organic waste and nutrients stocks and flows.

2.2 Identifying the key nutrient sources and flows: First and second stakeholder workshops

The first stakeholder consultation took place on 5 July 2022 and was focused on developing an understanding of nutrient flows in Leicester and Leicestershire, key actors in the nutrient flow system, desired outcomes from the system, opportunities for change, and bottlenecks to transformation. Participants identified the key sources and the key steps in the nutrient flow systems relevant to Leicester and Leicestershire. A map of these sources and the links between different parts of the system was developed from this consultation. (Figure 2.1)

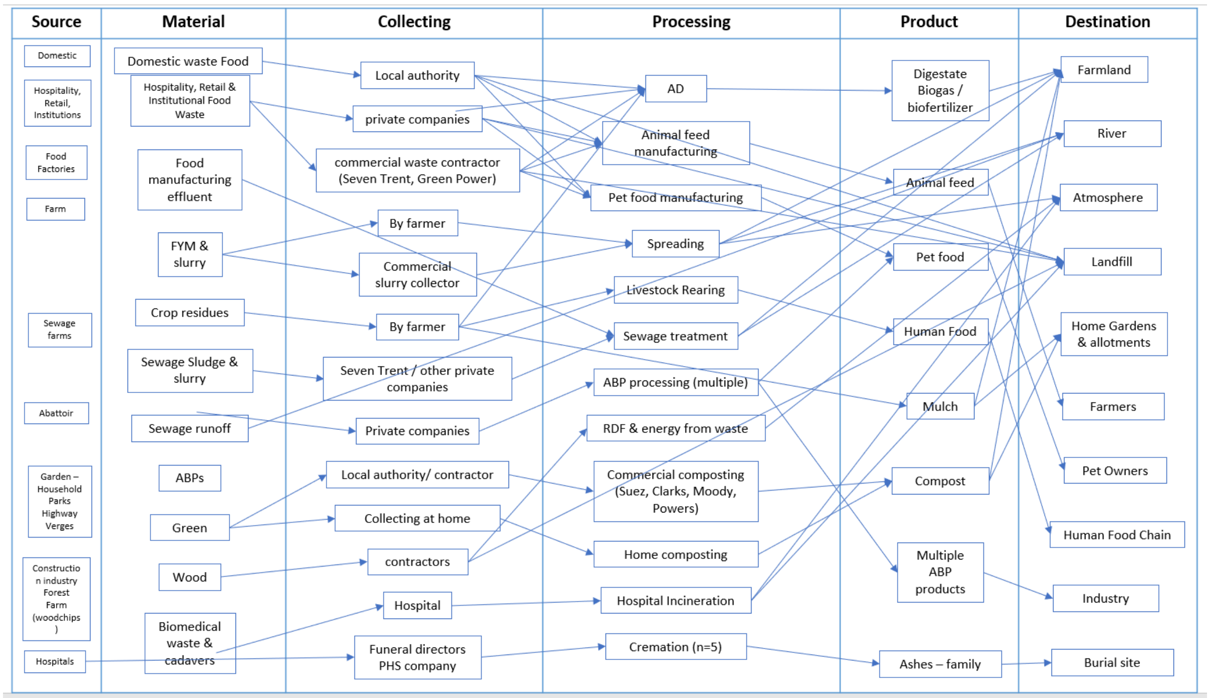


Figure 2.1: Map of nutrient sources and flows within the organic waste system

The discussion on mapping the nutrient flow system was followed by a second breakout session between two groups, exploring stakeholders that may be missing from the consultation given the nutrient flows under discussion, and the challenges and opportunities present in each material source for the nutrient flows. This rich discussion has been summarised as follows:

Key challenges and opportunities:

- Household behaviour, particularly in relation to food and garden waste and segregation of these materials at source.
- Issues of plastic and micro-plastic contamination for multiple materials.
- Institutional challenges in relation with overall coordination.
- Misalignment between national and local policies and regulation.
- Lack of power for councils for the circular economy strategy.
- A need for a joined-up strategy for the whole council.
- A need for relevant stakeholders in the system to understand the multiple types of farms.
- Challenges in managing responsibility and ownership for issues such as highway verge material collection and management.
- Investment differences across technologies (e.g., more investment in wet AD, as opposed to the more expensive dry AD).
- Concerns with wet wipes, long lasting POPs, and hormones in sewage, impacting end-use.
- Opportunities in managing upstream changes for material use, e.g., reviewing chemical use for construction timber.

The consultation with the stakeholders generated understanding of the key nutrient stocks and flows and the parts of the organic waste system that should be considered to explore the nutrient circularity opportunities at the local scale. Post workshop, the researchers scanned the literature and data portals in order to develop a systematic diagram of the nutrient stocks and flows (Figure 2.2) that can then be made quantitatively explicit for further modelling work i.e., Material Flow Analysis (MFA). Reviews of the literature and publicly available data (e.g., waste interrogator, wastedataflow.org) revealed the gaps in analysing the systems and anecdotes around how the systems operates. This ascertained the need for another stakeholder consultation.

For the consultation, the draft MFA model was developed which quantified the stocks and flows using the readily available data and assumptions. In order to fill the gaps and validate the assumptions, stakeholders were consulted in a second workshop and through one-on-one meetings.

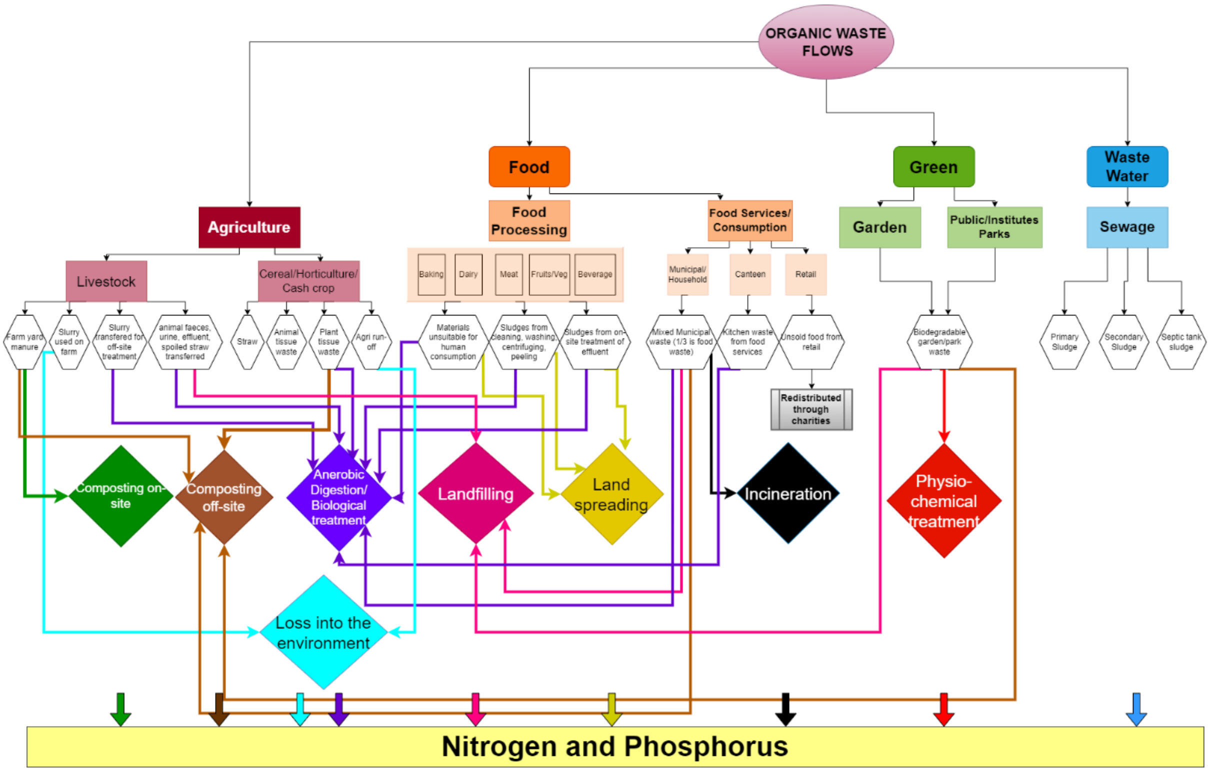


Figure 2.2: Organic waste flow system and nutrients stocks and flows

The second stakeholder consultation was organised in February 2023where the first draft of the quantitative model of the nutrients flows and the list of identified business and technical options were presented. Stakeholders were asked to identify the technical, economic, environmental and regulatory issues associated with the business and technical nutrient recovery options and to highlight if any element of the system was missed and if the numbers are sensible in the MFA model. They were also asked to identify potential options that could be viable in the Leicestershire context that were not included in the list. Several data related doubts were cleared up during the workshop and nutrient recovery opportunities were filtered for Leicestershire.

2.3 MFA method and data

2.3.1 Purpose and scope

The case study region ("the region") comprises Leicestershire County and Leicester City, with the city located at the centre of the county. The purpose of this mapping exercise was to quantify how nutrients, which include particularly nitrogen (N) and phosphorous (P), are embedded in the waste streams that are currently generated in the region and are distributed along the journey in which the waste streams are processed or disposed of. The key intended learning was to identify the most significant sources and sinks of nutrients, to reveal desirable focuses for future interventions to improve resources, economic and environmental performances of nutrients management in the region.

This mapping considered the following types of waste streams:

a. Green waste arising from gardening and maintenance of green spaces such as parks
b. Food waste arising from food processing and consumption
c. On farm slurry and manure wastes
d. Wastewater

For each type, the exact categories of streams included in the mapping are further described in Section 2.2.3. Other streams, including run-offs, were investigated in this work but the limited time and data availability meant no suitable results were produced for inclusion in the report.

This mapping focused on wastes generated within the region; wastes transported to this region from other locations were not included. Besides, streams of types a and b originating in the region are processed both in the region and elsewhere; both were considered in the mapping.

In terms of the year choice for data investigation, 2019 was chosen as the most recent year before the COVID-19 pandemic, although no significant variations were observed between 2019 and post-covid years data (note- only checked for sources where multiple-year data was available for inspection).

2.3.2 Approach to material flow mapping

The mapping was essentially a material flow analysis (MFA), completed by the combined use of the following data:

(i) Quantities of the raw waste streams (i.e., waste prior to treatment or disposal), in tonne/year;
(ii) Processing or disposal options applied to the raw waste streams;
(iii) Quantities of streams arising from the processing or disposal of the raw waste streams, in tonne/tonne raw waste; and
(iv) Content of nutrients (N, P) in each of these streams, in kg (nutrient)/kg (material).

(i) and (ii) were collected from a range of data sources, as explained in Section 2.2.3.1. (iii) and (iv) were primarily based on the mass balance modelling of waste processing and treatment options, which are referred to as "processing units" or (PUs) as explained in Section 2.2.3.2. Other approaches than using the PUs were additionally needed for the mapping of slurry and manure and wastewater, which are explained in Sections 2.2.3.5. and 2.2.3.6.

2.3.3 Raw waste streams and their destinations

2.3.3.1 Waste Data Interrogator, Environment Agency (EA) 2019

This EA dataset[i], records waste flows that are regulated by EA permits. It contains two Excel files dedicated to "waste received" and "waste removed", respectively. The first was the main one used in this study, which provides a detailed recording of the type and **quantity** of the waste flows received by facilities permitted by the EA for handling the waste. The origin of each waste flow, detailed to the level of Waste Planning Authority (WPA), is also documented. The waste type is classified according to European Waste Catalogue (EWC) chapters and sub-chapters[ii]. The types of activities on the waste, such as treatment, disposal, transfer and storage are also codified[iii]; an explanation of the codes, for example Recovery (R) and Disposal (D) codes were taken from the website www.watesupport.co.uk. This information was used to determine the **destination** of the waste under consideration (i.e., how it was treated or disposed of).

It should be noted that, although R&D codes are provided in the dataset, not all the supplied codes are sufficiently precise to allow the destination of a waste stream to be uniquely determined. Furthermore, some of the destinations are marked as transfer or storage, instead of a processing option, and the true destinations of these streams are not always clear. For these reasons, some assumptions had to be adopted in this mapping exercise, which in certain cases was based on the combined use of the R&D coding and the indicated “facility type”, as detailed in the following subsections.

In the “Waste received” Excel file, the sheet titled "2019 Waste received” was used for collecting data of green waste, food production/processing waste and part of the wastewater-related data, which are further explained below.

2.3.3.2 Green waste

Using the EA dataset, relevant waste flows were identified by “Origin WPA” -> “**Leicester City**” and “**Leicestershire**”, “SOC Sub Category” -> “**Green wastes**”.

The processing/disposal options applied to these flows were determined according to Tables 2.1 (for Leicestershire County) and 2.2 (for Leicester City).

Table 2.1: Coding adopted to determine green waste destinations: Leicestershire County

R&D code	Assumed destination
Waste treated within the county	
R03	Composting
R13	Composting
R03.02.01	Composting
R03.01.04	Composting
D01	Landfilling
D09	Other fates
D01.02	Landfilling
Waste treated outside the county	
R03.02.01	Composting
R10	Land treatment
R03	Composting
R13	Composting
R12	Other fates
D15	Landfilling
R03.04	Mechanical Processing

Table 2.2: Coding adopted to determine green waste destinations: Leicester City

R&D code	Assumed destination
Waste treated within the city	
R13	Composting
R13	Composting
D09	Other fates
R03.01.04	Composting
Waste treated outside the city	
R03.02.01	Composting
R13	Composting

2.3.3.3 Food production/processing waste

Using the EA dataset, relevant waste flows were identified by *“Origin WPA” (The Waste Planning Authority which the waste originates)* -> *“**Leicester City**”* and “**Leicestershire**”, “SOC Sub Category” -> *“**Wastes of food preparation and products**”*.

The processing/disposal options applied to these flows were determined according to Tables 2.3 (for Leicestershire County) and 2.4 (for Leicester City).

Table 2.3: Coding adopted to determine food production / processing waste destinations: Leicestershire County

R&D code/facility type	Assumed destination
Waste treated within the county	
D13	AD
R03.02.01	Composting
R03	AD
R10	Land spreading
Waste treated outside the county	
R03.03/AD	AD
R03.03/Biological treatment	AD
R10	Land spreading
D08	AD
R03	AD
D13/AD	AD
R09	Physical/chemical Processing
R03.03	Composting
R13	AD
R03.04	Mechanical processing
R03/composting	Composting
R03.01	AD
D15/ Haz Waste Transfer	Landfill
R01/ Animal By-Products Incinerator	Incineration
R05/Material Recycling Facility	Physical-Chemical Treatment
D09/Haz Waste Transfer / Treatment	Physical-Chemical Treatment
D05	Landfilling
D10	Incineration

Table 2.4: Coding adopted to determine food production / processing waste destinations: Leicester City

R&D code	Assumed destination
Waste treated within the city	
R13	AD
Waste treated outside the city	
R03.03	AD
R03.04	Mechanical processing

Note: that AD stands for anaerobic digestion.

2.3.3.4 *Food consumption waste*

The EA dataset was not ideal for mapping food consumption waste flows for this case study. This is because there is currently no separate food waste collection from households in this region, and non-household food consumption waste flows appear to be not straightforward to extract from the EA dataset. Therefore, the following method was adopted instead of using the EA dataset:

- Household food waste generation was estimated based on 0.16 tonnes/household/year quantified by an earlier study for Leicestershire[iv], and the numbers of household in the county (296400) and the city (137970) (source: ONS, UK).
- The destinations of the household food waste in the county follows those of the household residual waste and were determined as 62% to landfill and 38% to incineration (Source: Question 23 Residual waste 2019).
- The destination of the household food waste in the city was assumed to be AD, according to the information provided by the city to this study which stated that the organic fraction of the household residual waste is currently separated at a waste handling facility and then sent to AD.
- The quantity of non-household food waste was estimated, according to a WRAP report[v], to be Household food waste *0.165. The exact destination of this waste stream was not identified and was assumed to be AD for the mapping exercise.

2.3.3.5 Slurry and manure

The quantity and on-farm application destinations of slurry and manure waste as well as the nutrient content of the involved flows were determined based on the dataset “Estimates of manure volumes by livestock type and land use for England and Wales” by Defra, Environmental Information Data Centre” as described in Appendix A. Insignificant off-farm destinations exist, which were mapped based on the EA dataset introduced earlier.

2.3.3.6 Wastewater

The main wastewater stream is that centrally treated by the local water company, Severn Trent. The data provided by the company was for 2022, which reported ~100 million tonnes of wastewater being treated. The data however was accompanied by a note that 2022 was a relatively dry year and, in a wetter year, the wastewater volume could exceed 150 million tonnes due to the much greater volume of storm water. Therefore, this mapping adopted an annual volume of 125 million tonnes/year to approximate an average level. The nutrient content of the raw wastewater and the discharged treated water was based on Severn Trent’s data. The wastewater treatment results in primary and secondary sludges, which are both treated with AD; the wastewater treatment and AD PUs were used to quantify the sludge and AD effluent flows and their nutrient content.

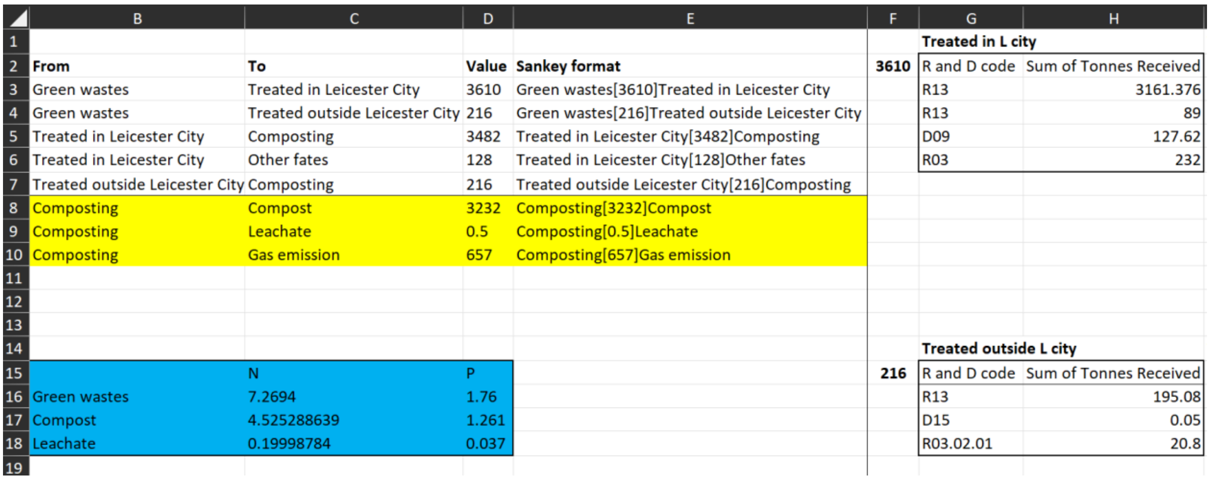
A second wastewater stream is that treated by septic tanks. This mapping included the septic tank sludge for the case study region and their destinations, all based on the EA dataset.

2.3.4 Modelling of Processing Units

Mass balance of Processing Units (PUs) was used as the basis for determining the output of organic waste processing. A description of the PUs is provided in Section 6.2.

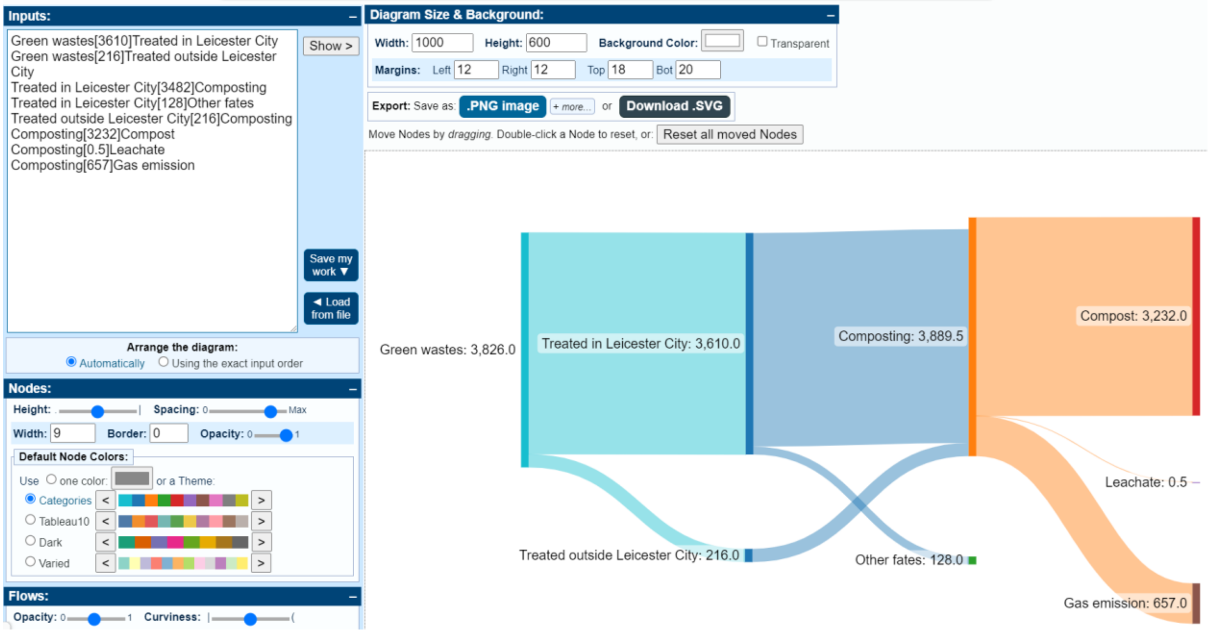
2.3.5 Generation of Sankey Diagrams

As mentioned above, this mapping combined data of raw waste streams and their processing/disposal. To visualise the results, an Excel spreadsheet model was developed which draws on information extracted from the EA dataset and other data sources, as well as the information from the PU modelling, to prepare information needed for constructing Sankey diagrams using the SankeyMATIC online tool[vi]. Using the green waste subsystem for Leicester City as an example, the Excel model and the use of SankeyMATIC are illustrated by Figures 2.3 and 2.4, respectively.



	B	C	D	E	F	G	H
1						**Treated in L city**	
2	**From**	**To**	**Value**	**Sankey format**	**3610**	R and D code	Sum of Tonnes Received
3	Green wastes	Treated in Leicester City	3610	Green wastes[3610]Treated in Leicester City		R13	3161.376
4	Green wastes	Treated outside Leicester City	216	Green wastes[216]Treated outside Leicester City		R13	89
5	Treated in Leicester City	Composting	3482	Treated in Leicester City[3482]Composting		D09	127.62
6	Treated in Leicester City	Other fates	128	Treated in Leicester City[128]Other fates		R03	232
7	Treated outside Leicester City	Composting	216	Treated outside Leicester City[216]Composting			
8	Composting	Compost	3232	Composting[3232]Compost			
9	Composting	Leachate	0.5	Composting[0.5]Leachate			
10	Composting	Gas emission	657	Composting[657]Gas emission			
11							
12							
13							
14						**Treated outside L city**	
15		N	P		**216**	R and D code	Sum of Tonnes Received
16	Green wastes	7.2694	1.76			R13	195.08
17	Compost	4.525288639	1.261			D15	0.05
18	Leachate	0.19998784	0.037			R03.02.01	20.8
19							

Figure 2.3: An illustrative example of preparing information for SankeyMATIC in an Excel model.



Inputs:

Green wastes[3610]Treated in Leicester City
Green wastes[216]Treated outside Leicester City
Treated in Leicester City[3482]Composting
Treated in Leicester City[128]Other fates
Treated outside Leicester City[216]Composting
Composting[3232]Compost
Composting[0.5]Leachate
Composting[657]Gas emission

Arrange the diagram: ● Automatically ○ Using the exact input order

Nodes: Height: Spacing: 0 Max; Width: 9 Border: 0 Opacity: 0 1

Default Node Colors: Use ○ one color: or a Theme: ● Categories ○ Tableau10 ○ Dark ○ Varied

Flows: Opacity: 0 1 Curviness:

Diagram Size & Background: Width: 1000 Height: 600 Background Color: ☐ Transparent

Margins: Left 12 Right 12 Top 18 Bot 20

Export: Save as: .PNG image + more... or Download .SVG

Move Nodes by *dragging*. Double-click a Node to reset, or: Reset all moved Nodes

Figure 2.4: An illustrative example of constructing a Sankey diagram using SankeyMATIC.

2.3.6 Towards an automatic data mapping tool for analysing organic waste data

In parallel to the above modelling work on the case study location, a preliminary exploration was made in creating a tool that can map the destinations of a specific type of organic waste originated in a chosen location, based on the EA's Waste Data Interrogator dataset. The intention is to show in principle how this national dataset can be used together with the models of Processing Units developed in this work, to automatically generate organic waste and nutrient flow visualisation in the form of Sankey diagrams. The implementation details and the illustrative results of this preliminary exploration are presented in Appendix E.

2.4 MFA results (inter-regional and intra-county flows)

The results of mapping the nutrient flows in the case study region are presented by a set of Sankey diagrams:

- Figure 2.5: a summary of the overall system;
- Figures 2.6 (a) and 2.6 (b): mapping of the green waste subsystem for the city and the county, respectively;
- Figures 2.7 (a) and 2.7 (b): mapping of the food waste subsystem for the city and the county, respectively;
- Figure 2.8: mapping of the slurry and manure subsystem for the region; and
- Figure 2.9: mapping of the wastewater subsystem for the region.

Each diagram presents the quantities of the raw waste streams and those arising from their processing or disposal. The N and P content are provided for the raw waste streams and other streams modelled in the PUs that are present in the current system (wastewater treatment, AD, compositing, incineration and landfill). Further N and P content data are shown for on-farm applications of slurry and manure streams. All quantities of material flows and nutrients are in tonne/year.

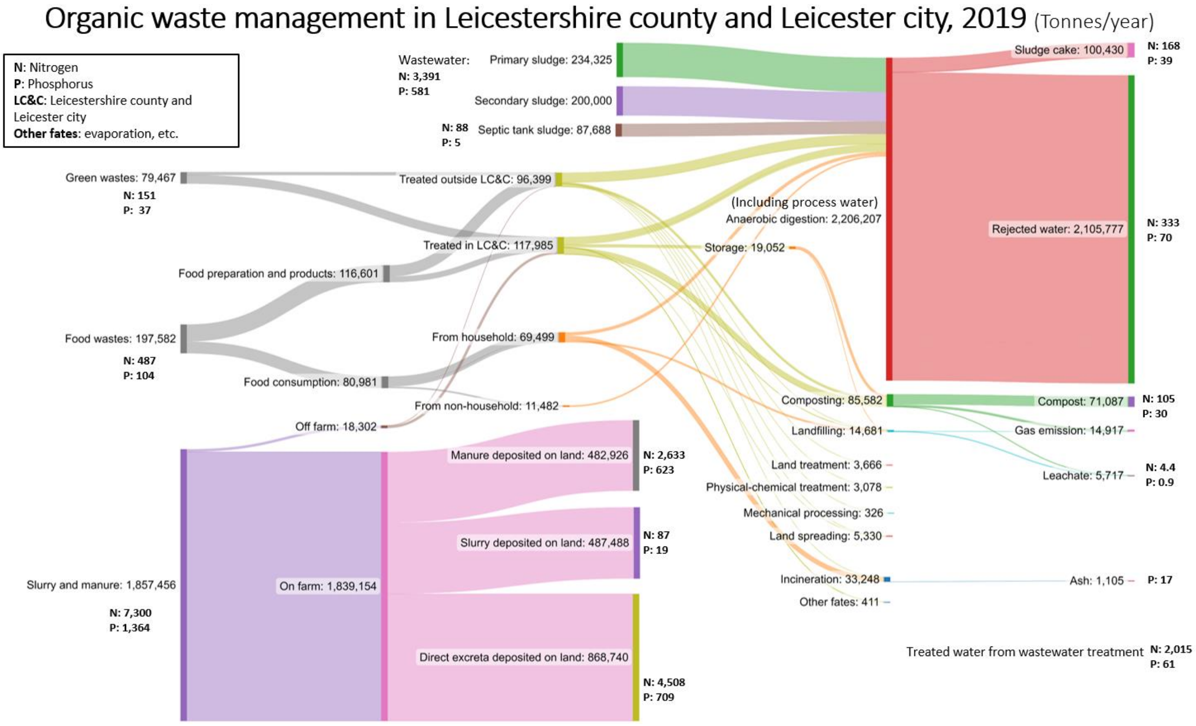


Figure 2.5: Overview of the flow mapping.

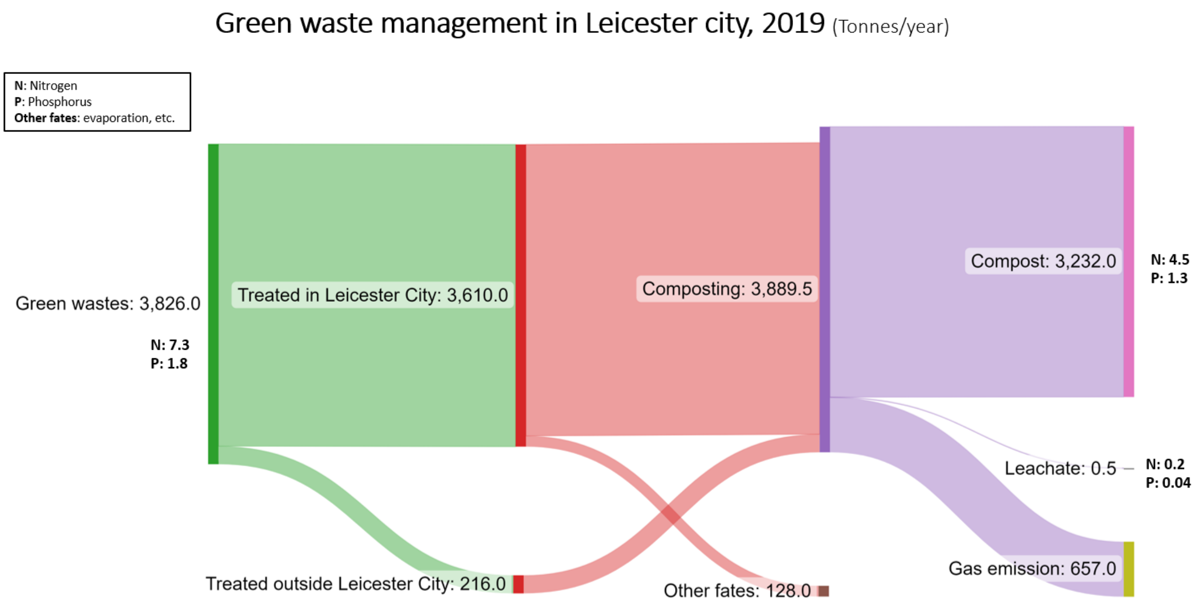


Figure 2.6: (a) Mapping of the green waste subsystem – Leicester City.

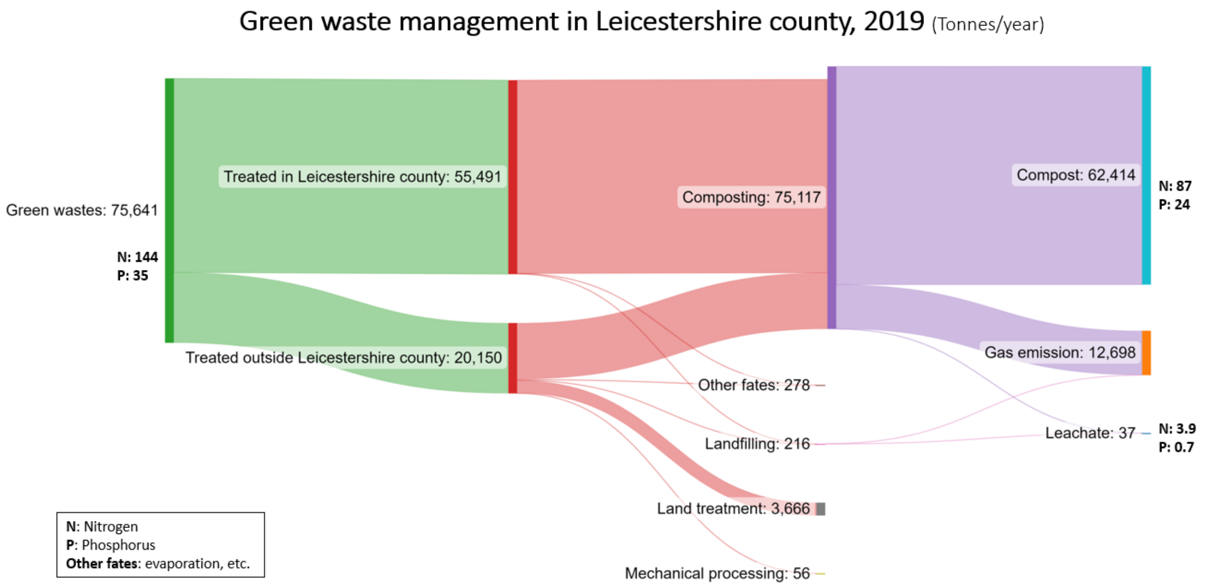


Figure 2.6: (b) Mapping of the green waste subsystem – Leicestershire County.

Food waste management in Leicester city, 2019 (Tonnes/year)

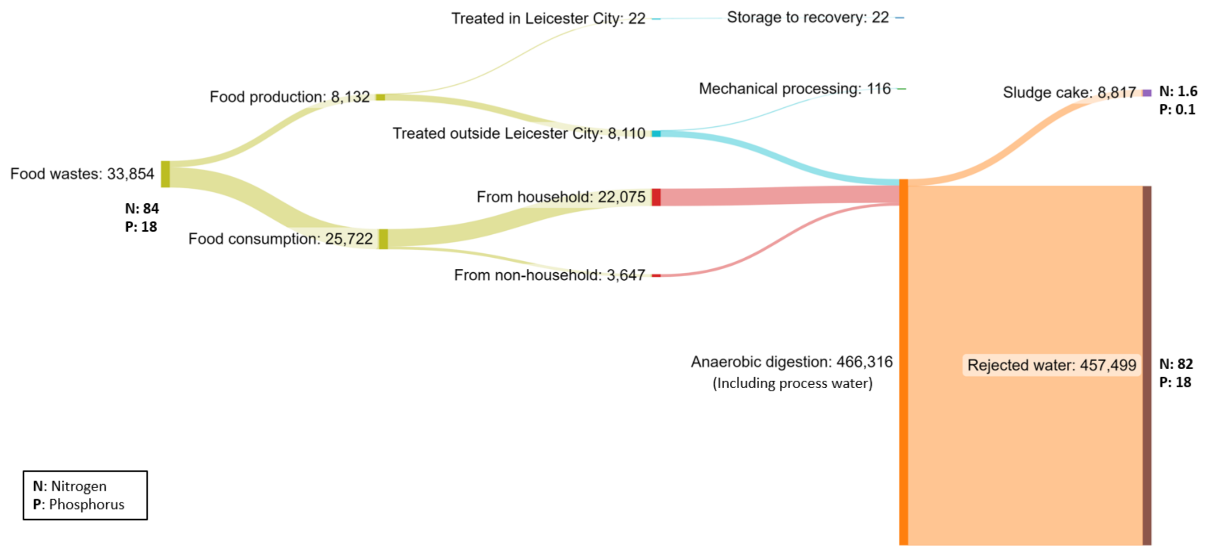


Figure 2.7: (a) Mapping of the food waste subsystem: Leicester City.

Food waste management in Leicestershire county, 2019 (Tonnes/year)

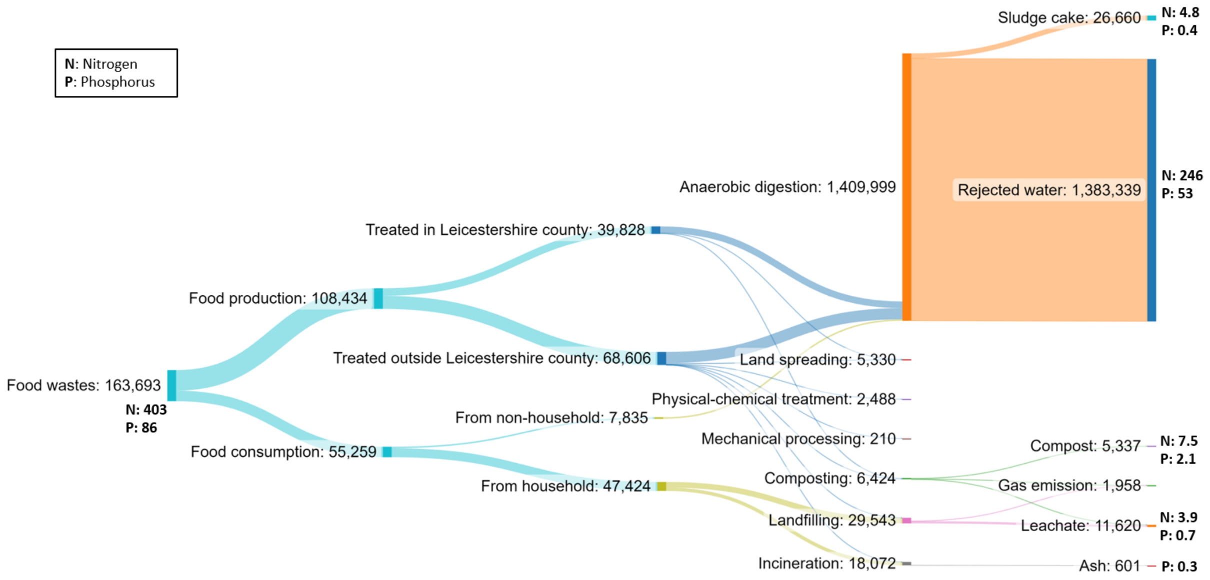


Figure 2.7: (b) Mapping of the food waste subsystem: Leicestershire County.

Slurry and manure management in Leicestershire county and Leicester city, 2019 (Tonnes/year)

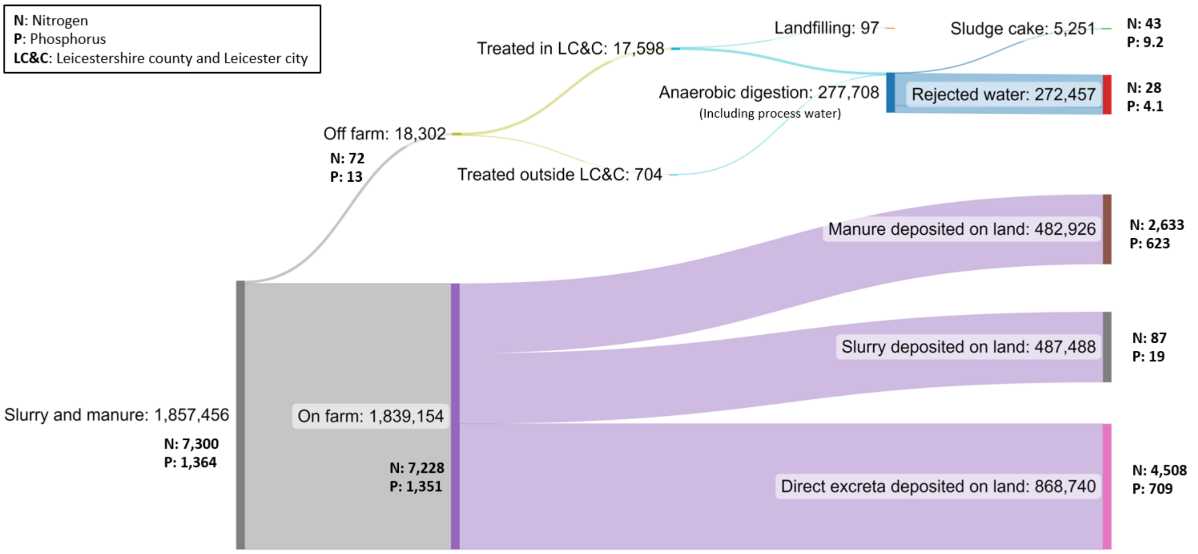


Figure 2.8: Mapping of the slurry and manure subsystem.

Wastewater management in Leicestershire county and Leicester city, 2019 (Tonnes/year)

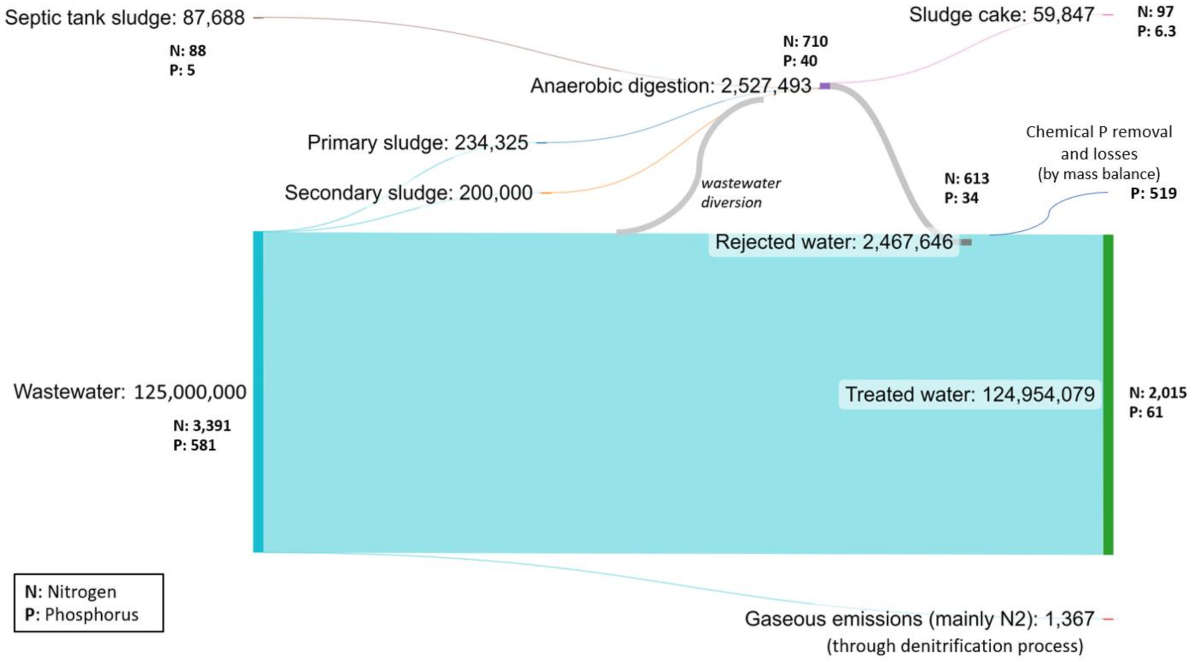
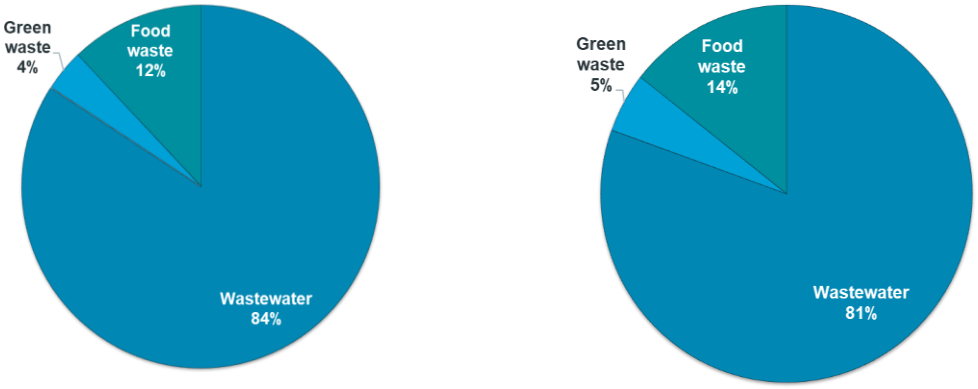
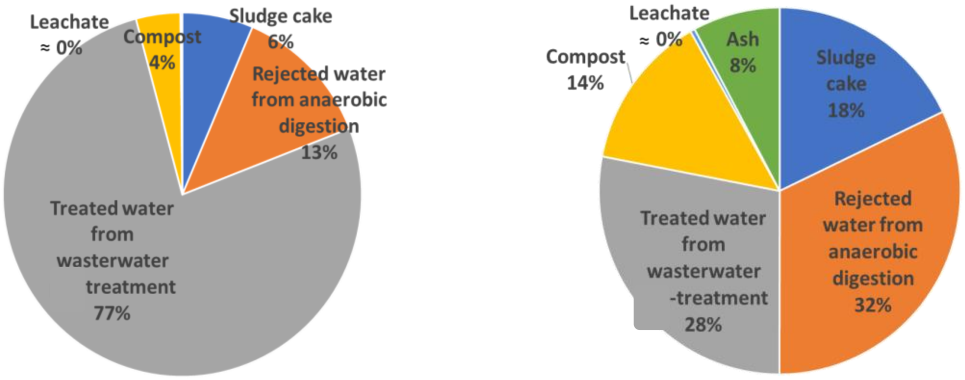


Figure 2.9: Mapping of the wastewater subsystem.

Based on the mapping, Figure 2.10 further shows the distribution of N and P in various sources and sinks (note that slurry and manure, and N loss during wastewater treatment in the form of N_2 gas, were excluded).



(a) Distribution of N in raw waste streams (sources) (b) Distribution of P in raw waste streams (sources)



(c) Distribution of N in processed streams (sinks) (d) Distribution of P in processed streams (sinks)

Figure 2.10: Distribution of N and P in sources and sinks. Slurry and manure flows were excluded. Sinks of N (plot c) excluded loss in the form of N2 gas in wastewater treatment.

2.5 Conclusions and limitations

From the Sankey diagram analysis, the following key observations are made:

A. The sources of nutrients in this region arising from waste flows, from large to small, are in the order of slurry and manure, wastewater, food waste and green waste. Roughly, nutrients in slurry and mature more than double those in wastewater, those in food wastes are only ~15% of those in wastewater, and those in green waste are ~1/3 of those in food waste.

B. Slurry and manure wastes are primarily "absorbed" on farm, with only a very insignificant fraction treated off farm. This means that, despite the dominating nutrient content of these streams, their current impact on waste management outside the farms is insignificant.

C. The wastewater sector, the second largest source of nutrients, is currently not retaining a significant amount of nutrients for useful purposes. As shown in Figure 7, nearly 80% of N and 30% of P embedded in liquid and solid flows from waste treatment/disposal in the region is discharged with treated water. Figure 6 further shows that N losses in the form of N_2 gas from wastewater treatment are also considerable, at more than 60% of the N loss in discharged water.

D. The food and green wastes arising in the region are in the range of nearly 200,000 tonne/year and over 100,000 tonnes, respectively, with the city takes a share of ~17% and 1/3, respectively. Between wastes from food production and consumption, the city has ~1/4 from the former, while its fraction in the country is ~2/3, which seems to be in line with the significant food processing industrial activities in the county. In terms of the locations of treatment, the city treats its green waste predominantly within the city, while its food waste is treated predominantly outside the city. For the county, ~25% of its green waste and ~75% of its food waste are treated outside the region.

E. Although food and green waste management share a rather small fraction of the nutrient sources and sinks, they together with the wastewater sludge AD treatment provide the main nutrient-rich materials, in the form of AD digestate cake and composts, that can in principle be considered as nutrient recovery products. Nutrients that are present in other sinks currently do not represent recovery. A particular example is the incineration ash, which contains 8% of P among all sinks (see Figure 7d), but it is not utilisable without further treatment.

F. Finally, AD represents ~6% and 18% of N and P sinks respectively (see Figure 7; note the exclusions) by the nutrients' presence in the (digestate) sludge cakes, but much greater fractions, at 18% and 32%, of N and P respectively in the rejected water. As recovering of N and P from AD rejected water is unlikely a common practice in the current system, these represent the largest nutrient losses next to those from wastewater treatment.

2.5.1 Take-away messages

The above observations point to several directions for future improvements:

1. Given the nutrient significance of slurry and manure, it is important to further understand and improve the fate of nutrients contained in the relevant streams.
2. The current wastewater treatment appears to be primarily driven by regulation compliance as opposed to resource recovery, leading to huge nutrient losses. This motivates both incremental (for short- or mid-term, e.g., improved N and P recovery from sludges and concentrated liquid streams) and disruptive (for long term, e.g., source-separation of nutrients by distributed operations) changes.
3. The nutrient circularity of AD, as a popular organic waste treatment option, could significantly benefit from improved nutrient recovery from its rejected water, which is particularly important for a region where the use of AD is likely to increase to meet policy requirements such as separated food waste collection.
4. The analysis of waste treatment locations suggests that a significant amount of food and green wastes is transported between regions, implying a haulage burden that has both economic and environmental consequences. Further understanding the drivers and alternative options could lead to a much-improved system design.

2.5.2 Limitations and future work

Within the intended scope of this mapping exercise, the results have been affected by the following limitations:

- Limited by the data that could be feasibly collected within the project, little attention has been given to losses and chemical changes of materials during transportation and storage.

- Where the R&D coding was not precise in the EA dataset, various assumptions have been made in determining the destinations, some of which are likely wrong. Another limitation arises from the presence of materials flows for transfer (as opposed to treatment or disposal) purposes, which could have resulted in double-counting which future analysis should further scrutinise.
- The PU modelling drew information from a wide range of literature that covers different material occurrences and process variations. Therefore, ideally a range, not a single point, of parameter values should have been collected, particularly in terms of the quantities of effluent streams and nutrient content. The mapping results presented here were based on only representative "point" values instead and therefore should be treated with caution, keeping in mind that variations do exist in reality.

Finally, this project has focused on waste streams. Beyond this scope, future work needs to include other nutrient flows such as run-offs, food and feed import and export, and chemical fertilizer input, to allow a more complete picture to be established for the nutrient flows (and possibly stocks) for the region, which is important to establish a better measurement of regional nutrient circularity.

Section 3: Analysis of inter-regional movement of organic waste in England

3.1 Purpose and approach

The nutrient flow mapping exercise on Leicestershire revealed that a large amount of food and green wastes generated within the region is transported to elsewhere for processing. As long-distance transport of a significant amount of waste represents considerable economic and environmental burdens, it became interesting within the project to investigate further the inter-regional organic waste movement, to gain an understanding of its degree at the national level.

An analysis has thus been conducted, using the EA dataset of waste flows as introduced earlier. We started first by taking a closer look at the movement of green and food wastes around the case study region. Subsequently, the net exports or imports of food and green wastes between regions in England were examined for the year 2019. The analysis and visualisation were carried out using Microsoft's Power BI.

3.2 Results and key observations

3.2.1 Import and export flows around Leicestershire County and Leicester City (LC&C)

Figure 3.1 shows that nearly 20 external locations sent green waste to LC&C for treatment, although most of these flows tended to be very small; all together, the imported green waste represented a negligible fraction of what was treated within LC&C. On the other hand, a sizable fraction of the green waste originated in LC&C was sent to other places for treatment, as already shown earlier in the results of nutrient flow mapping for the case study region. To better understand the distances of the movements, two tonnage versus distance plots are provided in Figure 3.2 for import (upper left) and export (upper right), respectively, which do not suggest the existence of significant high-volume, long-distance movements.

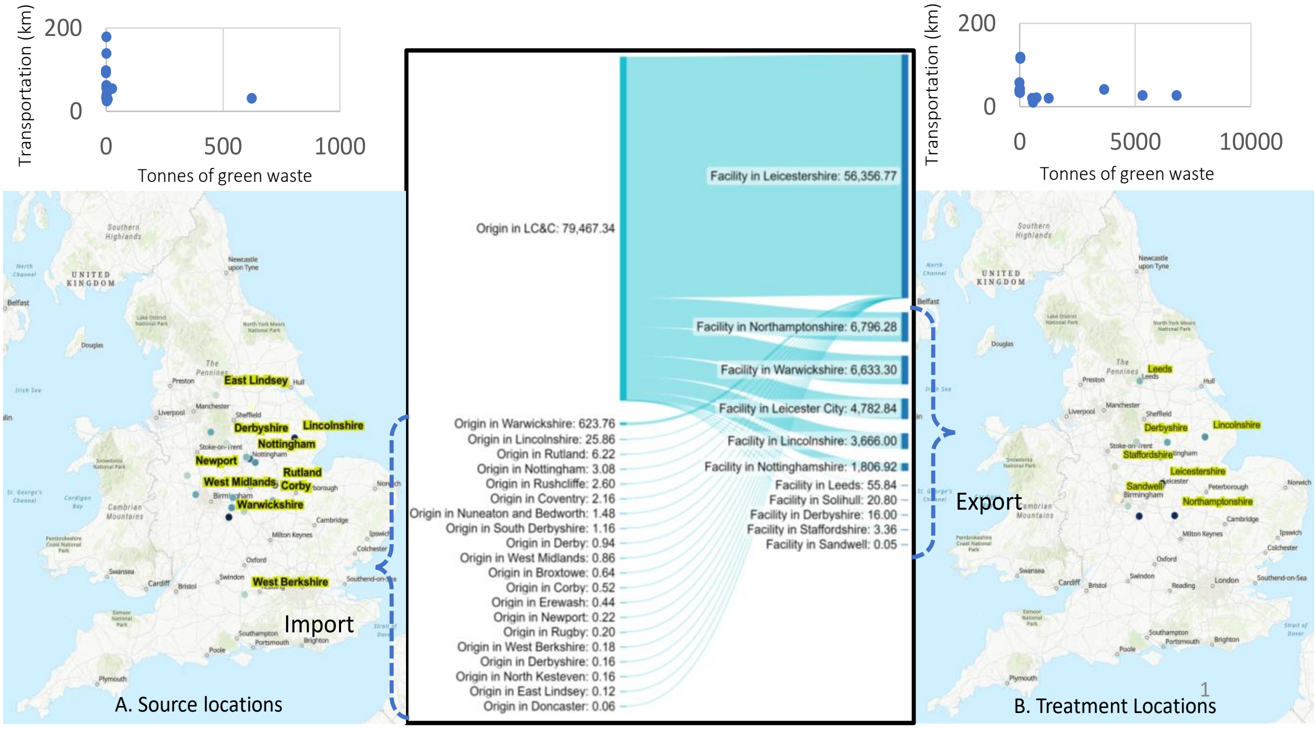


Figure 3.1: Imports and exports of green waste around LC&C.

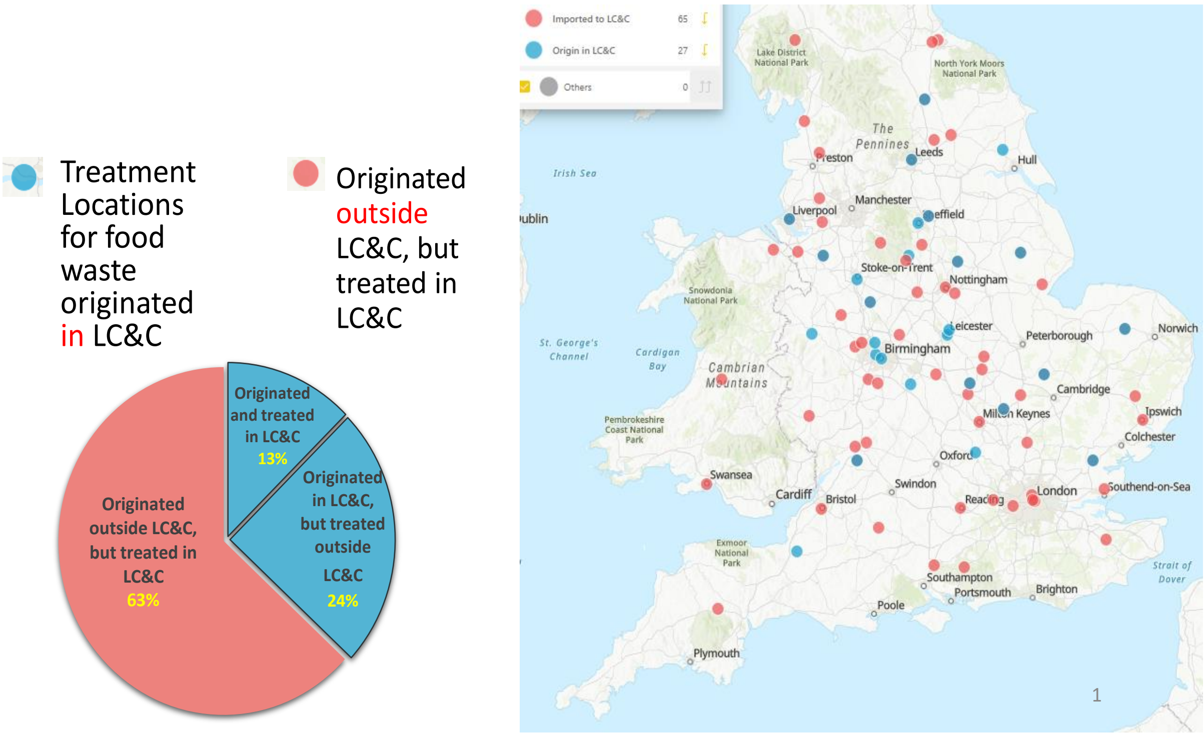


Figure 3.2: Imports and exports of food waste around LC&C.

The imports and exports of food waste around LC&C were analysed slightly differently, as shown in Figure 3.2. Among all the flows associated with LC&C, a high percentage (63%) is about LC&C's treatment of food waste that originated elsewhere, which is followed by the percentage (24%) of LC&C's food waste being treated in other locations. The fraction of food waste that both originates and is treated in LC&C is relatively insignificant (13%). Looking at the map shown in Figure 2, the geographical scope of the food waste movement from and into LC&C appears to be surprisingly wide.

3.2.2 Net imports and exports between regions in England

The results of inter-regional movement analysis on green and food waste are shown in Figures 3.3 and 3.4, respectively. In each case, there are 2-3 very noticeable net importers and exporters. Interestingly, the results appear to suggest the Yorkshire and the Humber region offers significant processing capacities to its two neighbours, namely East Midlands for green waste and Northwest for food waste. In terms of quantities, the largest regional net import/export of green waste is around 50,000 tonnes/year, while that of food waste appears to 10 times higher.

NB: It is important to note that, in principle, the sum of net exports of all regions should be balanced with the sum of net imports, which does not seem to be the case in the results shown here, particularly in Figure 3.4. Therefore, the results need to be treated with caution.

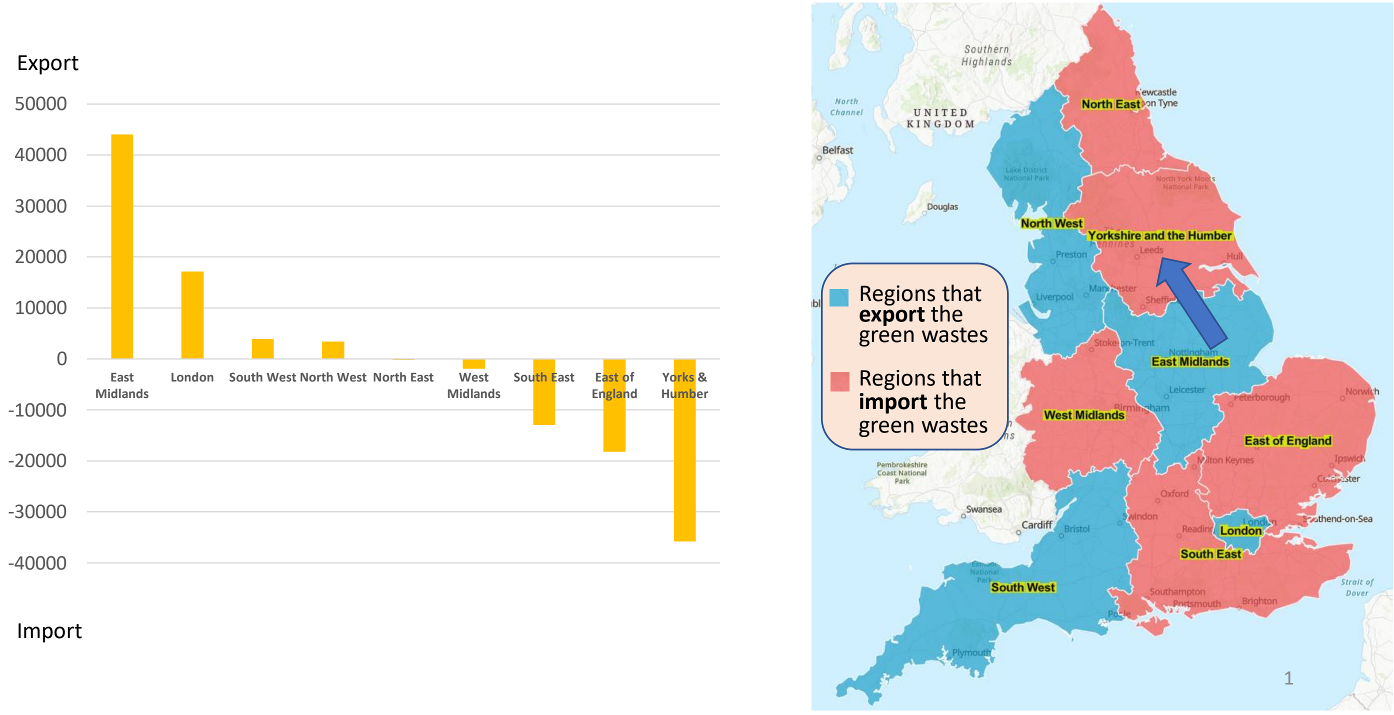


Figure 3.3: Net Imports and exports of green waste of regions in England.

Figure 3.4: Net Imports and exports of food waste of regions in England.

3.3 Conclusion

This preliminary analysis suggests that significant inter-regional movement of organic waste exists in England. Although it is beyond the scope of this study to uncover the exact drivers for such movements, the plausible reasons likely include the uneven distribution of processing capacities and contractual arrangements shaped by economic gains and business partnerships. It would be interesting to see how future changes could be introduced for reducing unnecessary or undesirable movements of waste, particularly against the legislation-driven, emerging dynamics of organic waste collection which may re-shape both the overall demand for treatment capacities and the local balance of demand and supply.

Section 4: Re-design nutrient flows- business opportunities

4.1 Background and Context

As part of this Agile Initiative Sprint project: *Systemic innovation to transform regional nutrient flows for environmental and socioeconomic benefits*, 3Keel worked to identify opportunities, challenges, and strategies for business innovation related to closing loops in nutrient cycling in Leicestershire. Increasing nutrient recovery from 'waste' streams is a key lever for both reducing environmental harms associated with loss of excess nutrients to the wider environment, and ultimately reducing emissions in line with a net zero trajectory through increasing the circularity of the economy. The project investigated the food, agriculture and water systems as these are the main vehicles for throughput of nutrients, as well as focusing on Nitrogen (N) and Phosphorus (P) as the focus nutrients. 3Keel's work ran in parallel with the workstreams of the academic team to model nutrient flows across the county.

Part One of this work (autumn 2022) focused on developing 'search criteria' for business clusters that would engage in the types of innovation involved in this project. In consultation with the academic team, we identified eight initial "problem areas" with the potential for solutions to improve circularity and reduce nutrient losses. **Part Two** (spring 2023) involved the creation of an initial report 'Business Needs, Opportunities and Challenges', based on in-depth interviews with a cross-sector stakeholder group. This report highlighted six key opportunity areas. The final stage of our work (**Part Three**, summer 2023) is represented in this report, which builds on the preceding work through further research as well as insights generated from a stakeholder workshop in May 2023. The final report adds greater detail around the four intervention areas of greatest interest to the academic team and stakeholders, as well as suggesting the key actors who might need to be mobilised to take advantage of opportunities, and how they might come together. Further information on the prioritisation process is given in Appendix A.

4.2 Introducing the opportunities

The 4 opportunity areas detailed in this report are:

1. **Upstream wastewater solutions** - intervening prior to nutrients entering the wastewater system.
2. **Transformation of digestate** - utilising technology to ensure that the nutrients contained within digestate can be more fully utilised by crops.
3. **Downstream farming interventions** - farming differently to apply nutrients more sparingly and prevent loss to the wider environment.
4. **Nutrient co-location** - tackling the challenges associated with moving nutrient-rich materials by situating sources and uses close together.

Within these opportunity areas are a range of more specific sub-opportunities that are detailed in the report body.

The kinds of solutions laid out in the report are sorely needed - the drivers for closing gaps in the nutrient cycle are clear. The pollution of UK waterways with excess nutrients has reached critical levels, with only 14% of UK rivers meeting the standard for good ecological status, considered to be the worst in Europe.[vii] Agricultural profligacy with nitrogen leads to huge demand for artificial fertilisers with a heavy cost in terms of CO_2 emissions; synthetic fertilisers and manures represent five percent of the world's greenhouse gas emissions — more than global aviation and shipping combined.[viii] Furthermore, phosphorus is a scarce and non-renewable resource globally that is considered essential for future food production.

There are opportunities here for business to be part of the solution, however, many of these are complex, technical, and require multiple stakeholders to come together to overcome barriers. This kind of systemic innovation requires businesses to take a long-term perspective on potential opportunities. There are few quick fixes or easy wins.

Part of this context is that the business opportunities around improvements in nutrient flows in Leicestershire exist generally within a highly regulated context. Waste, water and agricultural regulations are amongst the key drivers for how nutrients are currently being cycled across the county, as well as representing key barriers for some opportunities. For example, the regulatory environment drives how and to what extent wastewater is currently treated to remove nutrients, to keep within discharge limits. In general, these nutrients within water are seen as a 'problem' to be dealt with, not an opportunity to be capitalised on.

Regulations also constrain how and when recovered nutrients can be redistributed to land or used elsewhere within the food chain. Such regulations are vital for protecting the environment and human health but may also serve to limit innovation. Key interactions are therefore needed between the changing regulatory environment and the kinds of business opportunities that exist. Potential opportunities may only be fully realisable through policy change.

Many opportunities have been explored for decades but have not reached commercial viability or scale. This is therefore a prime space for 'systemic innovation' - actors from across the system need to be aligned in discussion from an early stage in order to co-create and pilot solutions together, identify barriers and work across the system to remove them. It is vital that government, regulators, utilities, private companies, farmers and third sector actors are all involved in these discussions.

Funding for convening, research, and innovation is one important ingredient in allowing this to take place. Other external factors also have a significant influence on the changing viability of opportunities – for example, there are now increased drivers for nutrient conservation and use of recovered nutrients at farm level due to the increasing cost of synthetic inputs caused by geopolitical factors.

4.3 Opportunity 1: Upstream wastewater solutions

Opportunity 1:
Upstream
wastewater
solutions

- **Challenge**: Wastewater is a significant carrier of excess nutrients, primarily from sewage but also from some industrial sources. These nutrients are costly and difficult to remove, and even when removed during water treatment, tend not to be recycled. Increasing load on wastewater systems means that they are becoming a significant source of environmental pollution. (Figure 4.1)
- **Opportunity**: Nutrients can be captured and recycled before they enter the wastewater system, and limiting the extent to which excess rainwater enters the system can prevent system overload. (Figure 4.2)

Much of the focus around nutrients in wastewater flows is on removing nutrients once they are already in waste streams. However, systemic upstream interventions can prevent nutrients from entering wastewater in the first place, reducing the reliance on costly removal technologies. When N and P are in wastewater, they are highly diluted with both general household water use and with surface water entering the wastewater system. Extracting these diluted nutrients is a greater challenge than if they could be captured in more concentrated form earlier in the process, with the nutrients ideally recycled into agriculture via products such as fertiliser or animal feed.

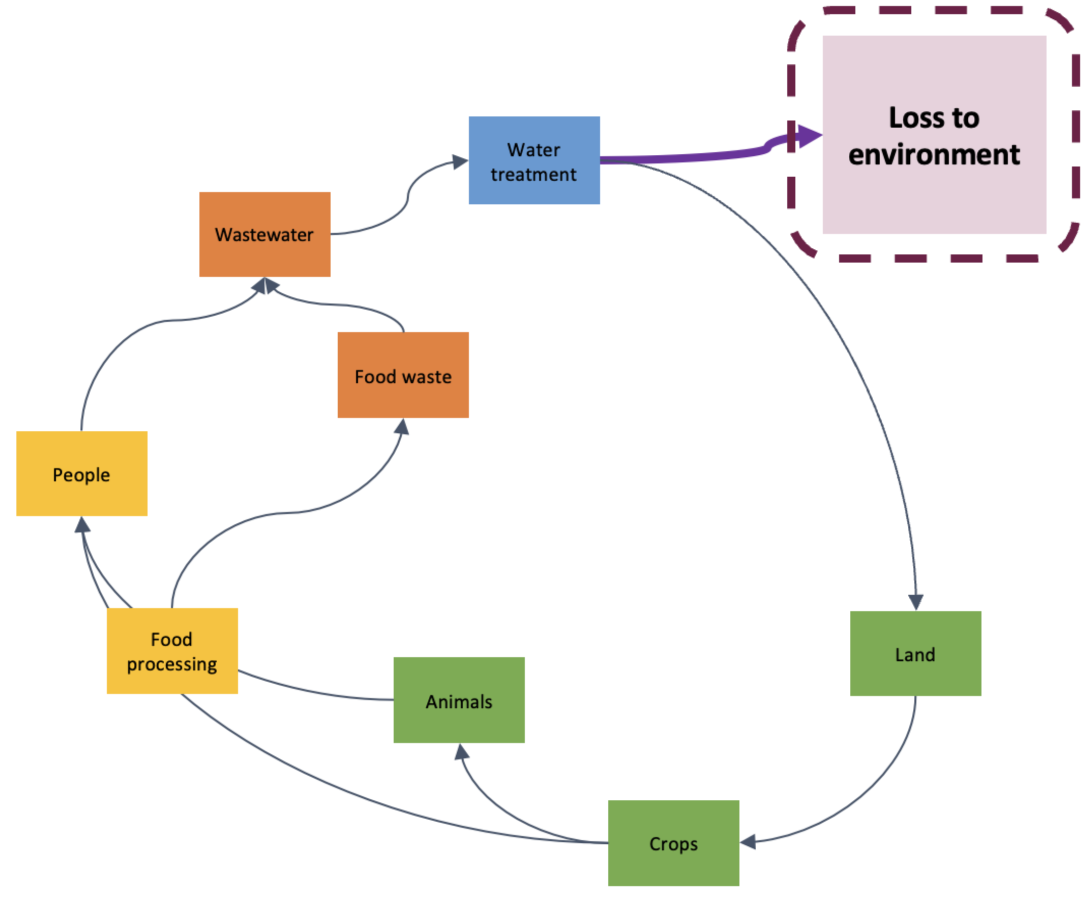


Figure 4.1: Upstream wastewater: challenge

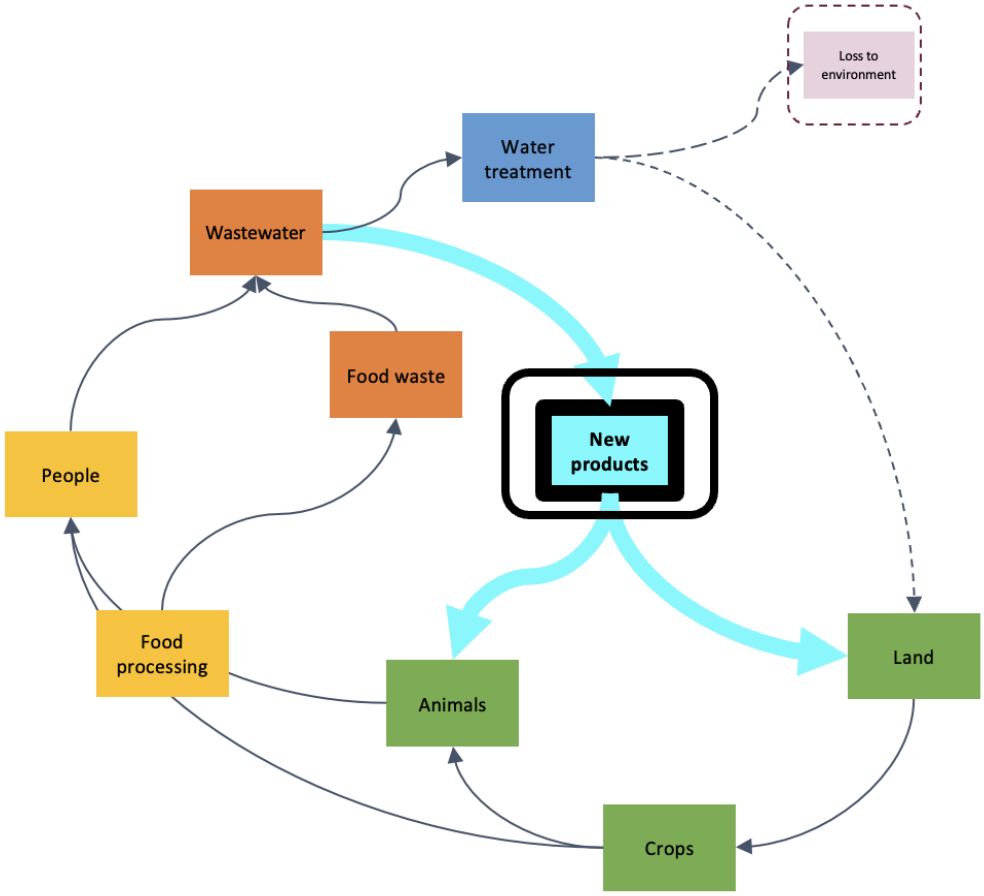


Figure 4.2: Upstream wastewater: solutions

4.3.1 Key opportunities

There are several potential areas of intervention that could be applicable to both new build development as well as retrofits to existing infrastructure:

4.3.1.1 Sustainable Urban Drainage Systems (SUDS)

SUDS interventions - such as permeable surfaces, soakaways, wetlands and holding ponds - reduce the amount of rainwater entering the wastewater system meaning that nutrients remain at higher concentrations in collected wastewater. Importantly, SUDS also help to reduce the risk of system overload after intense rainfall, which is increasingly common due to climate change and increasing populations. Overload can result in localised flooding and pollution events, and the release of pollution into watercourses at CSOs (Combined Sewer Overflows) or from wastewater treatment plants. These have been a focus of public scrutiny recently for their role in diffuse water pollution and eutrophication, contributing to the poor ecological condition of many of the UK's waterways.

SUDS provides co-benefits in the form of improved biodiversity, cooling, amenity and recreation in urban areas. SUDS is expected to become mandatory in new developments from 2024 through the implementation of Schedule 3 to the Flood and Water Management Act 2010, which also removes developers' automatic right to connect surface water runoff to the public sewer network.[ix] This will present opportunities for businesses to design, install and maintain such systems. Also of relevance is Severn Trent's £76m investment in SUDS in nearby Mansfield, which acts as a demonstrator of what can be achieved through intense focus on SUDS in one area.[x]

The nutrient recovery benefit of SUDS is indirect but significant, as it facilitates existing infrastructure (where present) to capture nutrients more effectively, and prevents loss to watercourses, with associated pollution.

Who will be interested in this opportunity?

A variety of factors are beginning to combine to make SUDS a more compelling proposition, including new legislation and the pressure on water companies to reduce sewer overflows.

- **Water companies:** SUDS can help them to meet their obligations in treating water and reducing water pollution. While there is an initial investment, there is the potential for financial benefits longer term. Water companies are however constrained by their regulator in the degree to which they can invest in measures and need to demonstrate very clear benefit and cost-effectiveness - collaborative strategy and funding could be key to enabling water company engagement.
- **Local authorities:** As Lead Local Flood Authorities (LLFAs), councils have a responsibility to coordinate the strategy for managing flood risk, for which SUDS could play an important role in urban areas. Councils will also have control of many of the public areas that might be suitable for SUDS.
- **Real estate developers:** SUDS will increasingly need to become a standard approach as developers are mandated to implement such measures - SUDS can also be a condition of permission to build in order to ensure that new developments do not increase local flood risk.
- **Landscape contractors:** There is an opportunity here for skilled contractors to collaborate with other parties to create innovative and exciting SUDS schemes and solutions.

Barriers: Lack of direct incentives, cost of implementation, commercialisation, cost of maintenance, scalability, regulated nature of water utilities.

Enablers: Regulation, local planning system, investment, pressure from communities, collaboration for cost-sharing amongst actors.

4.3.1.2 Urine separation

Urine is rich in nitrogen, potassium and phosphorus as well as other minerals and compounds that can be used in plant growth. Indeed, it contains 70% of the nitrogen, and 50% of the phosphorus and potassium in all household waste and wastewater fractions.[xi] It has been shown to be an effective fertiliser in agricultural systems and the nutrients are available in water soluble ionic form readily available for plant uptake.[xii] However, when urine enters the wastewater system it becomes costly and complex to extract these nutrients due to dilution. Much of the nitrogen is lost through treatment processes.

Urine separation at source is feasible and has been demonstrated through decades of research and operationalisation in Sweden, where there are more than 10,000 porcelain urine-separating toilets and 10-15 larger, mostly municipal systems (2006 data).[xiii] There is an opportunity for businesses to provide and maintain urine separation systems as well as for agriculture to tap into new low carbon sources of fertiliser. However, due to system lock-in for current ways of operating, urine separation is unlikely to achieve traction without enabling conditions such as incentives from regulators or local authorities or co-funding from water utilities. In Sweden most systems are managed by municipalities.

If urine collection could be mainstreamed, the potential is significant - a US study suggested that if the urine of only 10% of the US population could be collected, it could displace 330 tonnes of manufactured nitrogen and 20 tonnes of phosphorus per day.[xiv] This would amount to over 100,000 tonnes of nitrogen annually. For reference, the UK uses around 1m tonnes of manufactured nitrogen per year.[xv]

Who will be interested in this opportunity?

Urine separation is a classic case of system lock-in where although the solution makes sense from a societal perspective, the fact that large-scale infrastructure is not set up to support it makes it hard to implement in practice. Implementation would therefore require creative and innovative collaborations with an appetite for experimentation. Key actors could include:

- **Housing or commercial property developers:** This would work better for large-scale developments in order to make the logistics of infrastructure and collection work. It is likely that large commercial developments would be an easier initial target as individual households may be less keen to embrace non-standard toilets. The incentives for developers to get involved are relatively low and motivation would need to revolve around potential reputation or CSR benefits or be linked to permissions to build.
- **Local authorities:** Local authorities in nutrient-sensitive areas could work to encourage or mandate schemes that design in urine separation at the planning stage.
- **Water companies:** Water companies could ultimately stand to benefit from urine separation if it could be rolled out at scale in areas where water nutrient targets are being exceeded and other avenues such as catchment nutrient balancing or increased treatment capacity are not viable or not sufficient.
- **Agriculture:** Farmers would need to accept using a novel fertiliser on their fields (although urine has been used in agriculture historically for millennia) and overcome concerns around issues such as antibiotic resistance. However, this could represent a future low-carbon, local source of plant nutrition.
- **Regulators:** There would need to be regulatory approval for the use of urine in fields.
- **Innovators:** Technological innovations could make the use of urine in agriculture more feasible - for example by removing the water from urine to leave a pelletised product, making it easier to store, transport and apply. There are already start-up companies like Sanitation 360 who aim to move such innovations forward.[xvi]

Barriers: No existing systems in place, cost of implementation, commercialisation, scalability, regulatory approval for use of urine, storage and transportation.

Enablers: Regulation, local planning system, investment, pressure from communities, increasing price of manufacturer fertiliser, net zero ambitions.

4.3.1.3 Cultivating microalgae from food processing wastewater

Wastewater flows from food processing plants offer a unique opportunity in that these flows are rich in nutrient content yet have low toxicity and pathogen content as the nutrient source is destined for human consumption. Generally, wastewater from food processing goes into mainstream water treatment processes where the nutrient content is diluted, and much is lost.

However, research suggests that this wastewater could be a good growing medium for microalgae which would use the nutrients as a food source and then in turn be used as animal feed.[xvii] While microalgae can be used for a wide range of applications, directing towards animal feed allows nutrients to be retained within the food cycle. Key targets within the food and drink sector for rolling this out could include meat processors, dairy processors, breweries and wineries.

Who will be interested in this opportunity?

- **Food processors:** Companies involved in the food processing industry would be the key players as technology for microalgae production would need to be based at their sites and potentially operated by them. At this point there are few direct drivers for companies to engage in this, although if taken to scale there is potential for it to provide additional revenue streams and business diversification.
- **Regulators:** Regulators would need to approve the use of microalgae produced in this way for animal feed.
- **Farmers:** Farmers would need to accept a novel feedstuff for their animals, though trials suggest that microalgae can be a beneficial part of a feed mix.[xviii,xix] Drivers for engaging with novel feeds include the rising cost of conventional feed on international markets as well as concerns over exposure to soy sourced from deforestation areas - so there is an emerging demand for alternatives.
- **Innovators**: Some of the main barriers to mainstreaming microalgae are around commercialisation of the technology, especially achieving cost effective processing. So innovators are required to help realise this technology.

Barriers: Regulatory approval for microalgae feed, lack of direct incentives for food processors, risk of resistance to novel feed inputs from farmers.

Enablers: Net zero ambitions, commercialisation potential of technology, current levels of interest around microalgae.

4.3.2 Summary of barriers, opportunities and data needs-option 1

Table 4.1: Drivers, barriers, opportunities, and data needs in making Option-1 viable.

Key drivers	Barriers/Opportunities	Data/resource requirements
Cost	●Upstream collection will induce transportation cost depending on volumes and distance from the treatment facility ●Separate sewage system would be required, incurring massive costs	●Need to create a business case with robust data ●There is need for successful examples to get funding
Physical Infrastructure	● Significant infrastructure challenges with source separation - new network for collecting rural wastewater ●The new housing developments can potentially build infrastructure for separate urine collection	● There is need for identifying risks in implementing this option (e.g., urine separation) on a household like infrastructural upgrades etc.
Market Demand	●Mass of N&P that could be recovered from Wastewater at a local scale generally not significant enough to secure a market ●The products need to be something that's in demand ●Customers need to be on board and enough demand	
Policy	●AMP (asset management programme) drives down concentration of nutrients in wastewater	● Need to understand how the different options are

		helping UK to meet some of the challenges that are set out in policy goals.
Cultural Practices / behaviour	●Behaviours need to adapt to the technical changes- use of toilets (dilutes waste), ● Changing diet (to less P rich food) can contribute to reducing nutrient load in wastewater stream. ●Social acceptance of source separation of nutrients (toilets) is a challenge - getting people to use them is a big challenge as it is very difficult to change habits at a larger scale.	●Public awareness and capacity building
Stakeholder Links	●Many of the policy and decision makers need to cooperate, and change current practises around designing, building and using drainage systems. ●The balance of nutrients within these streams are going to be changing over time and really underlines the importance of stakeholder linkages.	
Technology		●Need for data and research into environmental impacts of technologies
Nutrient flow system	●In the small rural wastewater treatment plants, it doesn't receive much treatment and it's the concentration of P and N in the treated wastewater from these plants that's causing issues of nutrient pollution in rural water streams. The environmental impact is enormous and should be part of nutrient use efficiency plan.	

4.3.3 Strategies for action

Leicestershire could become a leader in pushing for novel upstream wastewater solutions including working with water companies, planners, businesses and real estate developers. This could represent an opportunity for water companies to reduce burden on the wastewater system; for agriculture to tap into new concentrated and low contamination recovered nutrient sources; for companies and developers to innovate and meet sustainability objectives; and for technology providers to put in place the systems required to achieve these aims.

This suite of interventions offers ways of intervening in the nutrient cycle before nutrients have even entered the wastewater system, sidestepping some of the barriers to removing them once they are there. SUDS does this indirectly by reducing the overall volume of water in the wastewater system, making sewer overflows and environmental pollution from nutrients less likely and raising concentrations of nutrients in wastewater streams, thereby increasing the viability and effectiveness of extraction later in the system. Urine collection and microalgae production are opportunities that recover nutrients early whilst they are still more concentrated, making extraction easier.

Barriers exist for all these opportunities. SUDS is the closest to becoming mainstream, and there are more obvious direct regulatory levers that could be pulled to enable this. Examples include Schedule 3 to the Flood and Water Management Act 2010 - this establishes a process to ensure that new developments include high quality SUDS and removes the automatic right of developers to connect to the wastewater network. The local planning system could be one further lever within this.

Opportunities around urine separation and microalgae production require greater levels of technical innovation as well as systemic changes to allow them to flourish. These would require collaborative innovation to take place and could be an opportunity for Leicestershire to convene actors to push these areas forward.

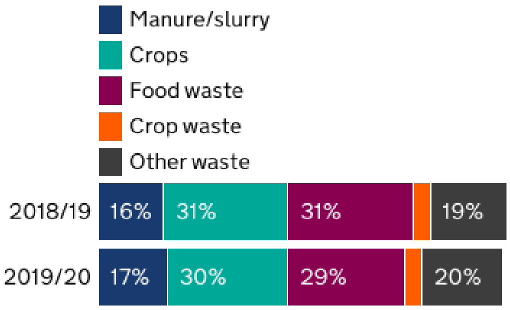
Recommendations:

- Take steps to ensure that SUDS is included as a standard in new developments in high-risk areas.
- Conduct a county-wide assessment of the potential for SUDS retrofit linked to reducing over-use of CSOs.
- Convene hackathon style gatherings of targeted groups of relevant actors around each of the opportunities for microalgae cultivation and urine separation.

4.4 Opportunity 2: Transforming digestate

- **Challenge:** The nutrients captured from waste streams using anaerobic digestion (AD) are not attractive to farmers and are not effectively valorised or used, causing attendant loss of nutrients once digestate is applied to fields. (Figure 4.3.)
- **Opportunity:** New technologies can transform digestate into stable high value, targeted fertiliser products with known nutrient values, facilitating high value end use and reducing the potential for loss of recycled nutrients. (Figure 4.4.)

Figure 2.1: Use of Feedstocks in operational AD plants by feedstock tonnage per annum, 2018/19 and 2019/20.



Source: NNFCC Anaerobic Digestion Deployment in the UK

Anaerobic digestion is becoming a more commonplace solution for processing sewage sludge, food waste and slurries and manures from agriculture. Supported by government subsidies (e.g., non-domestic Renewable Heat Incentive (RHI), Green Gas Support System) the number of plants has grown so that the volume of energy produced from AD in the UK doubled between 2015 and 2020.[xx] While energy crops make a significant contribution to AD feedstocks, most feedstocks are from waste streams (Figure 4.3.).

In addition to the sectors shown above, the UK now treats 93% of the country's sewage sludge in AD plants, up from 75% in 2012.[xxi] Moreover, following the UK's 2018 Resources and Waste Strategy, the government outlined its plans to introduce separate food waste collections for all households and businesses by 2023 (although at the time of writing, the date is yet to be finalised). The measures would induce a 1.35m tonnes uplift in food waste collected by 2029.

In addition to producing energy in the form of biomethane, AD plants produce nutrient-rich digestate that can be used as a fertiliser. Digestate is particularly high in available nitrogen content when compared with livestock slurries. It can be spread whole or separated into liquor and fibres and utilised separately.

However, there are drawbacks to AD digestate from a farmer perspective, and as a result digestate is not a highly valued material and is often thought of as a waste by-product:

- The nutrient mix in digestate will vary according to the material fed into the plant, and the result can be inconsistent - so farmers do not always know what they are applying to the soil, unless the digestate is analysed prior to application.
- Digestate, especially from food waste, can contain levels of plastic contamination that are unacceptable to end users or do not meet the required standards. Other potential contaminants include heavy metals, pathogens, antibiotics and PFAS chemicals.[xxii]
- AD digestate is less flexible than synthetic fertilisers in terms of the timing of its application: ground conditions and crop development need to be considered regarding nutrient uptake and potential for environmental pollution.
- The bioavailability of the nutrients makes it possible to overload crops - a significant amount of the nutrient content applied to land is likely to be wasted. There is a particular risk of over-application and accumulation of P and K.
- Digestate is bulky and therefore both difficult and expensive to transport and store (see also opportunity 4).

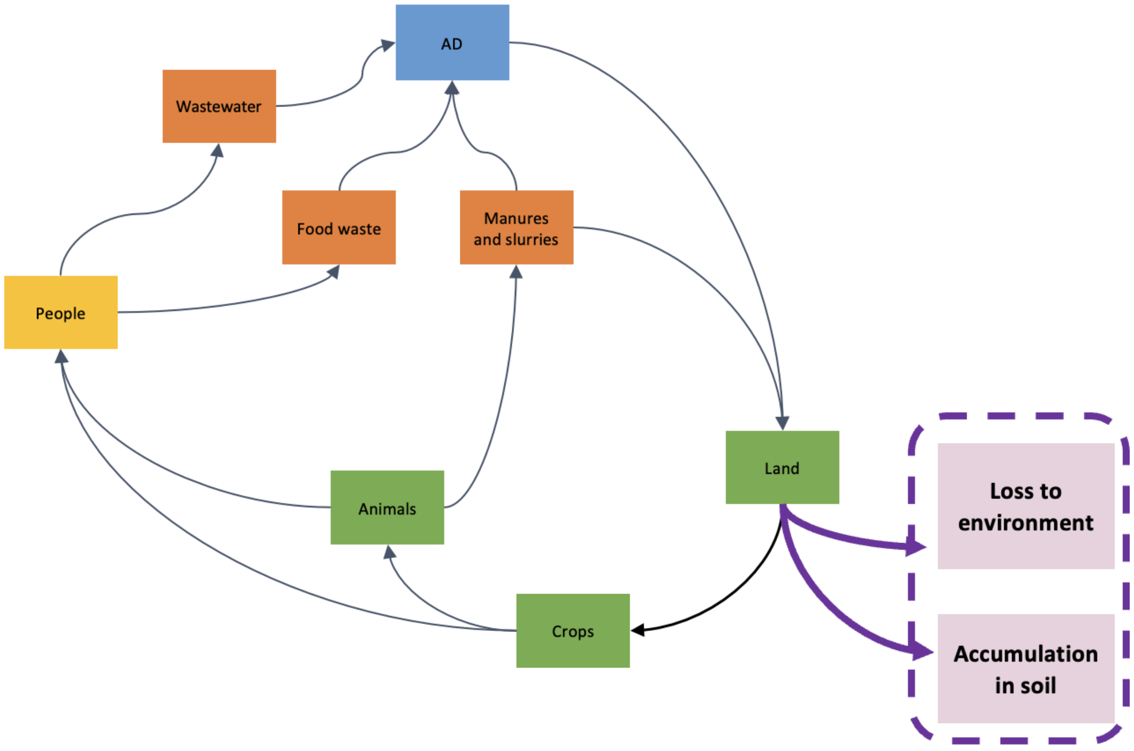


Figure 4.3: Transforming digestate: challenge

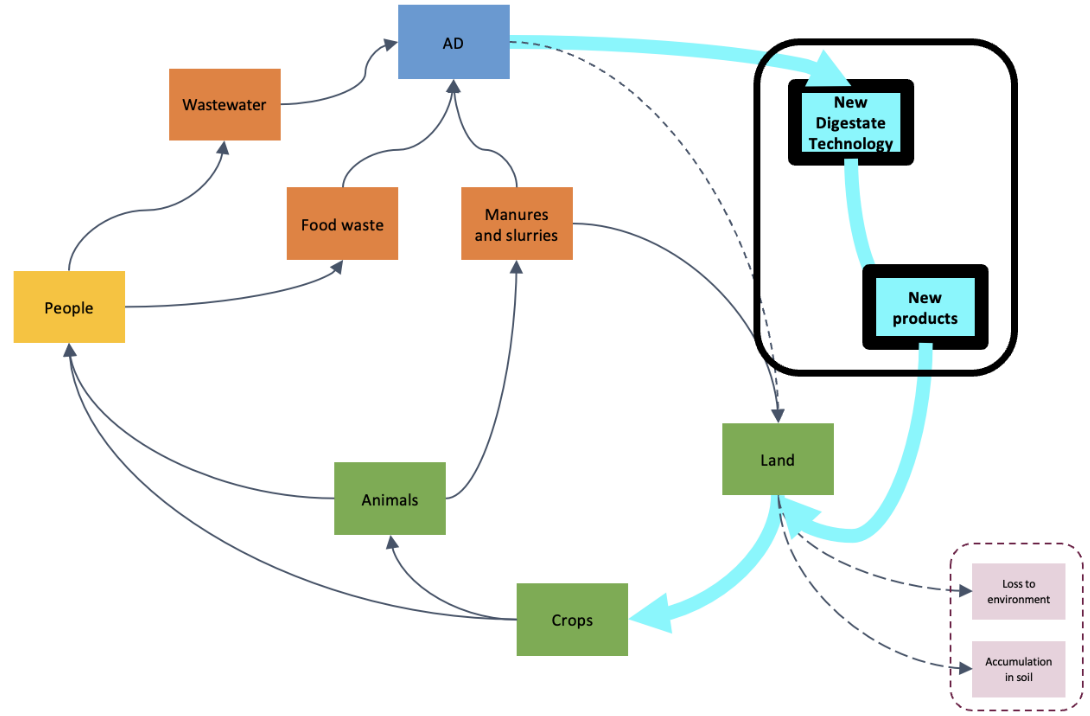


Figure 4.4: Transforming digestate: solutions

4.4.1 Key opportunities

An important potential solution to the problems of digestate is further treatment of this material in order to transform it into more standardised, readily utilisable products prior to application. Trust is currently a big barrier for many farmers who might otherwise be interested in using recovered nutrients, with uncertainty about quality standards, and contamination with plastics, toxins or bacteria. Farmers are also not keen on using a product with low levels of standardisation in terms of nutrient content. Therefore, developing new kinds of products tailored to the end market will be key to improving utilisation of recovered nutrients.

Examples include:

4.4.1.1 Struvite precipitation

This is a technology applied at the liquid phase of anaerobic digestion. The process captures struvite (magnesium ammonium phosphate), which can otherwise cause problems in equipment when it forms on walls and in pipes. When captured and removed, struvite can be used as a slow-release fertiliser, replacing phosphate rock fertilisers. Severn Trent currently captures struvite at the Stoke Bardolph wastewater treatment plant in the East Midlands, its second largest plant in the country, serving a population equivalent of around 700,000 people.[xxiii] Companies like Ostara capture and market struvite, claiming to convert up to 50% of total influent P into fertiliser.[xxiv]

The main opportunities for water companies relating to struvite recovery are to avoid damage to equipment, compliance with tightening local limits on P in discharged wastewater, and the potential for monetising the sale of struvite as a fertiliser. Research suggests that if struvite recovery could be mainstreamed across the UK's wastewater treatment plants, the import of around 7,000 tonnes of mineral P could be avoided, or around 5% of the UK's total annual imports.[xxv]

Who will be interested in this opportunity?

- **Water companies:** Wastewater treatment plants suffer from an accumulation of struvite, particularly those that have anaerobic digesters. Struvite can form as a solid precipitate, blocking pipes leading to costly repairs. Mitigating this risk would lower operating costs; meanwhile the product could also be sold as fertiliser, providing an additional income stream.
- **Regulators:** The UK Government has committed to reduce phosphorus loadings from treated wastewater by 80% by 2038 against a 2020 baseline. Increasing circularity via struvite precipitation would help to deliver on this goal. Struvite would also need to be assessed before it could be applied to land.
- **Environmental organisations:** Removing phosphorus from waterways will mitigate the extent of eutrophication, which is of importance to organisations such as The Rivers Trust.
- **Research institutions:** As struvite precipitation is a new and emerging technology. Research institutions are working to improve the efficiency, effectiveness and new application of struvite precipitation technology.

Barriers: Cost of installation; process complexity; phosphorus concentrations within wastewater streams being high enough to make economically feasible; nascent market for struvite making it difficult to recover costs.

Enablers: Government ambition and goals; declining cost of technology; technological advances; public awareness of issues attached to eutrophication.

4.4.1.2 Ammonia stripping

This is carried out through a process that produces ammonia gas from liquid digestate, which is then recovered to form ammonium sulphate fertiliser.[xxvi] Examples include Nijhuis AECO-NAR technology, with an ammonia removal efficiency of 80-90%.[xxvii] Feasibility studies have also investigated the production of hydrogen from ammonia and biogas at AD plants.[xxviii]

Who will be interested in this opportunity?

- **Water companies:** Ammonia stripping can help to reduce the amount of ammonia in wastewater, which can improve the treatment process and reduce the environmental impact of the plant.
- **Fertiliser manufacturer:** Ammonia stripping can provide a new source of nitrogen for fertiliser production, which can help to reduce the reliance on finite resources such as phosphate rock.
- **Regulators and environmental groups:** Ammonia stripping can help to reduce the amount of ammonia that is released into the environment, which can benefit both human health and the environment.

Barriers: Cost of implementation; energy consumption of technology; operational complexity; storage and transfer.

Enablers: Regulation, local planning system, investment, declining cost of technology; technological advances, collaboration for cost-sharing amongst actors.

4.4.1.3 Other technologies

A variety of other novel technological solutions are at an early stage of development. An example with high relevance for Leicestershire is CCm Technologies, who have a pilot plant at Severn Trent's Minworth sewage works, taking solid treated digestate plus waste CO_2, ammonia, and heat to create a pelletised fertiliser product. CCm produces a low carbon fertiliser source that is designed to be a flexible, easily stored and applied product using recovered nutrients, but also contains carbon so enriches soil carbon alongside boosting fertility.

CCm's technology uses captured carbon dioxide from industrial power generation to stabilise agricultural and industrial waste streams, and use these to create new fertiliser products with significantly lower than usual carbon and resource footprints. Food waste, sewage sludge and organic agri-residues provide a substrate for the added nutrients which are then applied to the land. In Leicester this technology is planned for deployment at PepsiCo's Walkers potato processing plant. Using the food waste in the making of Walkers crisps, the anaerobic digester is projected to be able to generate nearly 75% of electricity used in the plant and CCm's innovation will use the by-product waste from this process to create low-carbon fertiliser.[xxix] Increased carbon into the soil also has co-benefits for farmers, specifically in that it improves soil structure, permeability, and increases biodiversity within the soil. This causes an overall improvement to soil health which leads to better yield production. The slow release CCm fertilisers also allows for increased spreading windows with reduced impact from weather conditions due to a high proportion of organic fibre within the fertiliser pellet, benefiting farmers. Legislation regulations such as the Spreading to Land regulations[xxx] are currently a key barrier to using waste as a feedstock to this process.

Who will be interested in this opportunity?

- **Farmers:** Farmers would be applying these products to their land and would need proof of concept that these technologies are both safe, compliant with regulators and cost effective.
- **Regulators:** Regulators would need to approve these products for use on land and in the food system
- **Water companies:** Water companies can utilise CCm's process to capture carbon dioxide to stabilise, nitrogen, phosphate and organic chemicals held within waste streams at a water utility sites, turning them into sustainable plant nutrients.
- **Government:** increasing nutrient circularity via more utilisable digestate will contribute to government goals regarding nitrogen and phosphorus use.
- **Food sector:** Companies producing significant quantities of food waste might look to partner with innovative farmers to integrate the technology on-farm.

Barriers: Cost of implementation; scalability; sourcing suitable partnerships; complexity of application.

Enablers: Regulation (particularly around application to land), local planning system, investment, declining cost of technology; technological advances, collaboration for cost-sharing amongst actors.

4.4.1.4 Dry Anaerobic Digestion

Beyond transforming digestate content, Leicestershire could look to produce a more utilisable digestate via dry-AD (dAD), rather than the predominantly 'wet' (wAD) used in the UK. Anaerobic digestion is predominantly 'wet' (wAD) in the UK, where the proportion of dry matter in the material that is processed is less than 15%. However, in Europe installed dry-AD (dAD) capacity, which can process a feedstock with a dry matter content of 15-45%, is significantly higher.

One of the primary benefits of dAD is that it can "receive and process a wider range of feedstocks such as co-mingled garden and food wastes whilst also having the capacity to service food-only recycling collections."[xxxi] This advantage allows authorities to develop a collection process that provides best value against collection costs. dAD plants have the potential for screening the output into products of varying quality. This produces a compost that can be used by a broader range of actors, beyond the farm gate, opening the product up to new markets, enhancing use and nutrient circularity.

Who will be interested in this opportunity?

- **Local authorities:** Local authorities are responsible for waste management in their areas. They are increasingly looking for ways to reduce the amount of waste that is sent to landfill. dAD is a promising technology that can help to achieve this goal.
- **Farmers:** Farmers are looking for ways to reduce their reliance on synthetic fertilisers. dAD can help to achieve this by providing a source of nutrients that can be recycled back into the agricultural system.
- **Energy companies:** Energy companies are looking for ways to generate renewable energy. dAD can help to achieve this by producing biogas that can be used to generate electricity and heat.

Barriers: Cost of implementation; feedstock availability; technological complexity and skill base; regulation.

Enablers: Government policy; growing demand for renewable energy; technological improvements.

4.4.2 Summary of barriers, opportunities and data needs- option 2

Table 4.2: Drivers, barriers, opportunities, and data needs in making Option-2 viable

Key drivers	Factors affecting feasibility	Data/resources requirements	Impact
Cost	●Competition for food waste among AD plants may affect price of AD based fertiliser ●Waste transportation incurs cost and important factor in determining profit to AD companies which means distance travelled by the waste needs to be optimised to generate incentive for the AD companies to upscale AD products ●Lower AD fertiliser cost and effort in application is the main criteria for farmers but it is also very individual to certain farmers	●The condition of soil and type of crops determine the nutrients that can be applied and digestate based fertiliser may not be suitable for all lands. Mapping and classification of land is required.	
Physical Infrastructure	●Need to increase the capacity of AD processing units for the anticipated separate food waste collection		
Market Demand	●There is a lot of work happening in Holland, Belgium and other countries on testing the market demand of digestate products- putting in pellets for export	●The use of digestate based fertilisers needs to be well documented to build the knowledge and for farmers to build	●Application of digestate, to land which has a high P index can further increase loss of phosphorus to water.

		trust in the product. There is some work on this in Scotland. ●Need case studies on comparison between digestate based fertiliser product, biochar and hydrochar.	●Farmers do not want apply material to their land if it's got microplastics or the risk of other contaminants. If the digestate quality is not improved, there will be nutrient surplus in many regions.
Policy	●There should be incentives to build new AD plants for processing increasing food waste coming to AD after separate food waste collection enforcement. ●Margins for farmers is small and taking risks with new products is not financially viable. Land management incentives may be required.		●There is a need for short, medium, and long-term visions and a framework (the government to set the direction) for thinking about the whole system. ● Government should set short-, medium- and long-term frameworks for alternative circular economy approaches
Regulations	●PAS110 certification allows certain concentrations of chemical contaminants. But there is no clear information about the long-term impact of the chemicals like PBDEs and PFOS ●Need to update regulations on use of waste derived materials ●There is need for regulatory standards for quality of digestate products ●The regulations on sale and purchase of AD by-products are unclear	●Digestate is a product that can be easily tailored to needs but there are no standard products for one particular type of farming. This can be looked into from a regulatory perspective. ●ADs are built as an energy technology and digestate is seen as a problem. The regulations for AD digestate do not allow for extracting nutrients from digestate but regulations are being reviewed, however there is not enough funding into risk assessment of digestate products usage in agriculture.	

Cultural Practices/behaviour	●There is a need for cultural and perspective shift for enhancing nutrient re-use in agriculture. ●Farmers don't want to use digestate as they will need to use anti-bacterial as well If farmers move to regenerative agriculture, then there will be less demand for digestate based fertilisers. ●Farmers have reservation on the use of digestate based fertilisers ●Farmers don't want to use digestate as they will need to use anti-bacterial as well ●Dried out slurry (one of the products) for animal bedding barrier is supermarkets won't buy milk that's been produced from animals living on animal faeces (slurry) ●Skills/labours for spreading organic fertilizers are not available easily and most people don't want to work in this field because its messy and possibly unhygienic ●There are issues related to storage and odour. People complain about smell and handling is inconvenient. ●People think putting food waste in residual waste bin is easier, collected faster, no problem of flies, no smell etc	●There is a widespread transition to compost packaging and compostable bin liners. There is not sufficient research on the impact of these materials on the quality of digestate and subsequently soil health if applied on field. ●Future research should map the direction of travel for compostable packaging and similar materials in order to identify solutions to tackle the contamination of digestate from a systems perspective.	●Mixing plastic waste with organic waste affects the quality of AD fertiliser and therefore compromises soil health. Compostable materials may have the same effect.
Stakeholder Links	●Need to link together key players involved in collection, processing, use of nutrients and look at potentially small-scale co-location. ●Local authorities have no influence on businesses. LLEP can play a key role in encouraging this intervention.	●Stakeholder network for data sharing is primal for developing a systems transformation plan	
Technology	●Application of digestate in agriculture farm requires technical skills and the process can be difficult ●The quality is not consistent as the digestate come from different sources and also depends on the input organic waste composition. ●Plastic packaging of food items is an issue. AD plants need to have a de packaging plant bolted onto their AD facility. However, it doesn't capture the micro plastics.	●Need to assess which and how the technology reduces pollutants in digestate ●Need to assess how the nutrient run-off can be reduced ●Need to make a case on digestate properties compared with commercial fertilisers. How is it better than chemical fertilisers?	

	●Technology needed to tackle chemical, micro-plastic and microbial contamination	●Need to investigate when/what stage of crop growth this should be applied in order to minimise nutrient losses	
Systems perspective	●Separate food waste collection going to AD may have a knock-on effect. It means more waste going to AD and more digestate which can be a problem if no one wants to use it. ●The contamination of plastics and packaging in the food waste derived from households is very low. It's from the restaurants and the commercial sector that it's high. ●Compost liners is problem in the waste system. Some AD plants can strip them out and some don't. They don't break down quick enough and AD doesn't get to a high enough temperature and are sent for incineration. But councils are still providing the residents with compost liners because the perception is that it's still better than single use plastic liners. There is need for a systematic change in how waste is disposed at the household level. ●Systematic changes are required to take micro-plastics, and ubiquitous forever chemicals like PBDEs and PFOS out of the nutrient flows loop and prevent them from building in the environment.	●People involved in the waste collection, processing and application needs to come together to generate an information base that answer- Where can the recovery products can be properly applied? How does it get properly applied? In what circumstances? ●Need up to date and periodic data on land management, soil and land use for planning fertiliser input	●Waste is highly contaminated and more digestate from AD will be a problem if no one wants to use it

4.4.3 Strategies for action

Leicestershire could lay the foundations for innovative and novel trials to take place around transforming digestate into a more utilisable product. Establishing an operating environment in which water companies, farmers, government, food businesses and innovators can trial digestate schemes could represent an opportunity for water companies to reduce the operating costs; for farmers to lower their synthetic fertiliser use; and for environmental objectives to be achieved.

The examples listed above are not exhaustive, however they represent some potentially meaningful solutions to increasing nutrient circularity within digestate plants. Of particular note is CCm technologies treatment process, which already has a presence in the region. The case study of PepsiCo's plant offers a good example of how food businesses might integrate this technology into local processing plants. To take this technology further, the regulatory environment will need to shift to being more accommodating of land spreading through reviewing restrictions on usage of material from sewage systems.

Although anaerobic digestion to treat food waste and other materials is now a well-established technology in the UK, barriers exist for all the opportunities outlined; in particular, the cost of implementing these measures. Trials might allay these financial burdens somewhat, allowing the technology to develop and prove feasibility. Furthermore, a WRAP report underlined that, amongst survey respondents, the top barrier to expanding the anaerobic digestion market was securing a larger supply of feedstock.[xxxii] This might be addressed in Leicestershire when mandatory separate food waste segregation comes into force, although uptake from households could be boosted via trials to support the roll out of the process.

Recommendations:

- Actively engage food businesses to partner with innovative companies such as CCm Technologies.
- Put in place separate food waste bins across the county.
- Support or encourage water companies to implement novel technologies within their operations such as ammonia stripping and struvite precipitation.

4.5 Opportunity 3: Downstream farming interventions

Opportunity 3:
Downstream
farming
interventions

- **Challenge**: Recovered nutrients, and other farming inputs, are not always applied to land in an efficient manner leading to deficit, excess and loss to the environment.
- **Opportunity**: Farmers can adopt financially beneficial regenerative agriculture practices that keep nutrients in the ground. They can also deploy affordable and accessible soil mapping, sampling solutions and variable rate technologies that minimise nutrient loss.

Conventional agricultural practices and their intensification, while supporting global and regional population growth, have had detrimental effects on aspects of the environment, namely soil health. Here two separate but interrelated interventions, regenerative agriculture and precision application technologies, have been identified as opportunities for businesses to increase profitability alongside nutrient circularity.

The mechanisms and relationships of regenerative agriculture, which place an emphasis on soil health, stand to better equip farmers with the tools to develop nutrient circularity through both reducing nutrient inputs and minimising nutrient losses, whilst delivering potential financial benefits and integrating novel technologies. Despite lacking a stable definition, regenerative agriculture has been conceptualised variously based on “processes (e.g., use of cover crops, the integration of livestock, and reducing or eliminating tillage), outcomes (e.g., to improve soil health, to sequester carbon, and to increase biodiversity), or combinations of the two.”[xxxiii]

Regenerative practices often utilise new technologies to achieve sustainable outcomes. One such approach revolves around precisely applying nutrients to the land to minimise deficit, excess and loss. Matching fertiliser inputs to site-specific field conditions requires measurement and understanding of soil spatial variability and crop nutrient status.[xxxiv] Appropriate fertiliser application can mitigate environmental harm while promoting nutrient use efficiency, making it more likely that valuable recovered nutrients are then optimally used rather than leaching from soil or accumulating in excessive concentrations in parts of the field. Precision application farming technologies have proliferated in recent years, indeed in England about 60% of the UK’s farmland is farmed integrating some form of precision technologies.[xxxv]

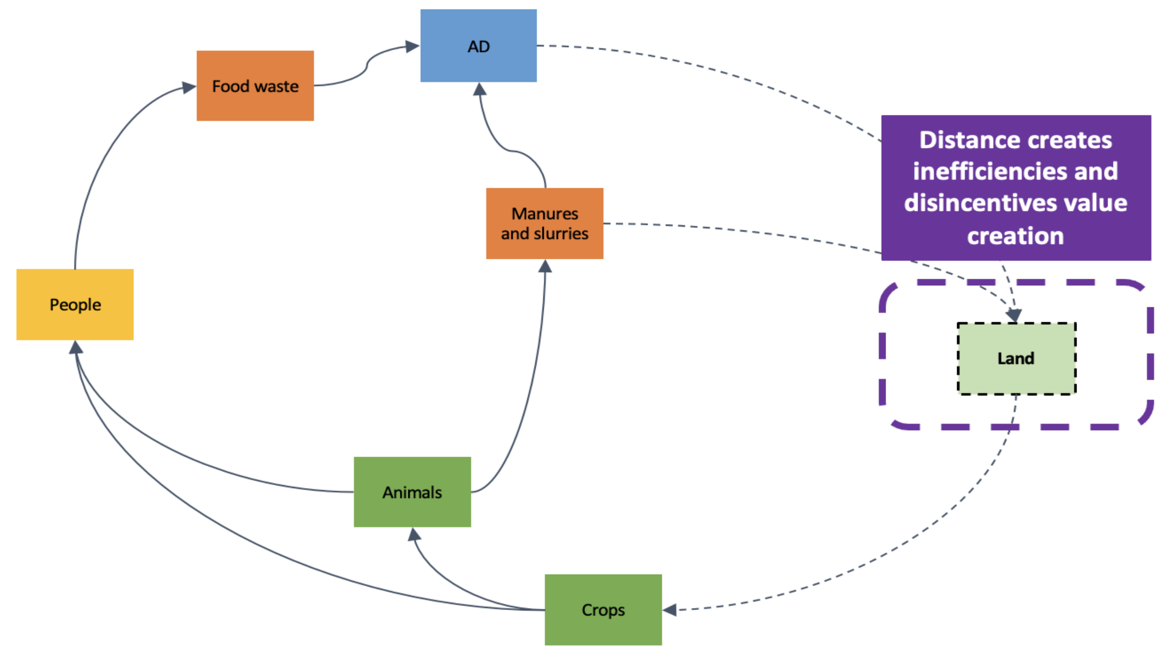


Figure 4.5: Downstream farming interventions: challenge

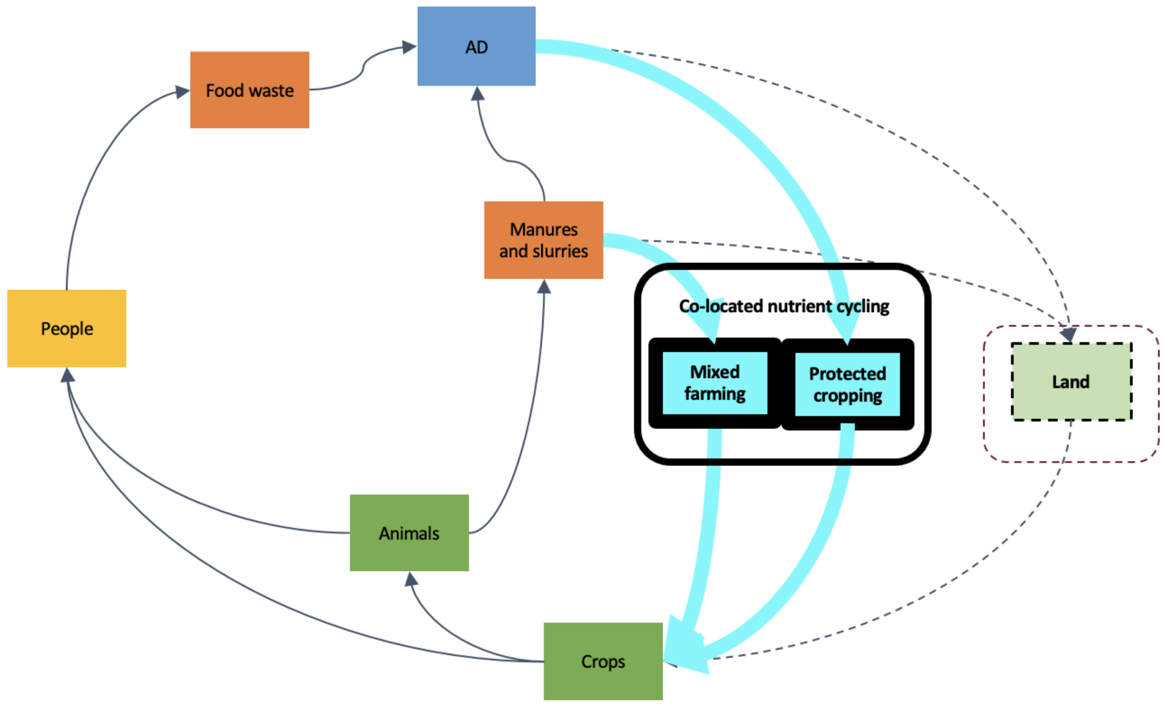


Figure 4.6: Downstream farming interventions: solutions

4.5.1 Key opportunities

Regenerative farming can be interpreted not as a single measure or technology, but rather a shift in approach. Just as site-specific crop management, the general goal of precision farming is not a single technology but an integration of technologies permitting the collection of data on an appropriate time scale. These approaches might look like some of the following opportunities:

4.5.1.1 Regenerative farming practices

A host of regenerative farming practices could be deployed on-farm to boost nutrient circularity. These might include:

- Planting cover crops, which can reduce nutrient leaching and runoff by providing ground cover over the winter period to intercept and reduce the impact of rainfall, whilst at the same time accumulating and storing nitrogen in the cover crop which would otherwise be leached from the soil into water courses. Cover crops can improve soil structure and counteract compaction, as well as protecting soils from erosion during winter and from sun oxidation. Combining cover crops with a year-long fallow also offers greater scope to introduce seed mixes with multiple benefits and reduces the need for pesticides and fertiliser during the year.
- Utilising a direct drilling system of seed placement, where soil is left undisturbed with crop residues on the surface from harvest until sowing. The technology minimises soil disturbance, thereby protecting the soil from water and wind erosion, maintaining its integrity and keeping nutrients in the soil.

The above two practices are indicative measures that a farmer might look to integrate into their land management plan. Regenerative practices span a wide range of measures and farming techniques that will vary in terms of their effectiveness from farm to farm. Understanding how to integrate regenerative agriculture practices will be best understood by the farmer and land advisor themselves, once they have been equipped with relevant education and training. From a business perspective, regenerative agriculture also stands to be profitable for farmers; Savills, a UK land agent, modelled an 18% increase in net margin for a regenerative farm after 6 years.[xxxvi] Another study, by Ecdysis Foundation, found a 78% increase in profitability through switching systems.[xxxvii] Bain & Company, corroborated these findings, however cautioned that farmers would need four years on average to realise these benefits and would likely damage profitability during the transition.[xxxviii] However, private and public funding schemes can allay the challenges in navigating this transition.

Who will be interested in this opportunity?

- **Farmers:** Farmers are most directly affected by the health of the soil, so they have a vested interest in using practices that will improve soil health and nutrient cycling. Regenerative farming practices can help to improve soil health by increasing organic matter content, reducing erosion, and increasing water infiltration. This can lead to increased crop yields, improved drought tolerance, and reduced reliance on synthetic fertilisers.
- **Food businesses:** As companies are increasingly wary of the risk climate change poses to their supply base, engaged food and drink businesses are looking to encourage regenerative farming practices to ensure security of their supply chains in a warmer world.
- **Water companies:** through measures that support catchment nutrient balancing and on-farm support schemes; though they are constrained by ‘Fair share’ principle in how much they are allowed to support farm-based measures.
- **Government:** Defra already provide the Sustainable Farming Incentive (SFI)[xxxix] which supports farmers to deploy regenerative farming practices.

Barriers: Lack of knowledge, initial investment, data privacy concerns, perceived market complexity, return on investment for farmers.
Enablers: Long-term increased resilience and profitability, farming clusters, demonstrator farms, public and private sector funding schemes.

4.5.1.2 Soil sampling and soil mapping

Soil sampling and mapping is the process of collecting soil samples from a field and analysing them to determine the nutrient content, physical properties, and biological activity of the soil, thereby facilitating the precision application of nutrients. The results of the analysis are then used to create a map of the field that shows the variation in soil properties. Soil sampling involves taking a sample of soil constituting 16 cores of soil from a field or from a "part field" to give the grower a soil analysis to help derive fertiliser decisions. The practice would improve farmers' visibility of nutrient rich or depleted areas of their farm, allowing farmers to assess the impact of land use change, reduce input costs through targeted fertiliser placement and reduce nutrient losses to the environment. Soil mapping uses a number of sensors to better understand different aspects of the soil across the farm's geography. Examples of this technology include Omnia's TerraMap[xl].

Who will be interested in this opportunity?

- **Farmers:** Farmers need to know the nutrient content of their soil in order to apply the right amount of fertiliser. Soil sampling and soil mapping can help farmers to identify areas of their land that are deficient in nutrients, so that they can apply fertiliser accordingly. This can help to improve crop yields and reduce the amount of fertiliser that is wasted.
- **Innovators:** The soil sampling and mapping sector is particularly lively and new start-ups are looking to trial or roll-out their products in the field.
- **Academic institutions**: Quantitative research into the impact of the precise application of nutrients is a relatively nascent field of study that is being driven by technological advancements. Academic institutions would likely be interested in the data obtained as part of these processes.

Barriers: Data privacy issues, initial funding, cost of research and development.

Enablers: Farming clusters, demonstrator farms, public and private sector funding schemes.

4.5.2 Summary of barriers, opportunities and data needs- option 3

Table 4.3: Drivers, barriers, opportunities, and data needs in making Option-3 viable

Key drivers	Factors affecting feasibility	Data/resources requirements	Impact
Cost	●Lowest cost ●Cuts across all of these with positives across all parts of the farm		●Co-dependent opportunities, and/or conflicting elements e.g. Regenerative agriculture is low input and low cost, and on the other hand there is need to capture more nutrients from waste streams and agriculture sector is the potential main consumer

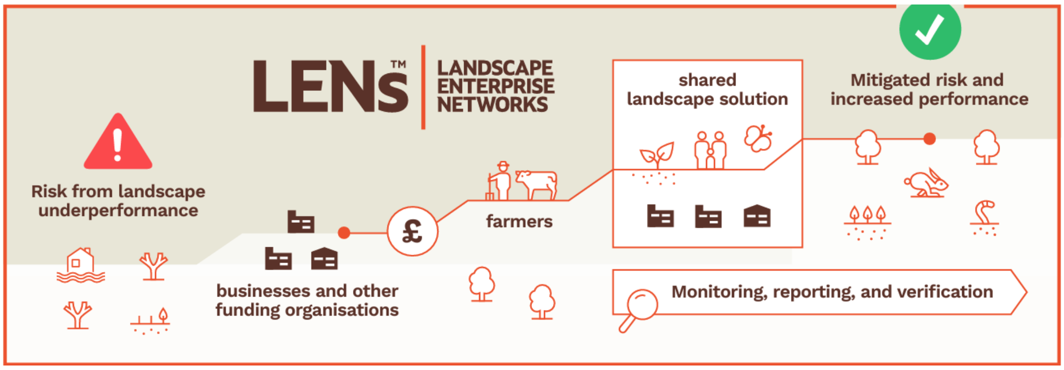
Market Demand	●Supermarkets can play an important role in de-risking new practices. They can provide assurance to farmers that they will buy products from new agri-practices	●Lack of spatial data on soil and water quality. Mapping would really help in understanding the nutrients input required for farming. ●Regenerative agriculture could reduce the demand for AD based fertilisers, which needs to be better understood	●Reduction in household waste AD based digestate demand can lead to nutrient surplus in some regions
Policy	●Are there incentives to encourage farmers to adopt regenerative agriculture ●Govt. through improved farmers' welfare standards can support farmers in adopting innovative nutrient efficient methods ●Farmers often need better financial incentives, that match incomes from farm production (grant support) ● Farm run-off also means cost loss to water from farmland. There are many government initiatives like catchment sensitive farming that encourages various approaches to reducing soil loss to water and nutrient loss to water.		
Cultural Practices / behaviour	●Most farmers work in isolation, and they stick with conventional ways because it's hard to make decisions ●Status and what other farmers are doing influences farmer's decisions		
Stakeholder Links	●Links important for data sharing between agencies ●This need that a space is created to provide farmers confidence to try new things		
Systems perspective	●Regenerative agriculture focuses on reduction of external inputs and focus more on very local nutrient cycling within the farm boundary and to minimise environmental impacts at the farm scale. However, this can impact the other sectors within the waste flow system and hence systems perspective is required when making changes at a farm scale.		

4.5.3 Strategies for action

Equipping farmers with the knowledge, training and equipment to transition to regenerative farming in Leicestershire could be achieved through establishing farming clusters. Farm clusters give organisation to groups of farms wanting to deliver communal targets and can significantly enhance environmental outcomes. Facilitating or financially supporting the establishment of local farmer clusters, with an express goal to improve soil health, would allow farmers to share knowledge, equipment and collaborate to develop their regenerative agriculture toolkit. Furthermore, it could act as a local proof of concept in new techniques, allowing farmers to understand which options could have the most benefit, set within a Leicestershire context, while also mitigating apprehension surrounding financial risk.

In Leicestershire, a number of policies, finance streams and initiatives could be implemented to allay the barriers outlined above and integrate new technologies onto farms. To address high capital costs, subsidies could be given to farmers either by the public or private sector. Landscape Enterprise Networks (LENs)[xli], a finance mechanism created by 3Keel that is already established in the UK and Europe, delivers private finance from companies invested in the landscape to farmers for nature-based solutions; a similar scheme might support farmers in Leicestershire. Support should also focus on establishing on-farm testing and trials. This would serve to demonstrate the economic advantage of precision agriculture, highlighting that costs have decreased dramatically in recent years, and provide a proof of concept to farmers in the local area. These schemes should dovetail with the establishment of farming clusters, which would allow knowledge to be disseminated across the region.

Case study: LENs in the East of England.



In 2021 the East of England LENs conducted its first set of annual transactions, as it now finalises its third trading cycle, the grant scheme has seen approximately £8m invested into regenerative agriculture practices. LENs brought together 8 diverse companies from a range of sectors, including: large food business (such as Nestle), water companies (Anglian Water) and local governments (West Northamptonshire County Council). All of whom have a vested interest in the landscape, although different goals that range from carbon sequestration to flood risk mitigation, to support over 100 farmers on their regenerative journey. LENs are operational in other English regions, such as Cumbria and Yorkshire, as well as Europe.

Recommendations:

- Look to establish farmer cluster groups in Leicestershire. This might practically look like providing seed funding for the group; providing a forum for discussion such as a meeting space; putting on agroecological training sessions with experts.
- Pilot projects with innovative technology start-ups in the region, by looking to connect these companies with land managers.

  Consider establishing a local LENs in the region through feasibility studies that assess local business demand for funding a more resilient landscape.

4.6 Opportunity 4: Nutrient co-location

Opportunity 4:
Nutrient co-location

- **Challenge**: Sources of recovered nutrients are often far from the prime agricultural land where they can be utilised - and transport costs make it inefficient to truck digestate over large distances. In areas of nutrient surplus, reapplying excess nutrients to the land has caused overload of nutrients, especially P.
- **Opportunity**: Sources of nutrient-rich waste such as food processors or animal agriculture can co-locate with nutrient extraction and crop production, reducing haulage barriers and creating economies of scale.

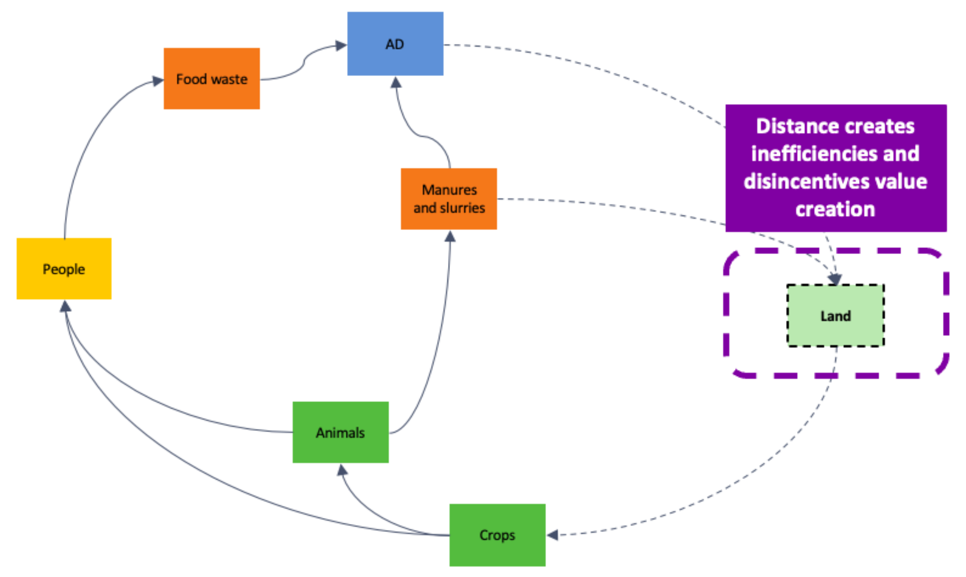


Figure 4.7: Nutrient co-location: challenges:

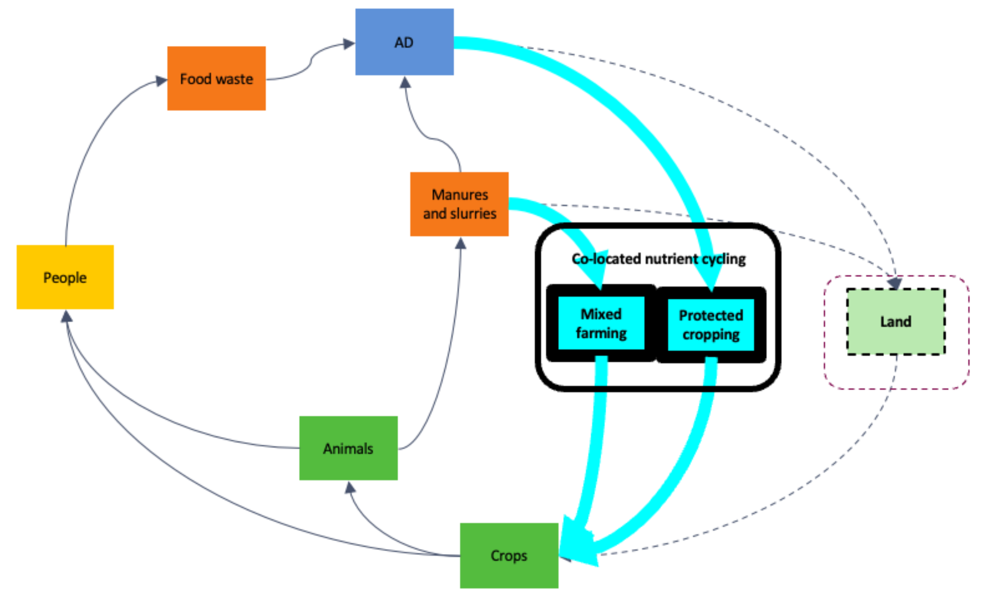


Figure 4.8: Nutrient co-location: opportunities

AD digestate, one of the primary sources of recovered nutrients, is bulky material which is costly to transport outside of the immediate area. The increasing number of AD units, including a significant number fed by energy crops rather than waste streams, is contributing to oversupply of AD digestate in specific areas, meaning that digestate needs to be transported longer distances to avoid breaching nutrient application limits. In particular there is a geographical imbalance caused by on-farm digester units in the west of the country being fed by animal manures and slurries - where there is limited cropland for spreading. Many soils in this region already have an excess of phosphorus, and over-application is likely to be a causal factor in well-documented watercourse pollution.[xlii]

Overall, the transport barrier makes effective nutrient cycling less economically viable and attractive. Separating out the phosphorus-rich solid fraction of the digestate from the bulkier liquor is one approach that would make the digestate easier to transport. Other approaches include incinerating the solid fraction to recover nutrients from the ashes, creating considerable volume reduction. However, this option is costly.

4.6.1 Key opportunities

The opportunities here revolve around informed combination of synergistic enterprises in geographical proximity, in particular ensuring that end users of recovered nutrients are close by to utilisable nutrient sources.

4.6.1.1 Mixed farming

One existing way of doing this is to return to a higher proportion of mixed farming in the UK, moving away from the trend towards specialisation of arable and livestock that has become common. By incorporating livestock and arable in a single farm unit, livestock manures and slurry can be utilised by the same business, eliminating transport costs and reducing the cost of purchased fertilisers for farmers. This is particularly attractive at this time as fertiliser costs increased dramatically due to the war in Ukraine and other wider geopolitical issues. Leicestershire as a county is well suited to mixed farming - although it is notable for cattle and dairy there is also good crop production land.

In a mixed farming system, in addition to spreading manures and slurries collected from animal sheds, crop rotations can include periods under grass for animal grazing, allowing fertility to accrue naturally through deposited manure. Including grass in rotations also helps to build soil health, reducing the amount of tillage and helping prevent the build-up of crop-specific pests and diseases in fields. Animals can also be incorporated into crop fields for specific purposes such as grazing crop residues. A mixed farming system may also incorporate the use of on-farm AD where there is a significant housed livestock component, making using of AD on crops.

Initiatives such as the Welland Valley Partnership and Welland Resource Protection Group[xliii] show how catchments can be managed holistically and collaboratively to improve the use of resources and reduce environmental harm. Leicestershire Farmer Will Oliver was recognised with Farmer’s Weekly Arable Farmer of the Year Award in 2022 for investing £3.6m in a broiler poultry unit on his arable farm, providing a cost-effective source of nutrients that replace the artificial fertilisers used previously. This has provided cost savings, improved organic matter in soil and an increase in arable yields.[xliv]

Who will be interested in this opportunity?

- **Farmers:** As per the example above, farmers are starting to see business advantages to mixed farming, enabling greater resilience, more efficient use of resources and diversified income streams.
- **Farming associations:** Farmer groups can help overcome barriers to mixed farming through knowledge sharing, peer to peer learning and other initiatives.
- **Government:** Government has a key interest in the kinds of outcomes delivered by mixed farming, including reduction in fertiliser use and potential reduction in diffuse nutrient pollution. While the Environmental Land Management Scheme (ELMS) supports some measures relevant to mixed farming, it does not explicitly incentivise mixed farming.

Barriers: Culture change, economic drivers towards specialisation, lack of knowledge or skills, lack of specific government support.

Enablers: Increasing cost of inputs, education and advocacy, consumer demand for more environmentally friendly products.

4.6.1.2 Co-location of AD and horticulture

A more speculative opportunity for synergies is around co-locating protected horticulture (i.e., greenhouses) with sources of recovered nutrients such as AD digestate. If the nutrients could be used directly to grow crops in greenhouses, transport issues would be eliminated. As greenhouse cropping is a much more controlled situation than in-field growing, the use of nutrients could also be more targeted, maximising efficiency of uptake by plants and minimising losses. Loss of excess nutrients to the environment could be minimised or eliminated.

While there are currently no commercial examples of digestate use in this way, there are excellent examples of this kind of industrial symbiosis with respect to waste heat from wastewater treatment plants and other industrial facilities - these include two large greenhouses in East Anglia run by Low Carbon Farming (Oasthouse Ventures) using waste heat from wastewater treatment to produce 12% of the UK's tomatoes,[xlv] and British Sugar's Wissington horticulture site, using waste heat and CO_2 from the nearby sugar processing plant to grow pharmaceutical crops.[xlvi] However, none of these horticultural sites currently also utilise the nutrients available from wastewater or sugar processing.

There is an opportunity here. Studies have found that digestate can be used in a number of different forms in horticulture - as whole and separated liquor digestate as organic fertiliser for soil-grown crops, as growing media ingredients, and for hydroponic production. Overall, such experiments have found that similar or better yields can be achieved compared to traditional methods.[xlvii,xlviii] If adopted at large scale, there could be an opportunity to use digestates in a far more targeted way than in field-scale agriculture, replacing the use of synthetic fertilisers and peat, with potential reductions in the carbon footprint of growing.

However, there are barriers - methods are still experimental rather than commercial in scale; there are concerns around potential food safety risks (though studies suggest this is not necessarily any higher than alternatives if appropriate management is pursued); and the Anaerobic Digestate Quality Protocol currently does not allow for use in protected horticulture.

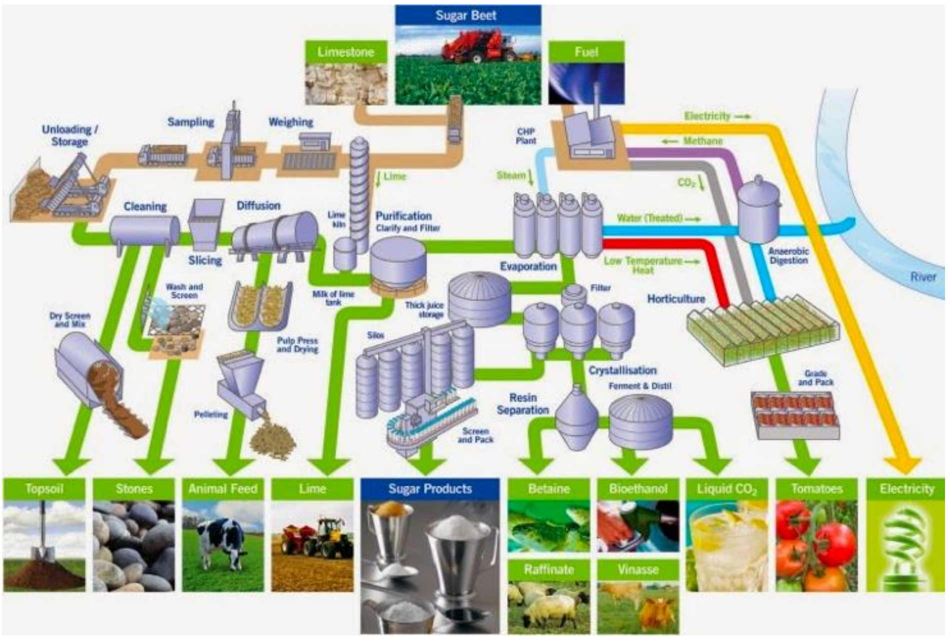
Who will be interested in this opportunity?

- **Growers:** Growers could be interested in tapping into a low-cost, low-carbon source of plant nutrition.
- **Operators of food processing facilities:** Due to the potential advantages of co-locating not just with sources of digestate but also waste heat and CO_2, larger production facilities generating these waste streams could be prime sites for this opportunity.
- **AD operators:** Use of digestate in horticulture could be a way of adding value to a co-product (digestate) that is currently relatively low value.
- **Regulators:** Regulators would be required to assess risk around this application of digestate and put in place appropriate processes and standards.
- **Capital providers:** Significant capital investment may be required to set up new greenhouse facilities, and capital providers can help by articulating and targeting the benefits of this low carbon horticultural approach.

Barriers: Perception barriers around use of recovered nutrients in food, lack of awareness, regulatory barriers, the need for additional science and scalable processes.

Enablers: Drive to reduce CO_2 emissions from agriculture and horticulture, increasing cost of manufactured plant nutrition inputs, potential for value add to digestate, further research and policy work.

Case study: Industrial symbiosis at British Sugar



British Sugar's greenhouses in Wissington, Suffolk, take waste heat and CO2 from the nearby sugar refinery, which is the largest in Europe. 115 million litres of irrigation water is also harvested from the greenhouse roofs annually. Up until 2016 the greenhouses produced 140 million tomatoes annually, but since then has been dedicated to the production of medical cannabis. Sugar processing waste (pressed beet pulp) is fed into an anaerobic digestion plant producing green electricity from biogas. The digestate is used in the local farming area for soil conditioning and fertiliser replacement, but it is not used in the greenhouses.

4.6.2 Summary of barriers, opportunities and data needs- option 4

Table 4.4: Drivers, barriers, opportunities, and data needs in making Option-4 viable

Key drivers	Factors affecting feasibility	Data/resources requirements	Impact
Cost	●Substantial investment is required for re-locating waste processing plants		●Saving on transportation costs
Physical Infrastructure	●Urban horticulture plots offer a good place to implement this option ●Planning authorities can incorporate infrastructural changes in town planning		
Market Demand		●Methods are still experimental rather than commercial in scale; there are concerns around potential food safety risks	
Regulations	●Needs to comply with food standards ●Anaerobic Digestate Quality Protocol currently does not allow for use in protected horticulture.		
Stakeholder Links	●Local plans should be made to place nutrient use, energy use, waste source closer for minimising carbon footprint. This requires alliances between stakeholders. ●Mix farming by creating alliances of farmers		

4.6.3 Strategies for Action

Leicestershire could build on its natural assets to become a hub for mixed farming, closing on-farm nutrient loops as much as possible rather than exporting off-site. This has the potential to be a business opportunity for farmers, who can save on the cost of importing nutrients from outside sources. While some of the ways in which the agricultural sector is changing make mixed farming a more advantageous possibility than it may have been previously, many of the overall logics of the agricultural economy still point towards specialisation, so there are barriers to overcome to make this kind of farming more commonplace. Achieving this is as much a cultural barrier as a technical one and will involve proactive knowledge exchange in the farming community.

Additional opportunities would come from mapping the significant sources of recovered nutrients across the county (such as AD plants or food manufacturing sites) to assess potential locations for using these nutrients in specific localised applications such as protected horticulture. While there has been significant research suggesting that digestate can be usefully used in horticulture, there are still regulatory and commercialisation barriers that need to be overcome for it to be taken forward. This will require a joined-up approach across different organisations, but existing business could play a key role in this by assessing the potential for such activities in their operations and engaging in discussions or pilots.

Recommendations:

- Work with farming groups to further understand the barriers to increasing mixed farming in Leicestershire.
- Convene food companies, government and innovators to articulate what needs to be done to overcome the barriers to utilising digestate in protected cropping settings and encourage commercialisation of this space.

4.7 Prioritisation with local stakeholders

The research team met the city council to understand commitments of the Council for governing and supporting nutrient circular economy in Leicestershire and where the re-design options fits into their plans so that the research team could tailor the outputs of this project to best support council's agenda. LCC is currently consulting experts for developing a land use management strategy and nature recovery strategies. Agriculture is a dominating source of nutrients that diffuses into the water system which may be posing ecological threat. There is limited evidence on the magnitude of this issue and strong evidence base is needed to develop nature recovery strategies for reducing the ecological risks of nutrient losses. The Leicestershire Climate and Nature Pact 2021 recognises 'nature recovery' as one of the six core components in tackling climate change and ecological decline:

'*Nature: halting ecological decline and supporting nature recovery. We will act to deliver local nature recovery, protecting and enhancing biodiversity in the County*.'[xlix]

The Council has plans to implement the food waste collection strategy by 2025 in line with the Environment Act 2021. The plan is to process the separately collected food waste in an Anaerobic Digestion (AD) facility but currently there are no AD plant contractors working with the council who takes food waste and produce fertiliser from digestate which is of standard quality. The biggest question beside the infrastructure challenge then is how can the food waste digestate can be applied to the land. For Opportunity 2, technologies that can be implemented for recovering nutrients from food waste AD can be explored with the capacities of existing food AD plants.

Defra is the national level decision maker and initiates policy reforms depending on its areas of priority. County councils hold limited power in influencing the priorities at the national scale. However, they can accumulate evidence and develop a case for prioritising waste management infrastructure in the national plans. For example, currently Leicestershire does not have AD facilities that take grass cutting waste but other counties (such as Lincolnshire) do. Depending on the support available from the national government, local authorities can enhance the efficiency of 'organic waste to resource' while also reducing GHG emissions associated with waste haulage and storage.

Amongst the four viable options assessed in consultation with the stakeholders, valorisation of AD digestate and utilising existing AD capacities for anticipated food waste was found to be the most holistic and viable option for tackling the nutrient loss problem in the Leicestershire County. The next section explores the most economically optimal way for utilising the existing AD facilities to process the future growth in collected organic waste by the authorities.

Section 5: Exploring the use of existing AD facilities to process separately collected household food waste

5.1 Challenge and objective of this investigation

The analysis of the current food waste treatment in the region suggests that the household food waste in Leicestershire is collected by "mixed" bins and primarily sent to incineration as part of the mixed stream. The waste collection in Leicester City is similar, although the organic fraction of the mixed waste is separated after collection and mainly sent to AD. Given the relative advantages of AD as recognised through the techno-economic-environmental comparison, it is envisaged that, in a future waste management system where household food waste is separately collected in the region, AD is most likely the preferred option for treatment. This waste stream could be treated by a new, centralised AD facility. However, the potential challenges associated with such a new development, such as investment required, timeliness and public acceptance, necessitates the exploration of other options.

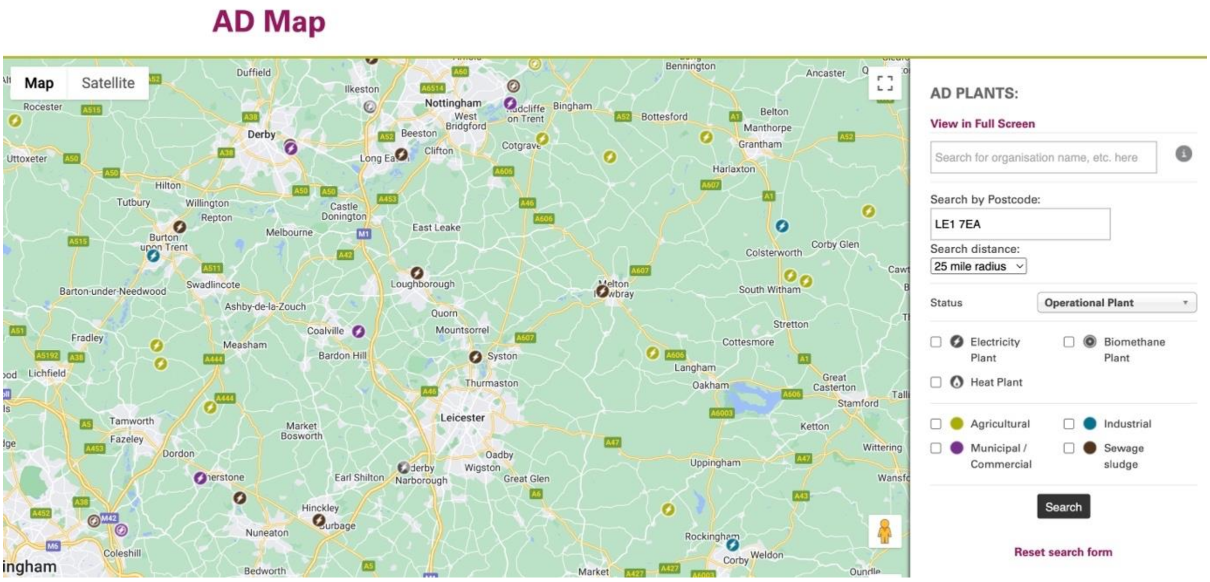
In this study, the possibility of using part of the existing AD capacities in the region to treat household food waste generated in LC & C city was investigated. In particular, designs that involve different categories of existing AD plants, all aiming at minimising the transportation burden of moving collected food waste to the processing sites, were established using mathematical optimisation models. Using on-farm AD facilities to treat food waste also offers the potential of reducing the distance between the production of nutrient-rich streams and their applications, which is in-line with the nutrient co-location opportunity identified earlier in the report.

5.2 Approach

5.2.1 Existing AD facilities and capacities

The ADBA database[l] was used to locate the existing AD plants within 25 miles of Leicester City centre, as shown in Figure 5.1. These plants include four types depending largely on the feedstock processed, namely agricultural (manure, crop residues), industrial (organic chemical by-products or wastes), Municipal/commercial (mainly food waste), and sewage sludge. To process food waste, municipal/commercial AD sites appear to provide a direct fit. Additionally, agricultural AD facilities, presumably located on farms (thus subsequently referred to as "on farm AD"), had been considered during the discussions with LCC as possible providers of AD capacities to treat separately collected household food waste. Therefore, these two types of AD plants have been included in this analysis; their numbers and capacities are shown in Table 5.1 (the details of individual sites are provided in Appendix C). Interestingly, these two types of AD sites in this region have comparable total capacities, at ~30,000 tonnes/year. Although the average capacity of the on-farm AD sites appears to be smaller than that of the food waste AD sites, the former has more sites located in the region, potentially offering destinations closer to the city and the county districts where food waste is collected.

It should be noted that the data collection was only possible for the installed capacities of the existing facilities. The extent to which these facilities can be used to treat extra waste streams would inevitably depend on their actual spare capacities, which were not possible to obtain during the project. The modelling work consequently had to use plausible levels.



AD PLANTS:

Search for organisation name, etc. here

Search by Postcode: LE1 7EA

Search distance: 25 mile radius

Status: Operational Plant

☐ Electricity Plant
☐ Biomethane Plant
☐ Heat Plant
☐ ● Agricultural
☐ ● Industrial
☐ ● Municipal / Commercial
☐ ● Sewage sludge

Figure 5.1: Existing AD facilities in the region (25 miles from Leicester City centre) (source: ADBA)

Table 5.1: Existing AD capacities in the region

AD capacity	On farm AD	Municipal/commercial (food waste) AD
Total capacity (t/year)	307,010	300,742
Number of sites	13	9
Average capacity (t/year)	23,616	33,415

5.2.2 Food waste processing demand

Household food wastes from both Leicester City and Leicestershire were considered. As shown in Table 5.2, the quantities were estimated based on 0.16 tonnes per household per year, an estimate reported in a previous study based on a food waste collection trial[li]. We further considered two levels of set out rate, 100% as the maximum and 47% which was adopted in one of the future options explored in the same study[lii].

Table 5.2: Projection of household food waste collection

Food waste generation	Leicester city	Leicestershire County
Per household FW generation (t/year)*	0.16	0.16
Total FW with 100% set out	22,075	47,424
Total FW with 47% set out	10,377	22,294**

5.2.3 Transport distances

To estimate realistic road transport distances, larger districts were divided into two or three sections which together with the smaller districts form 15 waste collection zones (see Appendix D for their details). Subsequently, the shortest road distance between the centre of each zone and each AD site was obtained by using OSRM (Open-Sourced Routing Machine)[liii]. The data table is included in Appendix C.

5.2.4 Optimisation model

A linear programming model was implemented (in GAMS) to determine the best collection zone – AD site links that minimise the total tonne-kilo meters of the system. In the model, one collection zone can send waste to one or more AD sites, and one AD sites can receive waste from one or more zones.

5.3 Results, discussion and conclusions

The optimisation model was applied to two levels of set-out rate, assuming 30% of spare capacity for each AD plant. Additionally, a lower level of spare capacity at 15% was explored with 100% set-out rate to consider a stressed scenario. On the types of AD plants, using either or both types (“food AD” and “farm AD”) were considered. The results of 9 cases in total are shown in Table 5.3.

Table 5.3: Modelling results of AD facility allocation for minimising transport

	Settings				Results						
Case	Setout rate	AD spare capacity	Using Food AD	Using Farm AD	Total transport (tonne-kilometers)	Average transport distance (km)	Transport to Food AD	Transport to Farm AD	Number of Food AD sites	Number of Farm AD sites	Total number of sites
1	100%	30%	X		806,381	11.6					
2	100%	30%		X	785,222	11.3					
3	100%	30%	X	X	538,819	7.8	46,976.00	22,523.00	7	6	13
4	47%	30%	X		361,443	11.1					
5	47%	30%		X	360,291	11.0					
6	47%	30%	X	X	247,927	7.6	22,046.00	10,625.00	4	6	10
7	100%	15%	X		Infeasible						
8	100%	15%		X	Infeasible						
9	100%	15%	X	X	609,465	8.8	46,640.00	22,859.00	9	13	22

The above results and the discussion of them with LCC suggested the following key messages:

- Using both food waste and on-farm AD plants could significantly reduce transport requirements, by ~30% compared to using only food waste AD plants (as evidenced by the average transport distances). This suggests that the original thought on using (local) farm AD sites has the potential advantages in terms of lowering the transport burden. Note that the analysis included in the model only considered the transport of AD feed from the origin to the processing facility; dealing with the application or disposal of digestates, not considered here, could equally benefit from on farm AD locations if suitable local capacity of assimilating digestates exists.
- Full household participation to food waste collection (i.e., 100% set-out) would require 15% or higher existing capacities of both types of AD plants.

- While sending household food waste to multiple facilities, including the farm AD sites, can potentially reduce the transport burden, it may significantly complicate contractual arrangements between the WPA or its districts and the waste processors. How to handle this complexity needs to be considered in the actual planning.

5.4 Future opportunities of optimisation modelling

During the project, a more comprehensive optimisation modelling framework had been developed for the general purpose of optimising the matches between the types of organic streams and the types of waste processing/nutrient recovery technologies, with the geographical setting of a given region, as shown in Figure 5.2. However, the prioritisation of the project work meant no sufficient parameterisation was carried out for this more generic model; instead, only a sub-model derived from it, as presented above, was applied. However, as partially demonstrated using the sub-model, optimisation modelling could play a useful role in the future re-design of the regional nutrient management system, where multiple economic and environmental objectives could be systematically explored. This does require more substantial data collection and broader discussion with the stakeholders, to make the model sensible and its results relevant to real-world decisions.

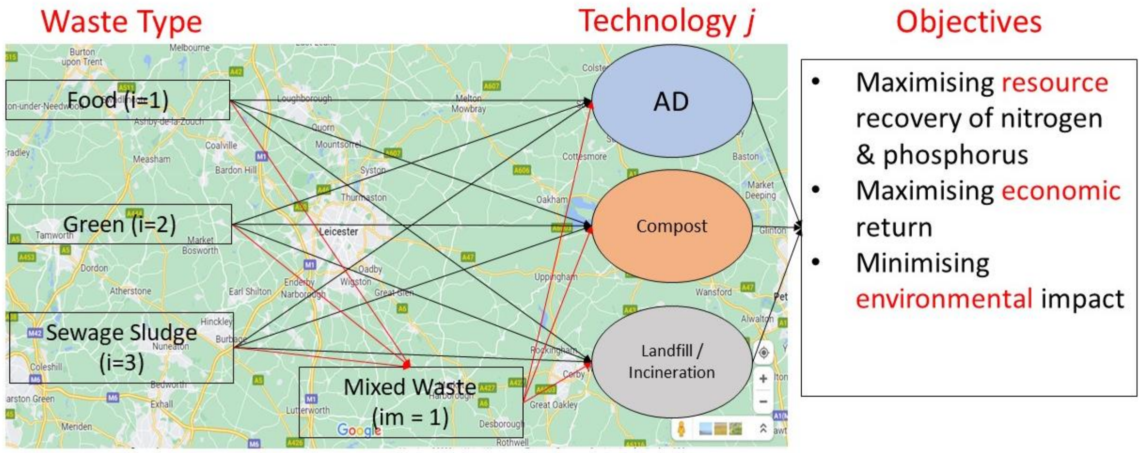


Figure 5.2: A more generic and comprehensive optimisation modelling framework

Section 6: Technoeconomic assessment of technologies for organic waste processing and nutrient recovery

6.1 Overview of waste treatment and nutrient recovery processing technology

This section discusses the primary and secondary nutrient recovery technologies that have been explored for organic waste treatment and nutrient recovery, followed by estimation of amount of potential nutrient recovery (Section 6.2), and capital and operating cost evaluations of these processing technologies (Section 6.3). Options appraisal relevant to the Leicestershire case study have been performed for various food waste treatment strategies by considering the economic performance and environmental impact associated with the processing technologies (Section 6.4).

In this context, primary processing technologies (Section 6.2) refer to the technologies employed for organic waste treatment to mitigate environmental impact and to divert them from landfills. These include anaerobic digestion, composting and incineration which have been widely employed in the UK. It should be noted that incineration is normally used for treatment of residual waste rather than pure organic waste streams. However, incineration has been included in the analysis to represent one of the possible destinations of organic waste.

Secondary processing technologies (Section 6.1.2) refer to the technologies employed for further treatment on organic waste in view of reducing the nutrient level to meet local discharge limits or to recover nutrients into value-added products. These include ammonia extraction and struvite precipitation. It should be noted that it is not within the scope of this work to explore an exhaustive list of technological options. Here, we have presented the two main commercially available technologies at higher Technology Readiness Level (TRL) that can potentially be adopted in the UK.

Error! Reference source not found. shows the general concept of wastewater treatment process in w hich typically involves a treatment process (e.g., activated sludge process) for removing contaminants to meet discharge standards, and a post-treatment process (e.g. anaerobic digestion) to stabilise, disinfect and control corrosion in the treated water system. Sludge cake (or solid digestate) and liquid effluent (or liquid digestate) are generated as products from anaerobic digestion. A nutrient recovery process can be added to further reducing contaminant level in the solid and liquid effluent streams and to recover valuable nutrients (e.g. N and P).

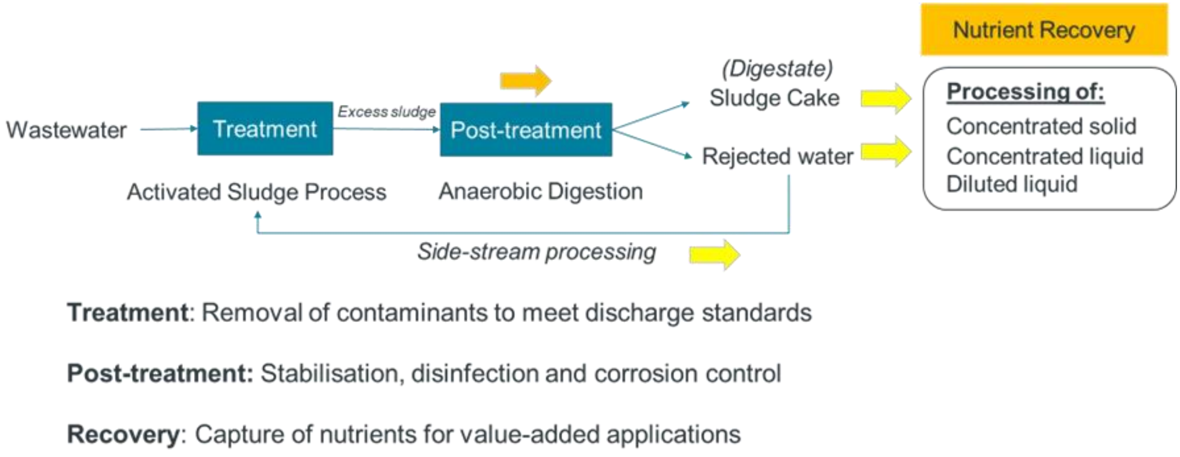


Figure 6.1: General concept of treatment, post-treatment and resource recovery in a wastewater treatment system.

6.1.1 Primary processing technology

6.1.1.1 Anaerobic digestion

Anaerobic digestion is a biological treatment process that involves the decomposition of organic materials in the absence of oxygen to produce biogas and nutrient-rich digestate. It is commonly used to treat a wide range of organic wastes, including food waste, agricultural residues, animal manure, sewage sludge, and others.

<u>Product</u>

The residue left after the digestion process is called digestate. It contains nutrients, organic matter, and minerals that can be used as a fertiliser or soil conditioner. Depending on the feedstock and digestion conditions, the digestate may require further processing or treatment before it can be safely applied to land. Digestate can be dewatered to separate solid fibres from liquid digestate. Nutrients (N and P) embedded in liquid digestate can be further recovered through secondary processing technologies. The biogas produced can be used as a renewable energy source for heating and electricity generation or can be upgraded into biomethane after purification and compression.

6.1.1.2 Composting

Composting is a biological treatment process that involves the decomposition of organic materials under the presence of oxygen into nutrient-rich soil amendments called compost. It is a widely applied treatment method to convert various types of organic waste, such as kitchen scraps, yard trimmings, leaves, agricultural residues, and certain types of paper, into a stabilised form which can be used as fertiliser. Compared to anaerobic digestion, it needs a proper feedstock mixing and should have a good combination of carbon to nitrogen ratio for creating a balanced compost pile. Compared to the continuous operation of anaerobic digesters, the composting process is in sequential phases, generally including temperature rising, moisture control, maturation, and curing.

<u>Product</u>

The resulting compost is rich in organic matter and nutrients. It can be used to improve soil structure (e.g., better microbial activity and water retention) and its nutrient content.

6.1.1.3 Incineration

Incineration is a type of waste-to-energy technologies that involves the controlled combustion of organic materials at high temperatures (ranging from 800°C to 1,200°C) to reduce waste volume by converting it into ash, gases, and heat energy. Compared to anaerobic digestion or composting, it can be used for various types of waste (including plastic waste), but it is generally more suited for treating mixed, combustible, non-recyclable and non-biodegradable waste. Compared to other options, incineration significantly reduces the volume of waste and help divert waste from landfills.

<u>Product</u>

The heat generated during the incineration process can be harnessed for energy recovery. The heat is used to produce steam, which drives turbines to generate electricity connecting to the local grid.

After combustion, the remaining solid materials are converted into ash. This ash can vary in composition and include non-combustible materials and minerals (e.g., phosphorus). Depending on local regulations, the ash may be sent to a landfill, treated further, or used in certain applications, such as construction materials.

General considerations for different options

Waste Reduction: The process reduces the volume of organic waste, diverting it from landfills and minimising methane emissions. The main considerations are the costs of waste collection and transportation.

Nutrient Recycling: Organic waste is rich in nutrients and can be recovered in view of reducing the use of synthetic fertilisers. Different primary processing technologies would create different chemical form of nutrients to be utilised for plant growth.

6.1.2 Secondary processing technology

6.1.2.1 Ammonia extraction (stripping and scrubbing)

Ammonia extraction is a process used for the recovery of nitrogen from wastewater or liquid solutions (e.g., liquid digestate). This process could be employed to remove excess ammonia in wastewater treatment facilities, industrial processes, and agricultural operations. Ammonia is a form of nitrogen that can be converted into various forms of fertiliser, contributing to nutrient recycling and reducing environmental impacts. The extraction system designs generally include a stripping column and condensation chamber. Depending on the specific application, the stripped liquid (reduced ammonia concentration) may be returned to the wastewater treatment process or further treated to meet regulatory standards.

Product

Ammonia recovered through this process can be converted into ammonia-based fertilisers, reducing the need for synthetic fertilisers and promoting sustainable agriculture. However, the ammonia stripping process requires intensive energy use, primarily for liquid heating and gas circulation, of which the operating costs and environmental impact should be taken in consideration.

6.1.2.2 Struvite Precipitation

Struvite precipitation is a process used to recover nitrogen and phosphorus from wastewater or incineration ash to reduce their environmental impacts and produce valuable fertilisers. Removing excess nitrogen and phosphorus from wastewater helps prevent nutrient pollution in water bodies, which can lead to eutrophication and harmful algal blooms. Struvite (magnesium ammonium phosphate hexahydrate) is a crystalline substance that forms when magnesium, ammonia, and phosphate ions combine under specific conditions. This process is employed in wastewater treatment facilities and other facilities dealing with nutrient-rich waste streams.

Product

The feasibility of introducing struvite precipitation in the UK depends on the price and market availability of the recovered struvite fertiliser to be applied in the agricultural sector. Meanwhile, specific chemicals are added to the wastewater to initiate the formation of struvite crystals. These chemicals typically include sources of magnesium (such as magnesium chloride or magnesium sulphate) and alkali (such as sodium hydroxide) to raise the pH of the solution. The concentrated struvite crystals are typically dried to reduce their moisture content and increase their stability, which would require energy input. Further, struvite precipitation needs to be integrated into the overall waste treatment system.

Considerations for different options

Concentration of nutrients: The type and composition of the original waste streams (and after primary processing treatment) must be thoroughly analysed to determine the specific nutrients of interest, as certain technologies may be better suited for recovering nitrogen, phosphorus, or other elements. More concentrated forms of nutrients usually indicate better cost efficiency for recovery.

Scale of operation and market/regulatory constraint: The infrastructure scale and market constraints play a significant role in technology selection for advanced resource recovery. Compatibility with existing waste management practices and regulatory compliance are also vital considerations.

Environmental implications: Environmental impact assessments should take into account unintended environmental consequences (e.g., extra energy consumption and potential contamination risks).

6.2 Estimation of nutrient flow at processing unit level using mass balance approach

This section presents the mass balance of primary processing units to assess the amount of nutrients that can potentially be recovered. These include anaerobic digestion of food waste and sewage sludge (Figure 6.2), composting of organic waste (Figure 6.3), incineration of food waste, sewage sludge and green waste (Figure 6.4) and wastewater treatment facility (Figure 6.5). Since the primary focus is to assess the amount of nutrient recovered, the diagrams do not show information on energy flows. The estimation builds on the combination of mass balance principles and experimental data from the literature. The selection of datasets from the literature was based on the most relevant geographic context in the UK or Western Europe as well as data availability. A detailed spreadsheet consisting of mass balance calculations for the processing units is available upon request.

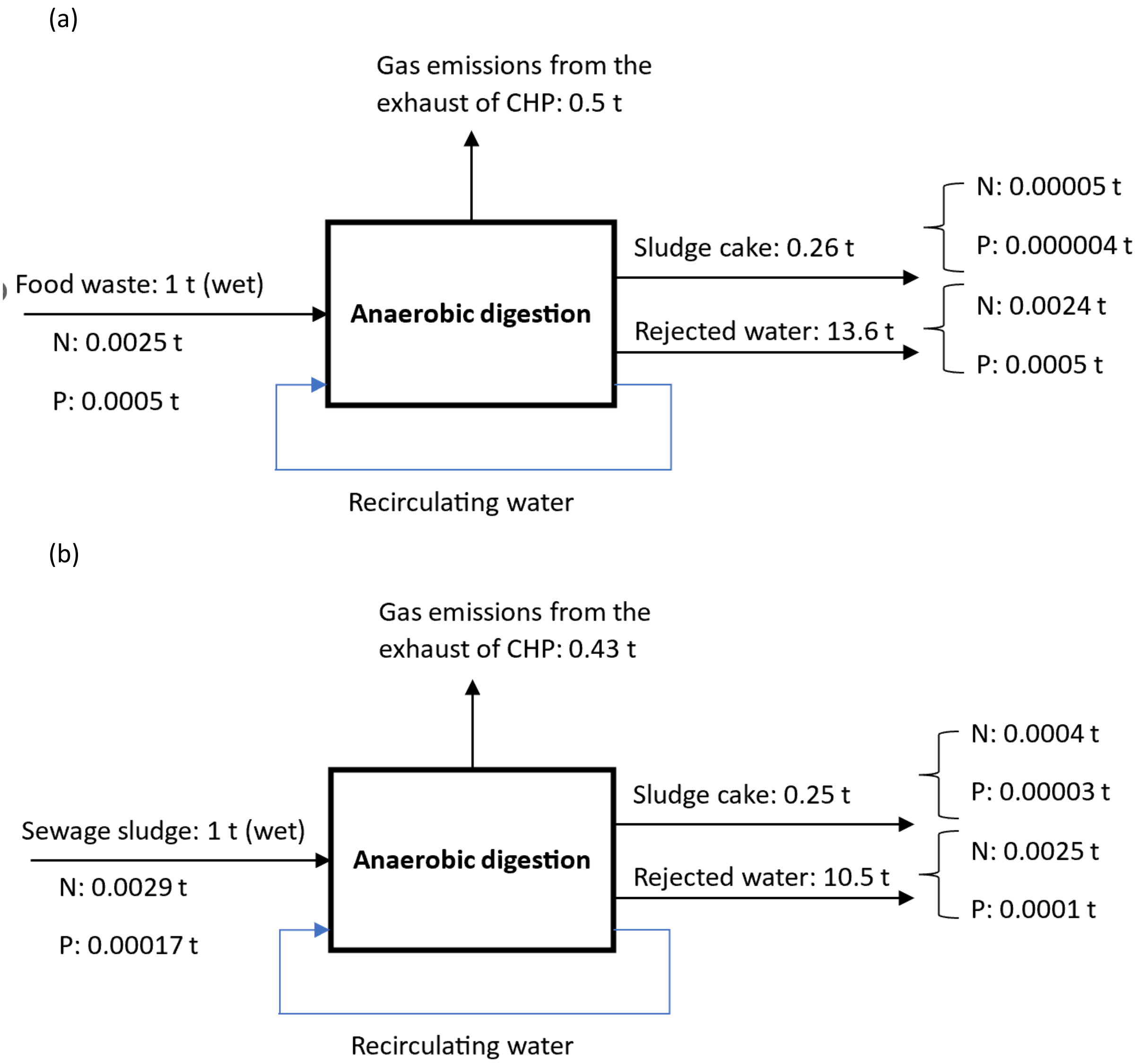
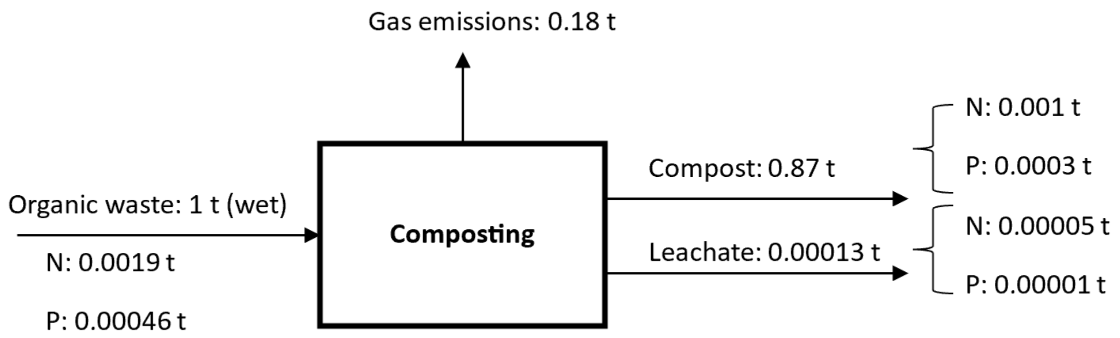


Figure 6.2: Mass balance of anaerobic digestion of (a) food waste; (b) sewage sludge.



Gas emissions comprise CO_2, CH_4, N_2O and CO.

Figure 6.3: Mass balance of composting.

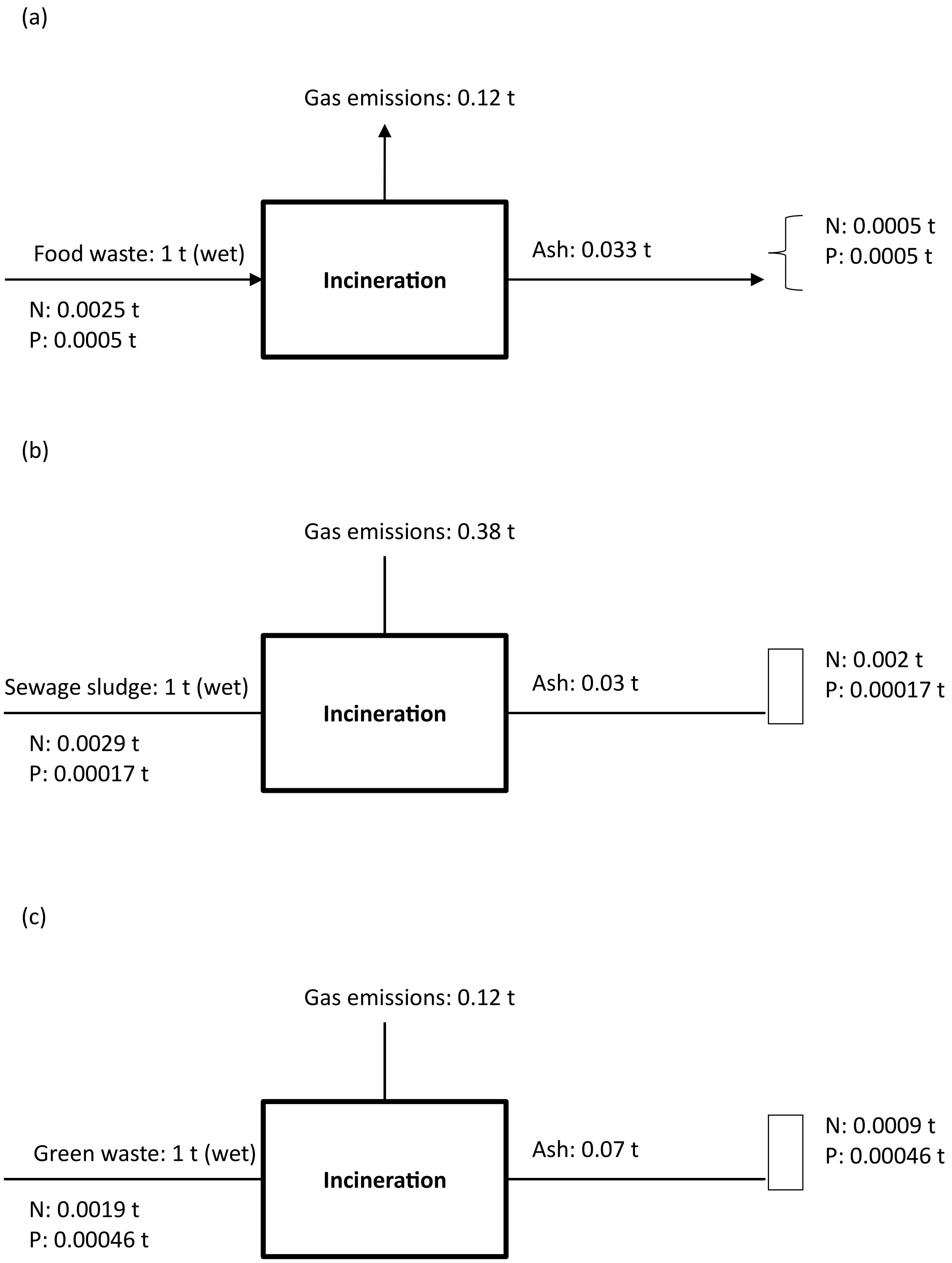


Figure 6.4: Mass balance of incineration of (a) food waste; (b) sewage sludge; and (c) green waste.

<u>Note:</u>

- Gas emissions comprise CO2 and N2O.
- The mass imbalance is due to water content being removed prior to incineration and coming out in the flue gas stream (not included in the diagram).

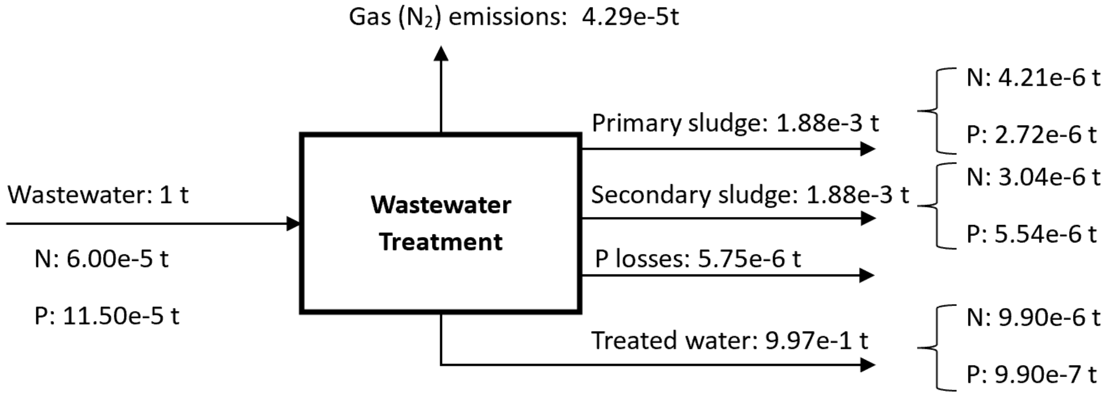


Figure 6.5: Mass balance of wastewater treatment facility.

Sources of data for mass balance estimation can be found in references [1]-[15], as shown in Table 6.1.

Table 6.1: Sources of data for mass balance estimation for primary processing units.

Processing unit	References
Anaerobic digestion of food waste	Banks et al. (2011) [1]
Anaerobic digestion of sewage sludge	Tezel et al. (2014) [2], Aragón-Briceño et al. [3]
Composting of organic waste	Anderson et al. (2010), (2011) [4,5]
Incineration of food waste	Banks et al. (2011) [1]
Incineration of sewage sludge	IPCC [6]
Incineration of green waste	Anderson et al. (2010), (2011) [4,5]
Wastewater treatment	Henze and Comeau (2008) [7], Environment Agency [8], Tezel et al. (2011) [9], Demirbas et al. (2017) [10], Cao and Pawlowski (2012) [11], Demirbas et al. (2016) [12], CIWEM (2011) [13], Kamizela and Kowalczyk (2019) [14], Havukainen et al. (2022) [15]

6.3 Economic evaluation of waste treatment and nutrient recovery technology

6.3.1 Methodology for cost estimation

The cost estimation methodology builds on the derivation of a correlation curve using CAPEX data from published case studies together with plant capacity. Chemical Engineering Plant Cost Index (CEPCI) was used to escalate the cost to year 2019, using equation (1). A detailed spreadsheet consisting of CAPEX correlation curves for anaerobic digestion, composting and incineration is available upon request.

$$C_p = C_o \ (I_p/I_o) \qquad \text{Equation (1)}$$

where

C_p is the present cost of equipment,

C_o is the original cost of equipment,

I_p is the present index value,

I_o is the original index value.

OPEX was estimated based on a fixed percentage of the CAPEX. The cost relationships were analysed using published case studies and industry benchmarks. This approach provides a quick estimation for budgeting purposes.

Terminology

CAPEX

CAPEX (Capital Expenditure) refers to the initial capital investment required to design and construct an environmental infrastructure project. It includes the costs associated with building physical assets, such as equipment, facilities, and infrastructure components. CAPEX is a one-time expenditure for initiating waste processing. Estimation of CAPEX is crucial for securing funding and planning the overall project.

Some key aspects of CAPEX:

- **Design and engineering**: Costs associated with planning, engineering, architectural design, and feasibility studies.
- **Construction**: Expenses for building physical structures, installing equipment, and constructing infrastructure components.
- **Equipment procurement**: Costs related to purchasing machinery, technology, and equipment required for the project.
- **Project management**: Expenses for overseeing and managing the project from inception to completion.

OPEX:

OPEX (Operating Expenditure) refers to the ongoing operational costs incurred to run and maintain an environmental infrastructure facility after its commissioning. These costs are recurrent and cover the day-to-day operations, maintenance, and administration of the facility. OPEX is essential for sustaining the facility's functionality over its operational lifespan. Efficient management of OPEX is crucial to ensure the facility's financial sustainability.

Some key aspects of OPEX:

- **Energy and utilities**: Expenses associated with electricity, water, fuel, and other utilities required for the facility's operation.
- **Chemicals and consumables**: Expenses for chemicals, materials, and consumables needed for treatment processes or other operational activities.
- **Labour and personnel:** Costs related to staffing and training of personnel required to operate and maintain the facility.

- **Maintenance and repairs**: Costs for regular maintenance, repairs, and replacement of equipment, machinery, and infrastructure components.

Notes: In this project, the costs of land acquisition, permitting compliance, and facility commissioning were not considered for both CAPEX and OPEX.

6.3.2 Basis and assumptions for CAPEX and OPEX estimation for processing technology

6.3.2.1 Anaerobic Digestion

The most apparent CAPEX of an anaerobic digestion facility comprises digesters, combined heat and power (CHP) unit, and other ancillary pre-processing or post-processing equipment. Gas collection, purification, and utilisation (e.g., for electricity generation) are included in the CHP unit. The breakdown of CAPEX for anaerobic digestion is presented in Table 6.2.

Table 6.2: Breakdown of CAPEX for anaerobic digestion [7].

Capacity (tonne/year)	180000	310000
Pre-processing	20.45%	20.50%
Digesters	65.06%	65.09%
Emission control	10.41%	10.43%
Process control	4.09%	3.98%

The OPEX of an anaerobic digestion facility comprises parasitic power for operating systems, maintenance, labour, and emission control (e.g., disposal of sorted impurities). Depending on the contract agreement, the OPEX of apparently identical plants may differ. There are also costs associated with acquiring, transporting, and pre-processing the organic waste materials before/after they enter the digester. Government incentives or subsidies may be sometimes available to help offset the OPEX.

6.3.2.2 Composting

The CAPEX of a composting facility is primarily the purchase and installation of composting containers and mechanical mixing equipment (e.g., windrow turners). The cost can vary significantly depending on the size and complexity of the system. For large-scale composting, aeration and ventilation systems may be required to ensure proper oxygen levels and temperature control within the compost piles. Depending on local regulations and community concerns, odour control and emissions management systems may need to be implemented, which could incur additional capital investment. Table 6.3 presents the breakdown of CAPEX for composting.

Table 6.3: Breakdown of CAPEX for composting [8].

Capacity (tonne/year)	5000	30000
Civil Works	26.47%	27.78%
Treatment Technology	24.51%	56.03%
Mobile Equipment	49.02%	16.19%

The OPEX of composting facility comprises parasitic power for operating systems, maintenance, labour, feedstock procurement (e.g., transportation service), compost distribution (e.g., packaging and marketing), and emission control (e.g., consumables used for gas purification).

6.3.2.3 Incineration

The CAPEX of incineration comprises combustion facilities, feeding equipment, air pollution control equipment, energy recovery equipment, and ash management facilities.

The OPEX of an incineration facility comprises parasitic power for operating systems, maintenance, labour, feedstock procurement (e.g., transportation service), and emission control (e.g., consumables used for gas purification and leachate treatment). The water content in organic waste (e.g., dewatered sewage sludge) could substantially increase energy costs for combustion.

6.4 Options Appraisal

Primary and secondary treatment options for food waste have been evaluated using a basis of 47,424 tonnes/year of estimated food waste generation in Leicestershire and Leicester City in 2019, presented in Table 6.4 and Table 6.5, respectively. The techno-economic assessment includes CAPEX, OPEX, and potential revenues (e.g., market value of recovered products) of the defined options. The environmental impact assessment mainly focuses on associated greenhouse gas emissions (in carbon dioxide equivalence). It should be noted that due to inconsistent system boundaries (e.g., struvite precipitation) in the literature, further examination of key variables and real-life details would be needed for the next phase application. The follow-up procedures include feedback incorporation, refining scenarios, and analysis iteration. It would also be necessary to consider changes in technological improvements, policy, or market conditions. The overall analysis of the defined options (against the baseline option of landfilling) allows for the preliminary exploration of potential outcomes and assesses the associated trade-offs of implementing a given system or process.

Table 6.4: Primary treatment of 47,424 tonnes of food waste/year.

Option	Potential nutrient content (tonne/year)		CAPEX (million £)	OPEX (million £/y)	GHG emissions (tonne $CO_{2\text{-eq}}$/y)
	Nitrogen	**Phosphorus**			
Landfilling	0	0	6.9	0.4	9194
Incineration	0	25.0	32.8	1.2	−484
Anaerobic digestion	116.9	25.0	22.7	1.8	−2229
Composting	58.0	16.2	9.7	0.6	2099

Note: *These are primary treatment units without nutrient recovery into elemental products.*

Table 6.5: Secondary treatment of 47,424 tonne food waste/year.

Option	Potential nutrient recovery (tonne/year)		CAPEX (million £)	OPEX (million £/y)	Economic value of the recovered nutrient product (million £/y)	GHG emissions (tonne $CO_{2\text{-}eq}$/y)
	Nitrogen	Phosphorus				
Struvite recovery from incineration ash	0	23.2	0.12	0.00052	0.0092	0.039
Ammonia extraction	103.1	0	5.6	1.2	0.18	0.34
Struvite recovery from liquid digestate	23	23	0.12	0.0018	0.05	−0.76
Ammonia extraction + Struvite recovery from liquid digestate	105.4	23	5.7	1.2	0.2	−0.41

Note: *These are secondary treatment units with nutrient recovery into elemental products. An average market price of struvite of £50 per tonne has been used in the analysis.*

Typical food waste treatment technologies, herein referred to as “primary treatment units”, aim to convert organic materials into more stable forms (such as compost which contains mixed nutrients co-mingled with other contaminants) which can be used as fertiliser or sent for landfilling or land spreading. They usually do not have capacity for nutrient recovery to create "pure" nitrogen or phosphorus-based products. While anaerobic digestion (AD) exhibits promising environmental benefits in terms of greenhouse gas (GHG) emissions reduction compared to composting, it comes with higher capital and operational expenses (CAPEX and OPEX).

In contrast, emerging food waste treatment technologies, herein referred to as “secondary treatment units”, allow further treatment of effluent or waste streams (liquid digestate or incineration ash) to remove or recover nutrient into marketable products. Struvite recovery from incineration ash is particularly efficient in phosphorus (P) recovery (>90%), as nitrogen (N) is released in gaseous form during incineration. On the other hand, ammonia extraction allows for the recovery of nitrogen (N) (>90%) but not phosphorus (P). Production of struvite from liquid digestate appears to be a viable option for future consideration owing to the capability of recovering >90% of N and P, giving GHG emission savings at moderate cost. This approach can be integrated with anaerobic digestion process, creating an integrated and sustainable food waste treatment solution.

Section 7: Key Takeaways

In this final part of the report, we provide a summary of the key learnings derived from qualitative and quantitative investigations carried out in this project and presented in the earlier sections of this report. Furthermore, we share several reflections based on the broader experience gained from dealing with data sources and interacting with stakeholders. Associated with each of these learnings and reflections, recommendations are suggested to benefit future work in this area at both the local level and the national level.

Learnings from research in this project:

1. Significant leakages of nutrients in the case study region. Within processed waste streams, discharged wastewater represents the most significant leakage of N and P, while rejected water from AD plants is the second most significant nutrient-leaking stream. On the other hand, the nutrient content in the land application/deposition of slurry and manure appears to overtake all other flows in the region, although the fate of these nutrients is yet to be quantified.

Recommendations:

R1-a: Enhanced nutrient recovery in wastewater treatment is needed to reduce the loss of resources and the negative impact to the environment. As well as improving the prevailing centralised wastewater treatment systems, decentralised schemes for at-source separation and recovery should be considered as a longer-term option (see also learning point 3).

R1-b: Sufficient consideration needs to be given to nutrient recovery from the rejected water of AD plants, particularly when their uses are expected to significantly expand to cope with the management of separately collected food waste.

R1-c: Further quantitative understanding of the fate of nutrients contained in slurry and manure following land application/deposition is required, together with the broader understanding of run-off in the region, to ensure that this significant nutrient flow is properly managed.

2. Movement of organic waste. There is clear evidence of sizable transportation of organic wastes between the case study region and other locations and between regions in England. Such haulage burdens would have economic and environmental implications, although the factors leading to these movements are yet to be analysed.

R2: Further quantification of existing significant movements of organic waste in the UK, understanding of their drivers and projection of dynamics considering the creation of additional waste streams (due to, for example, separate food waste collection) are recommended. These further learnings should then guide future policy decisions with respect to issues such as local/regional capacity matching and regulating waste transport to balance economic and environmental considerations.

3. Business opportunities for re-design. This project has identified four areas of business opportunity to improve regional nutrient management: **(i) Upstream wastewater solutions** - intervening prior to nutrients entering the wastewater system; **(ii) Transformation of digestate** - utilising technology to ensure that the nutrients contained within digestate can be more fully utilised by crops; **(iii) Downstream farming interventions** - farming differently to apply nutrients more sparingly and prevent loss to the wider environment and **(iv) Nutrient co-location** - tackling the challenges associated with moving nutrient-rich materials by situating sources and uses close together.

- **(ii)** calls for introduce of new nutrient recovery facilities which currently have rare presence in the UK even though the underpinning technologies have been demonstrated elsewhere. Their introduction will need to overcome barriers including capital investment; the preliminary techno-economic appraisal conducted in this project shows the production of struvite from liquid digestate appears to be a viable option for future consideration owing to its high degree of nutrient recovering while giving GHG emission savings at moderate cost.
- **(iv)** calls for careful consideration of the physical locations of facilities. As a relevant example, this project predicted, subject to the level of spared capacities, the reduction of haulage burdens by using multiple types of AD facilities, including those on-farm operations, in dealing with separately collected household food waste. However, such arrangements could bring contractual challenges between waste authorities and operators.
- **(i)** represents a significant change to the current wastewater management system, while **(iii)** calls for changes in the current farming practices.

R3-a: Building on the assessment by this project, business-led evaluation of nutrient recovery schemes, particularly those around AD, are recommended to consider not only technology costs but also the practicalities of forming partnerships required for economically feasible operation at a required scale.

R3-b: In the future planning of organic waste management, waste authorities are encouraged to consider a wide range of waste processing facilities (existing and new) in terms of their feed type, capacity and physical location, to balance the considerations of cost, environmental impact and resource efficiency, which could be supported by mathematical modelling tools.

R3-c: Where possible, discussion of short- to mid-term retrofit and expansion of the current waste processing facilities should connect to more fundamental changes such as decentralised treatment, for example in consultation with forward-looking estate developers, to seize emerging opportunities.

R3-d: Farming interventions hold significant potential for improving nutrient efficiency and reducing leakage, where opportunities should be explored through joined-up thinking between waste management and other initiatives such as Nature Recovery.

Wider reflections:

4. Stakeholder commitment and regional mechanisms for co-ordinated actions: For linking local policy with recommended solutions, there is need for commitment from multiple stakeholders, investment and consideration of multiple drivers and income streams in order to progress e.g., where are nutrients needed (and not needed), where are they going to be produced, commitment of local food waste collection to drive a more nutrient focused approach as oppose to traditional 'collect and dispose' practice. It was highlighted in various conversations with the stakeholders that the national policies embedded within political will takes precedence over the local motivations and requirements. However, there is a need for a bottom-up approach where the agency and capacity for planning changes and leadership is based on the needs and willingness of the actors at the grassroots level.

R4. As there is currently no suitable organisation to lead the creation and implementation of holistic organic waste management and resource recovery across domestic/public, agricultural, industrial and commercial sectors, discussion is recommended between national and local stakeholders to eventually establish such an organisation or mechanism, through either giving an existing body new power/capacity or creating a new body.

5. Regulatory reforms: There is a need to update regulations around use of fertilisers derived from organic waste as there could be consequences of applying recovered nutrient products on the soil health and environment and the current regulations does not give indications of these consequences. For example, green waste is processed into compost according to PAS100 certification. This certification allows for a certain percentage of plastic in the compost. Inevitably, this plastic can accumulate in the soil over time and create long-term issues.

R5: Consistency, completeness and operability of existing regulations or formal recommendations regarding nutrient-rich products need to be reviewed, to consider the balance between soil quality/productivity, resource efficiency and environmental and health impact.

6. Household behaviours: Organic waste contamination is one of the biggest barriers in enhancing the valorisation of AD digestate, which is key for closing the nutrient loop in an agrarian region. How people dispose wastes in bins and mix plastic waste with the organic waste is key in optimising the waste processing systems. If the waste is better managed at the source itself, it can prevent contamination of organic waste and therefore the resources in stripping the contamination.

R6: There should be more education and awareness-raising efforts targeted at the general public, to minimise the unnecessary burden introduced at source.

7. Robust and consistent data: There are significant discrepancies between the datasets acquired from multiple sources (e.g., LCC and EA). The waste handled by private contractors is not monitored by the council causing a data gap. Additionally, in Leicestershire, the district councils in general only collects trade green waste, parks and gardens waste and household general waste which is then disposed by the county council and they do no handle any other type of waste and hence possess no records of other waste streams On the other side, EA waste interrogator data contained many gaps. Firstly, this dataset was not intended to provide any details on quantity, quality and sale/purchase of by-products and end-products from waste processing facilities, modes of transportation of the waste, waste leakages, and the costs incurred. Secondly, this dataset appears to lack information on organic waste that does not end up in waste facilities and cause environmental and social problems such as waste from livestock agriculture that is stored and managed on the farms. Moreover, there is no explanation of how transfer stations are used or identification of the processes and people involved between waste in the bin to waste in the processing facility. Consistent micro-scale data pertaining to waste streams, recovered nutrients and farmers practices is required to plan for optimising nutrient recycling.

R7: A better understanding of the current data collection landscape across national and local levels is desirable for organic waste streams. This understanding should identify key gaps to be filled by additional data collection efforts and opportunities to connect and streamline multiple datasets.

Finally, the organic waste system is deeply interconnected and complex. The analysis from this project demonstrates the value of stakeholder-driven food systems mapping and data acquisition and the necessity of understanding the business and economic assessment of available technologies. There are multiple avenues for approaching a circular organic waste system requiring the buy-in of stakeholders at multiple levels and scales. There are opportunities for environmental and economic benefits across the system that have been demonstrated by the rapid interdisciplinary assessment in this project.

Appendices

Appendix A – Further information on part 1 and part 2 of the Section 3

Identification of initial focus areas

The eight initial areas included in scope during Part One of the project:

Wastewater

- Loss of nutrients from wastewater through Combined Sewer Overflows (CSOs) and wastewater treatment plant (WWTP) discharge
- Incomplete removal of nutrients from wastewater
- Poor utilisation rate of residues from wastewater treatment

Food waste

- High levels of food waste from households and business
- Poor utilisation of processed food waste

Green waste

- Ineffective usage of green waste

Agriculture

- Loss of nutrients from agricultural systems through runoff
- Degradation of soil organic carbon

These eight areas were then ranked on the basis of 1) scale of impact, 2) ability to influence through business, and 3) relevance to the wider project, to produce a list of six areas for further investigation. 'Degradation of soil organic carbon' was not selected as a search criterion, as soil carbon was not taken forward as a key theme for the overall project - it was decided that N and P would be the prime nutrients considered. 'High levels of food waste' was also not taken forward as it was considered that other actors are already focused extensively on this topic, and there would be unlikely to be significant value add from this project.

The two areas ranked as highest opportunity through this prioritisation process were:

- **Poor utilisation rate of residues from waste treatment (water and other waste streams)**: while we are becoming more successful at capturing nutrients from multiple waste streams, these recovered nutrients are not always usefully utilised or valued by end users.
- **Loss of nutrients from agricultural systems through runoff**: Related to poor utilisation, recovered nutrients (from AD, sewage sludge, compost, manures and slurries) may be applied to land in such ways as they are lost to the wider environment, causing environmental harm.

Identifying businesses for stakeholder interviews

Based on the six areas identified, we then conducted a stakeholder search across each area. The search criteria included incumbent businesses operating in the sector, start-up and growth businesses, sector actors such as networks and member bodies, as well as academics and researchers able to give systemic insights on the opportunities. This process benefited from the existing work by the academic team to identify initial stakeholders for a workshop in July 2022, many of whom were also included in our investigations.

The stakeholder search identified 40 potential stakeholders. Of these, we had capacity within the project to conduct 10 interviews. These were selected based on the highest potential to inform the project as well as availability for interview during the timeframe. Several high potential interviewees did not respond to our requests and are therefore not included in the final list - this represents a project risk as it may indicate that areas of potential interest have not been adequately covered. Potential interviewees were contacted by personalised email with an attached slide deck explaining the project and interview aims. Further interviewees were identified in-line through a ‘snowballing’ process of asking each interviewee for further contacts.

Interviewees represented the following sectors:

- Wastewater processing consultancy
- Agricultural industry body
- Regenerative agriculture sector
- Innovative nutrient recovery technologies
- Green waste processing
- Food manufacturing
- Water industry
- Academia

Appendix B

Description of "Estimates of manure volumes by livestock type and land use for England and Wales" by Defra, Environmental Information Data Centre

The Defra dataset, available at https://catalogue.ceh.ac.uk/documents/517717f7-d044-42cf-a332-a257e0e80b5c, contains estimates of annual volumes of manure produced by six broad farm livestock types for England and Wales at 10 km resolution, modelled with MANURES-GIS. The farm livestock classes are: dairy cattle; beef cattle; pigs; sheep and other livestock; laying hens; broilers and other poultry. The quantities produced by each type are subsequently apportioned into managed and field-deposited manure. The managed manure sources are categorised as beef farmyard manure, beef slurry, dairy farmyard manure, dairy slurry, broiler litter, layer manure, pig farmyard manure, pig slurry and sheep farmyard manure. The destinations are recorded as grass, winter arable, spring arable and direct excreta when grazing. For each 10 km square, the quantity of manure going from each source to each destination is estimated. The values specify amount of excreta, in kilograms for solid manure and in litres for liquid manure.

The livestock and cropping data used to parametrise MANURES-GIS are sourced from the 2010 June Survey from Defra and the Welsh Government.

Data used- beef farmyard manure, beef slurry, dairy farmyard manure, dairy slurry, broiler litter, layer manure, pig farmyard manure, pig slurry and sheep farmyard manure.

Units- kilograms/year

Calculations- Total P and N amounts (kg/ha) in handled manures (FYM, slurry and poultry manure) and Sheep grazing direct excreta. Values for N and P concentrations taken from the Supporting documentation Table 1 (extracted values in excel sheet 'aggregated FYM slurry and run-off'). Slurry unit was converted from litres to kg using the dry matter concentration values and the mass of dry matter in slurry was used as kilograms of slurry. The concentration of N and P in direct excreta was estimated using total excreta in England values from table 4 and total N and P in England values from table 5, the estimated concentration was then multiplied with total direct excreta tonnes to get estimate of total N and P amounts deposited in Leicestershire.

Appendix C: List of AD facilities considered in the study

ID	Total feedstock capacity (tpa)	Plant type	Operator	Site Name	Postcode	County	Year of commission-ing
ADFarm 1	86,000	Farm AD	A C Shropshire	A C Shropshire (Farm AD)	LE9 3LE	Leicestershire	2013
ADFood 1	45,000	Municipal/ Commercial	Biogen	Atherstone - Merevale & Blyth Estate	CV9 2LA	Warwickshire	2015
ADFarm 2	25,000	Agri	William Corbett Farms Ltd	Austrey House Farm	CV9 3EA	Warwickshire	2016
ADFarm 3	5,309	Agri	Belmont Farms Ltd	Belmont Farms	LE14 2QN	Leicestershire	2015
ADFarm 4	1,354	Agri	Jason Bayley	Biolectric Plant Ladyleys Farm	DE12 8EE	Staffordshire	2017
ADFarm 5	11,000	Agri	Channing Digester	Brandon Grange AD	CV8 3GE	Worcestershire	2014
ADFood 2	18,000	Industrial	Unilever	Burton Marmite factory	DE14 2AB	Staffordshire	2012
ADFarm 6	12,609	Agri	Cleat Hill Energy Limited	Cleat Hill Energy	B79 9HH	Staffordshire	2016
ADFood 3	50,000	Municipal/ Commercial	Bio Dynamic	Colwick Industrial Estate	NG4 2JT	Nottinghamshire	2015
ADFood 4	49,000	Municipal/ Commercial	Fernbrook Bio - Regen Holdings	Fernbrook AD Plant - Rothwell Lodge Farm - Fernbrook Bio	NN14 1SS	Northamptonshire	2010
ADFarm 7	11,945	Agri	Grange Biopower Limited	Grange Biopower	LE16 8EF	Harborough	2014
ADFood 5	44,242	Municipal/ Commercial	A C Shropshire	Green's Lodge Farm	LE67 4UY	Leicestershire	2016

ADFarm 8	22,800	Agri	Brinklow Biogas	Highwood Farm (Brinklow)	CV23 0NJ	Warwickshire	2015
ADFarm 9	5,501	Agri	Honeypot Farm	Honeypot	NG33 5LS	Lincolnshire	2016
ADFarm 10	3,692	Agri	Oakfields Farm	Oakfields Farm	NN6 8DS	Northamptonshire	2014
ADFood 6	20,000	Industrial	Orchard House Foods	Orchard House Foods	NN17 4SW	Northamptonshire	2010
ADFood 7	36,000	Municipal/ Commercial	Welland Waste Management Ltd	Pebble Hall Farm - Food Waste AD	LE17 6NJ	Northamptonshire	2015
ADFood 8	48,500	Municipal/ Commercial	Severn Trent Green Power	Servern Trent Green Power - Derby	DE21 7BR	Derbyshire	2019
ADFarm 11	40,000	Agri/ Industrial/ Municipal/ Commercial	Stanton Energy	Stanton Recycling Limited site-Ilkeston	DE7 4BG	Derbyshire	2021
ADFarm 12	20,000	Agri	Agrivert	Stragglethorpe Biogas AD plant (Samworth Farms)	NG12 3BA	Nottinghamshire	2014
ADFood 9	40,000	Municipal/ Commercial	Biffa	Wanlip	LE7 4PF	Leicestershire	2004
ADFarm 13	11,800	Agri	Works Farm (Merrivale Energy)	Works Farm	NG13 9JN	Nottinghamshire	2016

Appendix D: List of waste collection zones considered in this study

ID	District/sub-district	Modelled Annual tonnage (100% set-out)	Modelled Annal tonnage (47% set-out)
Zone1	NW upper	4257.6	2001.5
Zone2	NW lower	4257.6	2001.5
Zone3	H&B left	3529.0	1659.0
Zone4	H&B right	3529.0	1659.0
Zone5	Blaby	6296.5	2960.0
Zone6	Chamwood left	5471.2	2572.0
Zone7	Chamwood right	5471.2	2572.0
Zone8	Melton upper	1627.3	765.0
Zone9	Melton lower	1627.3	765.0
Zone10	Rutland left	1655.0	778.0
Zone11	Rutland right	1655.0	778.0
Zone12	Harborough left	2682.4	1261.0
Zone13	Harborough middle	2682.4	1261.0
Zone14	Harborough right	2682.4	1261.0
Zone15	Leicester City	10377.4	10377.4
County		47424.0	22294.0
City		10377.4	10377.4
total		57801.4	32671.4

Appendix E: A preliminary tool for automatic flow mapping based on the EA's Waste Data Interrogator

A python-coded tool was developed to demonstrate a possible way to automatically extract, compute and visualise organic waste and nutrient flows based on the EA's Waste Data Interrogator. Facility WPA, Site Category, Facility Type, Fate, Origin WPA, R and D code, and Tonnes Received were extracted from the EA data. First, the Origin WPA (e.g., Leicester City) and the SOC Sub Category (e.g., Green waste) were selected to filter out irrelevant data entries. To avoid double counting of entries for waste transfer within the Origin WPA, entries were excluded if their Facility WPA were the same as Origin WPA and their Site Category were "Transfer". Then, waste flows to Facility WPA outside and in Origin WPA were summed. Based on Facility Type and R&D code, processing units (PUs) were determined for the waste flow recorded in each entry (Table E1).

PU	R&D code	Facility Type
Composting	R13, R03.02.01, R03.02.02, R03.02	Composting
Landfill	D15, D09, D01	-
Incineration	D10, R01	-
Anaerobic digestion	R03.03.01, R03.03	Anaerobic digestion

Table E1. Classification of 4 PUs used in this study.

After waste flows to different PUs were summed, flows to end products (e.g., compost, leachate, sludge cake) of waste treatment were computed using mathematical models for 4 different PUs. The result of material flow analysis could be visualized as a Sankey diagram (Figure E1). In addition, the analysis pipeline could also compute nitrogen and phosphorus contents for total dry waste and end products after treatment (Figure E2).

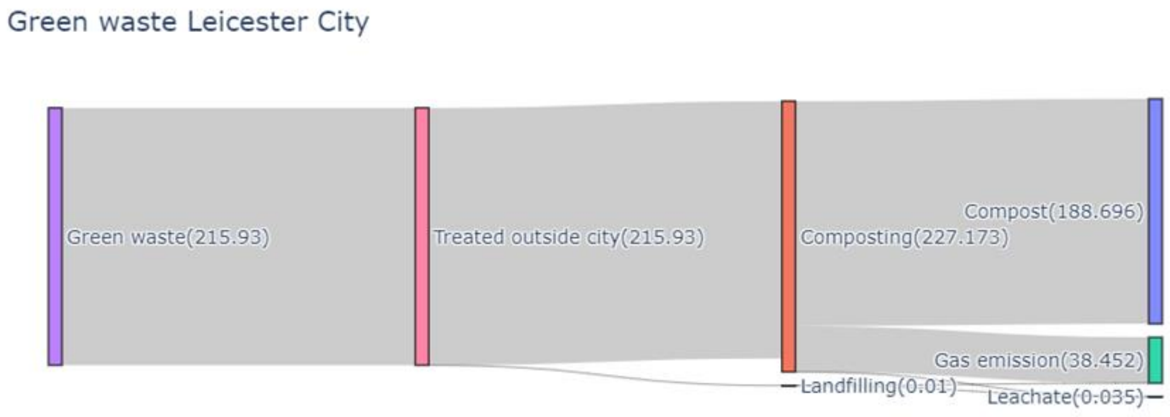


Figure E1. Sankey diagram of waste flows of green waste from Leicester City, the unit is tonnes.

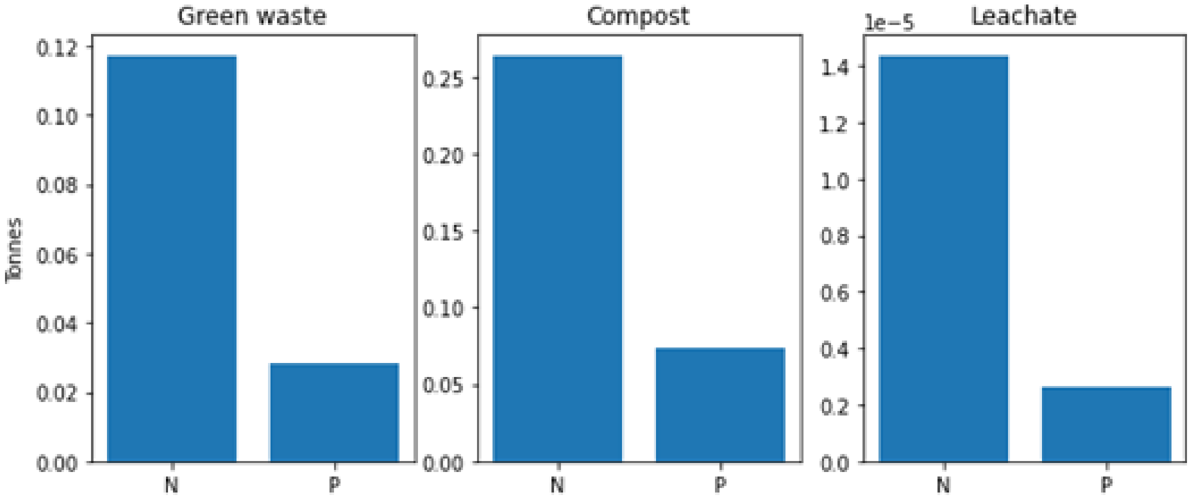


Figure E2. Nitrogen and phosphorus contents for total dry green waste from Leicester City and end products after treatment.

References

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[i] EA waste data interrogator 2019 available at https://www.data.gov.uk/dataset/d409b2ba-796c-4436-82c7-eb1831a9ef25/2019-waste-data-interrogator

[ii] Each waste type has a code and the definitions are available at https://dsposal.uk/ewc-codes/20/20-02/20-02-01/

[iii] An explanation of the codes, known as Recovery (R) and Disposal (D) codesis available at http://www.wastesupport.co.uk/recovery-and-disposal-codes/.

[iv] Draft Resources and Waste Strategy for Leicestershire 2022-2050, Options Appraisal.

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