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Circular economy opportunities for Scottish agriculture

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1 Executive summary

1.1 Aims

Scottish agriculture faces increasing pressure to reduce greenhouse gas emissions while improving resource efficiency and resilience. Circular economy (CE) approaches can help achieve these goals by reducing waste, making better use of materials, and supporting Scotland's wider climate and environmental ambitions.

This report reviews the current evidence on circular economy activity and principles in Scottish farming. It examines the actions that farmers and crofters in Scotland can take to transition to a more circular economy and, in turn, reduce greenhouse gas (GHG) emissions associated with the agriculture sector.

We examine how materials and products move through the Scottish agriculture system, including the quantity of waste generated, associated GHG emissions, and economic impact for farmers. We also examine the potential for specific circular economy actions.

1.2 Findings

This research shows clear opportunities to make Scottish farming more circular, delivering benefits for farmers and contributing to GHG reductions. However, it also presents a complex picture. Some materials already serve several competing uses, and some environmental and economic implications remain unclear. Farmers and businesses may also face challenges when implementing some circular economy approaches.

1.2.1 Material and product flows in Scottish agriculture

We found that the most significant material and product flows, included:

- waste manures and slurry (Output)
- fertilisers, especially nitrogen fertilisers, but also phosphate and potassium (Input)

- livestock feed: significant volumes of locally grown and imported feed (Input)
- food loss that could have been potentially edible (Output)
- crop wastes, including straw and other plant parts, such as carrot tops and potato haul (Output)
- fuel, mostly used in farm vehicles (Input)
- other waste materials (non-crop or livestock), including plastics, chemicals and discarded equipment (Output).

These material and product flows happen in significant quantities across Scottish agriculture. They are also associated with significant GHG emissions in Scotland and across wider supply chains.

Manure – which moves through the system in the largest quantity and produces the 5th largest GHG emissions of all the materials we assessed – primarily creates emissions in Scotland during storage and when spreading on land. Nitrogen fertiliser ranked much lower by quantity at 14th, but it created the highest GHG emissions in our assessment.

1.2.2 Options for improving circularity

We identified opportunities to improve circularity across the waste hierarchy. This includes actions to prevent waste occurring in the first place, as well as options for farmers to generate additional value from materials that were previous underused or treated as waste.

Taking into account potential emissions reduction, economic viability, and scope for application in Scotland, our analysis identified key options for improving circularity:

- **Reducing material inputs and preventing waste by:**
  - improving livestock feed-use efficiency and extending grazing to reduce purchase of feed
  - improving storage and using technology to avoid food loss
  - reducing plastic use through new management practices
- **Reusing materials:**
  - such as plastics containers and tree guards
  - by redistributing surplus food
- **Increasing recycling of agricultural plastics, through:**
  - better collection services
  - treating some materials by anaerobic digestion (AD), where wider need justifies the facilities
- **Continuing and extending the use of circular materials, including using:**
  - brewery waste to replace primary livestock feed materials
  - farm waste as a more sustainable feedstock for emerging off-farm industries, such as biorefining.

Table 1 below shows the results of our high-level assessment of selected circular economy options, which included key sources of emissions. Feasibility was assessed based on relevance to Scotland, existing uptake, and ease of adoption. We did not complete full life-cycle assessments.

Our assessment shows that redistributing edible food waste from farms could deliver the largest emissions reduction, at approximately 145,000 tonnes of CO_2e per year. Applying

biochar made from surplus straw to agricultural land showed the next largest potential reduction, however limitations in the background calculations mean there are important uncertainties and trade-offs in assessing options for straw and residues.

Table 1: Results of high-level assessment for selected circular options for agriculture in Scotland (please see Section 5.2.6 for method, scope of assessment and assumptions)

Material	Waste hierarchy	Action	Emissions reduction for Scotland (tonnes CO_2e/yr)	Feasibility to increase uptake
Feed	Reuse (animal feed)	Supplementing animal feed with brewery/ distillery waste	18,000	Medium
	Reduce consumption	Genetic improvements in beef for feed efficiency	4,840	Low
	Reuse (animal feed)	UK-produced insect protein reared on food-waste as feed	-42,200 (increase)	Low
	Reduce consumption	Extending grazing period for 50% of beef cattle population by 30 days	37,200	High
Food loss	Prevent waste	Shared grain storage facilities	18,700	Medium
	Reuse/ redistribution	Saving 22% edible on-farm food waste of fruit and vegetables	145,000	Medium
	Prevent waste	New equipment in dairy parlours to prevent milk loss	13,000	Medium
Plastic	Reduce consumption	BaleSafe silage additive, which reduces need for plastic silage wrap	15,300	Low
	Reuse	Refurbishment and re-use of plastic crop-covers and containers	62,700	Medium
	Recycle	Increase plastic recycling	45,100	Medium
Straw and residues	Recycle: biomaterial	Using straw as a horticultural growth medium	16,100	Medium
	Recycle: biomaterial	Conversion of straw to biochar and applied to 50% of arable land	101,000	Low
	Recycle: biomaterial	Upcycle high value materials (e.g. chemicals, antioxidants)	Unclear	Low
	Recycle: biomaterial	Upcycle bulk materials (e.g. construction materials)	Unclear	Low

1.2.3 Barriers and challenges

We identified several barriers and challenges that could limit wider adoption of circular opportunities in Scottish agriculture. These include:

- Limited knowledge and awareness of circular economy opportunities amongst farmers: some circular economy actions align well with general resource efficiency and regenerative agriculture, but driving behaviour change may be challenging
- The nature and distribution of agricultural materials create practical challenges: agriculture produces some unique materials, including contaminated and hard to recycle plastics. The remoteness of some farms also creates challenges for recycling services.
- Financial barriers limit uptake of some solutions: some circular economy options face challenging economies of scale or require upfront investment in infrastructure or equipment.
- Limited data availability and evidence hinder decision-making: better data availability could help refine priorities, allowing farmers, government, and researchers to streamline efforts.
- Evidence gaps remain due to the lack of data on material and product flows, including food loss and waste, fuels, plastics and feed. Some flows such as on-farm un-sold wool, chemicals and horticultural growing media are not routinely quantified.

1.3 Options for action by Scottish Government

The Scottish Government can play a key role in supporting the development and uptake of circular economy options in agriculture. These actions can benefit farmers, reduce emissions, and generate wider environmental benefits. Areas which government may wish to prioritise include:

- Supporting further data collection and reporting on the use, flows and waste of farm materials. This will improve accuracy of information and fill gaps on materials subject to some uncertainty, such as food loss and waste, or that have not already been quantified, such as wool waste.
- Supporting research and development of new and emerging circular solutions, with a focus on priority material and waste streams identified in this report. As data gaps on material flow volumes and emissions are addressed, priorities may shift.
- Integrating circular economy actions into wider farming transition programmes, including incentives for action for those that align to government goals.
- Supporting food waste redistribution from farms, connecting into systems being developed for other parts of the food system where appropriate.
- Considering the unique needs of the agricultural sector when designing circular economy systems and services for other sectors, for example synergies for collection of plastics or food waste.

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2 Glossary / Abbreviations table

Waste hierarchy	A framework ranking waste management practices from most to least environmentally friendly, prioritising waste prevention and reuse over recycling, recovery, and disposal.
Agriculture	The practice of farming, including cultivation of soil for crops and the rearing of livestock.
Crofting	A traditional Scottish system of small-scale farming and land tenure, combining agriculture with community and legal responsibilities.
Emissions factor (EF)	A value specifying greenhouse gas per unit of a given activity.
Circular economy	A model of production and consumption, which aims to keep existing materials and products in use as long as possible.
GHGs	Greenhouse gases
Haulm	The above-ground parts of a potato crop
SEPA	Scottish Environmental Protection Agency
ZWS	Zero Waste Scotland
AD	Anaerobic Digestion
CCP	Climate Change Plan
CCPu	Climate Change Plan Update
DEFRA	Department for Environment, Food and Rural Affairs (UK Government)
DESNZ	Department for Energy Security and Net Zero (UK Government)
REA	Rapid Evidence Assessment
N	Nitrogen
K_2O	Potassium
Ktoe	Kilotonnes of oil equivalent
P_2O_5	Phosphorous
DDGS	Dried distiller's grains with solubles
PAS	Pot ale syrup
SRUC	Scottish Rural University Consulting
AHDB	Agriculture and Horticulture Development Board
AD	Anaerobic digestion
CO_2e	Carbon dioxide equivalent
CXC	ClimateXChange
FAO	Food and Agriculture Organization
LULUCF	Land-Use, Land-Use Change, and Forestry

3 Introduction

3.1 Background and context

Scotland's climate change legislation sets a target date for net zero emissions of all greenhouse gases (GHGs) by 2045. To meet this target, the Scottish Government acknowledges that there is a need for rapid transformation across all sectors of economy and society. The Climate Change (Emissions Reduction Targets) (Scotland) Act 2019 provides that the Climate Change Plan (CCP) must set out the proposals and policies regarding the reduction of agricultural emissions; this includes circular economy initiatives. An updated plan was published in March 2026 (Scottish Government, 2026).

Circular economy (CE) activities also offer opportunities for farming in Scotland beyond GHG emissions reductions in agriculture. Circular actions contribute to reduced material use and improved resource efficiency, helping to address environmental impacts and improved climate resilience across product and material life cycles; the impacts include land-use, freshwater abstraction and pollution, air quality and biodiversity (WWF-UK, 2022). For farmers, resource use and waste have economic implications for their farm businesses – the rising cost of key farm inputs such as fuel, animal feed and fertilisers means there can be greater benefits from efficient use of these resources. Alongside these economic pressures, farmers are increasingly facing pressures from climate change impacts, such as more extreme or variable weather patterns – ensuring climate resilience of Scottish farming is critical.

Scotland has embedded circular economy principles into its legislative framework. The Circular Economy (Scotland) Act 2024 empowers ministers and local authorities to implement measures that increase reuse and recycling rates, modernise waste management, and reduce environmental impact. The Act also requires that Scottish Ministers publish a Circular Economy Strategy for Scotland (published March 2026) and make regulations to set circular economy targets in 2027.

Scotland's Circular Economy and Waste Route Map to 2030 sets out clear actions to deliver sustainable use of resources and progress a circular economy in Scotland and emphasises the importance of the food system and agriculture in this effort, particularly for reducing food waste. This ambition is mirrored in Scotland's vision to be a global leader in sustainable and regenerative agriculture.

This project will provide a source of evidence for further policy development around circular economy and agriculture in support of the CCP and the Scottish emissions reduction target.

3.2 Research aims

This research reviews the available knowledge and evidence about CE activity and principles in Scottish farming. The review examines the actions farmers and crofters in Scotland can take to contribute to a more circular economy, and in turn achieve an overall reduction in greenhouse gas emissions associated with the agriculture sector.

Key research questions:

- What are the opportunities to make Scottish agriculture more circular, considering key material and product streams and differences between sectors?
- What are examples of good practice in Scotland?
- What actions can farmers take to make activities more circular and move resource use up the waste hierarchy (for some priority product and resource streams)?
- What impacts will these actions have at the farm level (e.g. financial, climate or nature impacts)?
- What resources would a farmer need to make a change and what are the barriers?
- To what extent are the changes resilient to climate change?

3.3 Research scope and definitions

3.3.1 Material and product flows in scope

The research focused on material and product flows that are directly associated with farms and crofts in Scotland, excluding aquaculture. Wider value chain material flows that do not directly connect to the farms are also excluded (Figure 1). For example, food loss and waste which occur in a retail setting are largely not considered here. Influences from the wider value chain[1] – have been taken into account when considering the drivers and barriers for circular actions in agriculture.

When assessing impacts associated with material and product flows that directly connect to the farms, the wider lifecycle impacts have been taken into account where possible, for example emissions from manufacturing the materials as well as during use or application to land.

Figure 1: Scope of material and product flows for this research

3.3.2 Defining the circular economy

This research considers the scope for action across the waste hierarchy as a whole, including opportunities to reduce consumption. The Circular Economy (Scotland) Act 2024 prescribes a general waste hierarchy[2] prioritising waste prevention

[1] such as customer specifications or availability of recycled materials which shape on-farm material use and opportunities for farm wastes to be used in other parts of the value chain or economy

[2] The waste hierarchy used by Scottish Government can be viewed in Scotland's Circular Economy and Waste Route Map to 2030

followed by preparing for re-use, recycling, other recovery (including energy recovery) and lastly, disposal. Additionally, the UK government has defined a more nuanced waste hierarchy for food waste (Defra, 2024) which has been considered in some aspects of this study.

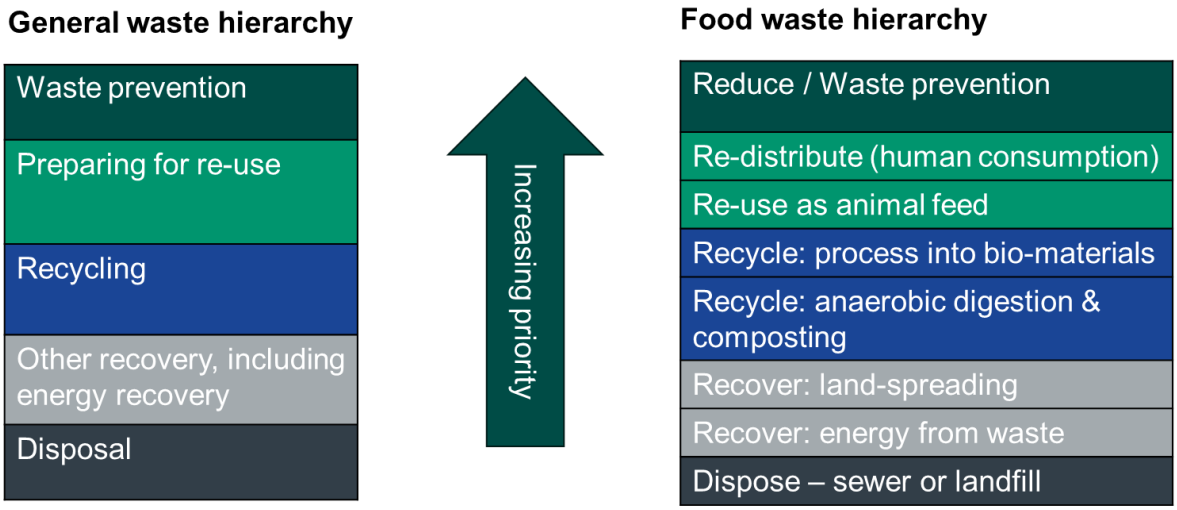

Figure 2: Waste hierarchies used within this research.

We have also been mindful of the definition of a circular economy as set out in the Circular Economy (Scotland) Act 2024 (See Appendix B for further details).

3.3.3 Issues and impacts considered

In line with the Circular Economy (Scotland) Act 2024 and requirements of the CCP, the research focused on GHG emissions impact and opportunities for mitigation. Economic implications for farmers and crofters have also been a key consideration. Additional considerations, such as wider environmental benefits and climate resilience have also been taken into account where possible but not quantified or assessed in detail.

This focus on emissions reduction has inevitably shaped the research findings. Other important aspects, such as security of supply, local community and consumer acceptability were outside the scope of this initial research. However, further analysis of these wider implications and potential opportunities will be needed to build a more complete understanding.

3.4 Methods and key limitations

A combination of research methods was used:

1. A rapid evidence assessment to gather and evaluate the academic literature and other relevant studies.
2. Quantification of material and product flows for Scottish agriculture and associated GHG emissions using various data sources (including national waste and GHG Inventory data where available, other data and relevant literature). A breakdown by key agriculture sectors was also created.

3. Prioritisation of key materials based primarily on GHG emissions, with consideration for other factors including economic impact and scope for improvement actions and policy (see Section 5 for further details of prioritisation approach).
4. Stakeholder engagement, via individual research interviews and a workshop to complement desk-research, quantification and prioritisation.
5. Assessment of GHG mitigation potential of key circular actions (methods varied by action – further details in Appendix E).

Full details of methods are provided in the relevant sections and Appendices.

There are limitations related to the methods:

- We set out to produce high-level assessment of material volumes and GHG emissions. For many materials and product streams the data available were relatively limited – across the different materials there were various challenges including completeness (e.g. gaps for some materials) and specificity (e.g. emissions data for similar products, not exact matches) and so assumptions (set out in Appendix E) were made to fill these gaps. Primary data were not collected. This may have limited the accuracy of the volume estimates and calculations for the prioritisation and GHG mitigation assessments. To reflect confidence in input data, output values are presented as rounded values.
- Due to the diversity of material and product streams, we used data from multiple sources, which reduces comparability across materials and products – efforts were made to use best available data sets. All data sources and any significant limitations are listed in Appendix D.

4 Material and product streams in Scottish agriculture

4.1 Overview of research findings

Research findings show the quantities of material and products flows for Scottish agriculture, their relative GHG emissions (total for Scotland and intensity by weight), key characteristics and sources, and the variations across the key agricultural sectors in Scotland.

4.1.1 Summary of material and product streams

Table 2 shows the main material and product flows related to Scottish agriculture with ranking by volume (tonnes) and GHG emissions, showing information on destinations where data was available or evidence allowed for well-informed assumptions to be made.

By quantity, several flows related to livestock farming - slurry, manure and feed - ranked most highly. Crop wastes (straw and crop residues) and food loss and waste were also significant in terms of quantities, together with fuel and fertilisers.

By GHG rank (total emissions), fuel and synthetic fertilisers are higher than by quantity but otherwise the GHG ranking is fairly similar to the quantity ranking (for those items for which data is available) with slurry, manure and feed all ranking highly.

Table 2: Main material and product flows in Scottish agriculture with GHG emissions, ranked (1 = highest volume or emissions)

Material/product	Flow type	Destination/use	Quantity (tonnes/yr)	Rank quantity	GHG emissions total for Scotland (tCO2e/yr)	Rank GHGs	GHG emissions intensity (per tonne)
Farmyard Manure	Waste	Land	7,400,000	1	383,000	5	52
Feed (grass and straw)	Input	n/a	6,250,000	2	No data	n/a	No data
Slurry	Waste	Land	5,180,000	3	268,000	7	52
Feed (local)	Input	n/a	1,530,000	4	285,000	6	186
Straw and crop residues	Waste	Other uses	914,000	5	0	25	No data
Straw and crop residues	Waste	To land	432,000	6	No data	n/a	No data
Straw and crop residues	Waste	Animal feed	380,000	7	0	25	No data
Total food loss	Waste	All destinations	354,000	8	647,000	3	1,830
Straw and crop residues	Waste	Unused	294,000	9	No data	n/a	No data
Fuel (tonne oil equivalent)	Input	n/a	242,000	10	747,000	2	3,088
Farmyard Manure	Waste	AD	216,000	11	No data	n/a	No data
Feed (imported)	Input	n/a	186,000	12	34,600	11	186
Slurry	Waste	AD	151,000	13	No data	n/a	No data
Synthetic N	Input	n/a	114,000	14	847,000	1	7,426
Synthetic K (K2O)	Input	n/a	51,000	15	21,100	12	414
Peat	Input	n/a	45,600	16	80,600	9	1,767
Other growing media	Input	n/a	41,100	17	298	22	7
Chemical wastes	Waste	Disposal and recycling	37,400	18	448,000	4	11,995
Synthetic P (P2O5)	Input	n/a	29,000	19	15,700	15	542
Plastic wastes	Waste	Disposal and recycling	24,000	20	76,400	10 b	3,179
Other organic fertiliser	Input	n/a	9,870	21	97,000	8	9,828
Undifferentiated materials	Waste	Disposal	4,500	22	1,250	19	277
Metallic wastes	Waste	Recycled	4,480	23	17,100	13	3,829
Discarded vehicles	Waste	Recycled	3,870	24	18	24	5
Used oils	Waste	Disposal/recovery	3,380	25	15,600	6	4,620
Pesticide	Input	n/a	1,350	26	16,100	14	11,988

Material/product	Flow type	Destination/use	Quantity (tonnes/yr)	Rank quantity	GHG emissions total for Scotland (tCO2e/yr)	Rank GHGs	GHG emissions intensity (per tonne)
Rubber wastes	Waste	Recovery (energy)	816	27	2,730	18	3,339
Paper and cardboard wastes	Waste	Recycled	764	28	988	20	1,293
Wood wastes	Waste	Recovery/recycling	631	29	173	23	274
Glass wastes	Waste	Disposal and recycling	615	30	3,790	17	6,166
Discarded equipment	Waste	Recycled	250	31	871	21	3,484

Notes on exclusions:

- Outputs of useable/saleable products are excluded from the analysis as these are not deemed opportunities for circular action. If the outputs of agriculture are wasted at another point in the value chain these are deemed outside of scope of this study. We also deemed that alternative uses (e.g. higher value use) of products and materials that are not waste or surplus are outside scope.
- A few materials could not be quantified due to lack of data or because project constraints did now allow – these were:
    - Medicines/veterinary products
    - Electricity use
    - Water use
    - Carcass losses – deemed outside scope as loss occurs at abattoir, although this is taken account of to a certain extent in the food loss data.
    - Wool waste – several stakeholders and media articles indicated that wool waste is a significant issue in Scotland but no data on volume / scale of the issue was found.
- GHG emissions for some materials could not be calculated for multiple waste flows because data was unavailable on the disposal routes or other assumptions. Where possible, emissions associated with both the disposal of waste materials and primary production were included. This was not possible for all materials, for example it was not feasible for agricultural machinery, as the typical product lifetime was unknown and therefore attribution of emissions to one year was not feasible.

4.2 Material and product summaries

The main materials and product flows that are relevant for Scottish agriculture are listed below in Table 3, and their key characteristics, taking into consideration evidence from the literature review, data analysis above and any relevant stakeholder insights from the interviews and workshop that are set out in more detail in Appendices A, C, and D.

Table 3. Main material and product streams in Scottish agriculture and a description of their characteristics

Material / product	Description
Slurry and manure	Excrement from livestock collected on farms, excluding that directly deposited onto land by grazing livestock.
Livestock feed	A combination of grassland grazing, silage made from harvested grass/forage crops, straw and supplementary feeds (either grown on the farm, bought in from local sources or imported).
Fertilisers and pesticides	Synthetic nitrogen, phosphorous and potassium fertilisers and manufactured plant protection products.
Straw and crop residues	All the parts of crops which are not edible or the primary product, for example cereal straw or fruit and vegetable leaves and stalks (such as carrot tops) and potato leaves and stalks.
Food loss and waste	Arising on farm, including in-field waste such as unharvested products, milk spilt during milking, out graded products and post-harvest wastes such as rejected on unsold products.
Plastics	Plastic silage wrap, flexible plastic used in horticulture and plastic containers and bags from agricultural chemicals and inputs.
Machinery and equipment	End of life vehicles primarily with some other equipment.
Chemicals	Primarily sheep dip and unused pesticides.
Fuel	Mostly used in vehicles and other machinery.
Horticultural growing media	Including peat-based materials, wood and bark chips, coconut fibre (coir), compost, spent mushroom compost, and mineral based substrates.
Other wastes	Less specific to agriculture, including glass, metallic wastes, mixed and undifferentiated materials, rubber wastes, used oils, and wood wastes.

4.3 Agriculture Sector Differences

Material and product flows set out in Table 2 were broken down to show quantity and associated GHG emissions for each of five key farming sectors in Scotland (for method see Appendix D).

Table 4 shows the top material and product flows across the five key sectors by quantity and GHGs emissions. Whilst the significance of different material and product flows varies across farming sectors to a certain extent, many of the same materials appear in each sector, except for manure and slurry which is an output from the livestock sectors only.

Much of the manure and slurry are already applied as a fertiliser to land. To avoid double counting, this is not shown as an input to arable and horticulture.

Some key themes come out which are relevant across all:

- The flow of nutrients in feed; manure and slurry; fertilisers and crop residues and food loss are most significant across all sectors (some nutrients arise in one sector and flow into another e.g. manure and slurry use in crop production).
- Smaller flows of problematic materials, such as plastics and chemicals also happen across sectors (noting the distribution across sectors is subject to some uncertainty).

Some notable characteristics for specific sectors:

- Beef and dairy: key inputs of feed and fertilisers are significant in terms of quantity and emissions, as is food loss – the emissions are particularly high.
- Sheep: despite grazing, supplementary feeds are significant, alongside fertilisers, as key inputs. Food loss is also significant in terms of quantity and emissions.
- Arable: Whilst much straw and crop residues are used for various purposes, the unused portion is still the second highest material flow, based on the data used here – although there is some uncertainty about the quantity of surplus straw in practice, as farmers would not usually collect straw without a planned use and if not collected, it is likely left on the land providing benefits. Food loss is also significant for this sector. Chemical waste appears high, but there is some uncertainty over the method of allocating to the sector. Fertilisers are the key input and emissions source.
- Horticulture: Peat-based growing media stands out with the highest emissions, along with food loss and waste.

There are similarities between sectors which make it possible to make some assumptions about other sectors. Pigs and poultry, similarly to dairy will generally have significant volumes of manure and slurry, and also consume large quantities of non-grass feed. Similar to other sectors they may generate some plastic wastes from feed packaging. Food loss and waste is likely to be similar to other livestock sectors.

Table 4: Overview of top material and product flows by quantity and by GHG emissions for each sector

BEEF		DAIRY		SHEEP		HORTICULTURE		ARABLE	
Tonnes	**GHGs**	**Tonnes**	**GHGs**	**Tonnes**	**GHGs**	**Tonnes**	**GHGs**	**Tonnes**	**GHGs**
1. Manure 2. Slurry 3. Feed (local) 4. Feed (import) 5. Food loss 6. Fertilisers 7. Chemical wastes 8. Plastic wastes	1. Nitrogen fertiliser 2. Food loss 3. Manure 4. Slurry 5. Feed (local) 6. Chemical wastes 7. Other organic N fertiliser 8. Plastic wastes	1. Slurry 2. Manure 3. Feed (local) 4. Food loss 5. Feed (import) 6. Fertiliser 7. Chemical wastes 8. Plastic wastes	1. Feed (local) 2. Feed (Import) 3. Manure 4. Food loss 5. Slurry 6. Nitrogen fertiliser 7. Chemical wastes 8. Other organic N fertiliser 9. Plastic wastes	1. Feed (local) 2. Manure 3. Slurry 4. Fertilisers 5. Feed (import) 6. Food loss 7. Chemical wastes 8. Plastic wastes	1. Feed (local) 2. Feed (Import) 3. Nitrogen fertiliser 4. Food loss 5. Chemical wastes 6. Manure 7. Slurry 8. Other organic N fertiliser 9. Plastic wastes	1. Straw and residues 2. Food loss 3. Peat growing media 4. Other growing media 5. Fertilisers 6. Chemical wastes	1. Peat growing media 2. Chemical wastes 3. Food loss 4. Nitrogen fertiliser 5. Plastic wastes	1. Straw and residues (used) 2. Straw and residues (unused) 3. Food loss 4. Fertilisers 5. Chemical wastes 6. Plastic wastes	1. Nitrogen fertiliser 2. Chemical wastes 3. Food loss 4. Other organic N fertiliser 5. Plastic wastes 6. Pesticide

5 Actions for priority material and product streams

5.1 Rationale for prioritisation

We prioritised four key product and material flows for further research into circular options on-farm based on a multi-step process set out in Figure 3.

This process was applied utilising the results of the assessment of quantities and GHG emissions set out in Section 4 above as the first step and then a qualitative analysis was on desk research and the knowledge of the project and steering group. Consideration was given to whether specialist research was already underway into a specific opportunity, or existing or planned policy was already focused on any of the materials. For detailed results of the prioritisation see Appendix D.

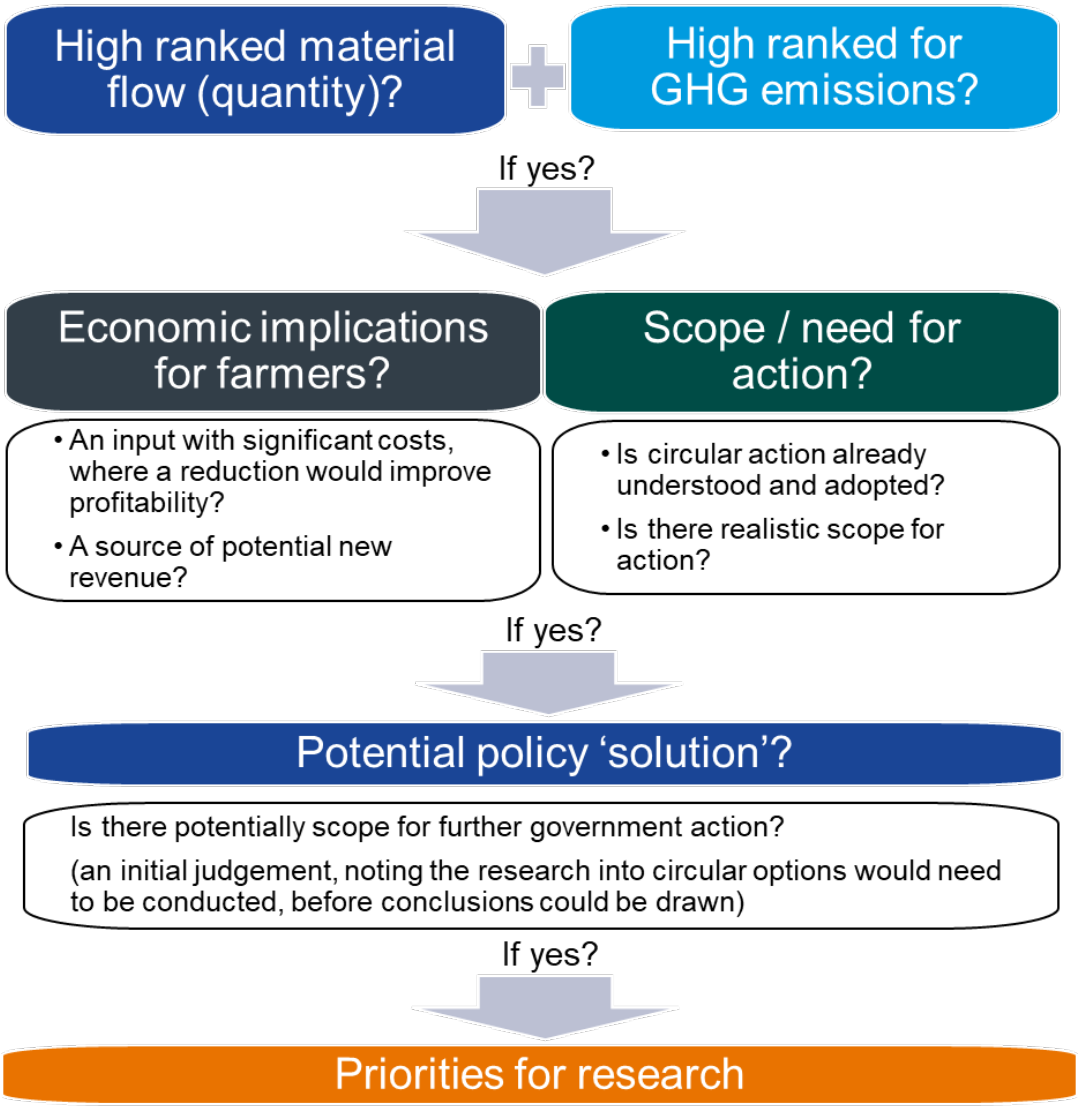

Figure 3: Prioritisation process for material and product streams

Four key product and material streams were prioritised for further research:

1. **Livestock feed, excluding grass and straw:** a key input cost for livestock farmers, for which policy has focused on efficiency improvements. Looking at this issue from a circular economy perspective may yield new opportunities.
2. **Food loss and waste:** this scored highly on all criteria and is a priority in general, not just on farms, for Scottish Government, with potential additional food security benefits. The Circular Economy Strategy also includes 'The Food System' as a priority sector.
3. **Straw and crop residues:** whilst some straw and crop residues are already utilised, the input data show that there is a significant portion still unused which could be a potential source of additional income for farmers. Whilst there was some uncertainty over the availability of this unused portion in practice, straw and crop residues was felt to warrant further exploration due to multiple potential uses.
4. **Plastic wastes:** a significant source of GHG emissions, and difficult for farmers to deal with: whilst plastics recycling is well established for other sectors the types of plastic waste and the unavoidable contamination means that services for farmers are less available. Alternative solutions across the waste hierarchy are considered a current knowledge and research gap. Plastics also create additional problems through environmental and food chain contamination, so tackling this issue brings potential for additional benefits.

Other key areas which are significant but were not prioritised for further research in this study:

1. **Slurry and manures:** management is a key part of existing Scottish Government policy, regulations and farm support. Whilst there is scope for improvement, the solutions are well known and supported through other ongoing research programmes, and so it was felt further research was not a priority for this project.
2. **Fertilisers:** practices to ensure efficient use of fertiliser and more efficient use of slurry and manure as a circular source of nutrients are already commonplace and well addressed in Scottish Government policy, support for farmers and through other ongoing research programmes. Additional research was deemed not a priority for this project.
3. **Peat-based growing media**: CXC is already supporting a research study focused on opportunities for alternatives for peat growing media in Scottish horticulture (Macdonald and Everett, 2026).

5.1.1 Case study: Sustainable and regenerative agriculture: code of practice

In June 2025 the Scottish Government published the 'Sustainable and regenerative agriculture: code of practice'. This was a requirement of the Agriculture and Rural Communities (Scotland) Act 2024 and will be a key source of information for farmers looking to take forward climate and nature friendly actions, linked to the Future Support Framework. Many of the circular economy actions on-farm relate to nutrient use and cycling in agriculture. Effective use and cycling of nutrients and soil health are a key aspect of

regenerative agriculture. This more recent adoption of the code of practice can play a key role in supporting circularity of nutrient flows and resource use within agricultural systems.

The code aims to establish common, evidence-based standards for good practice and to encourage continuous improvement and development. The key purpose is to ensure a balance between producing high quality food in an economically and environmentally sustainable way. It also provides a selection of voluntary Management Actions or Measures, which detail individual sustainable or regenerative practices, how these could be implemented and how they can provide climate, nature and business benefits.

5.1.2 Implementation

The Code is not a requirement and does not create any legal obligations. The Scottish Government recognises there may be an overlap with some of the management actions and measures described in the code and funding available via the Future Support Framework.

Farming support in Scotland is evolving. Some funding which is available in the short to medium term will support circularity in agriculture systems, particularly in relation to efficient resource use and improving soils. The Code lays the basis for further circular actions to be supported.

The Code refers to five regenerative principles – we have set out here their relevance for circular economy.

Table 5: Five regenerative principles set out in the Code.

Principle and code definition	Relevance for circular economy
Minimise Soil Disturbance: This involves practices like no-till or reduced tillage, which helps preserve soil structure, reduce erosion, and maintain a healthy soil ecosystem.	No- till and reduced tillage may **reduce** fuel usage and improving soil health may **reduce** the need for chemical pesticide and fertiliser applications.
Maximise Crop Diversity: Cultivating a variety of crops, including cover crops, intercropping, and crop rotation, promotes biodiversity, improves nutrient cycles, and enhances resilience to pests and diseases.	Enhanced resilience to pests and diseases, along with improved nutrient cycles may **reduce** the need for synthetic fertilisers and pesticides.
Keep Soil Covered: Maintaining a cover of plant material, either through cover crops or crop residues, helps protect the soil from erosion, improves soil moisture, and enhances soil health.	Crop residues are **reused**. Improved soil health and the input of nutrients from cover crops and residues may result in **reduced** synthetic fertiliser needs.
Maintain Living Roots: Keeping roots in the soil year-round, through practices like cover cropping, improves soil structure, increases organic matter, and enhances nutrient availability.	Enhanced organic matter and nutrient availability may **reduce** synthetic fertiliser input needs.
Integrate Livestock: Integrating livestock into the farming system can improve soil health, promote nutrient cycling, and help with weed and pest control.	Nutrients in animal excreta are **reused**, adding nutrients for growing crops / grass, **reducing** synthetic fertiliser input needs, and control of weeds and pesticides may **reduce** pesticide input needs.

5.2 Options for action

For each of the four priority material and product streams we identified potential examples of circular actions for farms through desk research and via stakeholder consultation. Actions are summarised here, and followed by a comparative evaluation of some of the key options for each of the four materials and product streams. For the options evaluation we calculated the potential impacts of the actions identified above both on the quantity of the material and on the emissions associated with these materials. The results are presented in Table 6.

We selected some key actions for assessment based on the following criteria:

- Relevance and feasibility for Scottish agriculture, including relevance to different sectors
- Examples across the waste hierarchy levels
- Feasibility of calculation.

It should be noted that, due to the complexity of agricultural systems and of implementing circular economy measures, as well as the broad range of actions we have investigated, the results presented here are only indicative. Furthermore, implementing any of the actions is likely to impact the implementation of another action, for example if more straw is used in production of bio-based materials there may be less available for use as livestock feed. This is again the result of the complex nature of making agriculture more circular. These action interactions were not considered in the results presented and so the emissions reductions are not cumulative.

We found that the circular options for the four material and product streams vary in terms of their feasibility and readiness for deployment; and also the scale of emissions mitigation they could potentially deliver and which location and emissions inventory category the mitigation relates to. Some also have potential to deliver co-benefits such as economic benefit for farmers, or additional environmental benefits such as reduced environmental contamination or climate resilience. An overview of these is provided below and summarised in Table 6.

Further detail on methods can be found in Appendix D.

5.2.1 Livestock feed

5.2.1.1 Circular actions for livestock feed

Making livestock feed more circular primarily relies on reducing total feed demand, and displacing imported feed inputs with surplus or waste derived feeds. Creating resilient local feed supply chains can also be beneficial, cutting fuel use for transport.

The Scotch Whisky industry generates large quantities of co-products, specifically draff and pot ale, which are increasingly viewed as vital components of a circular economy. Historically, these materials were a primary source of animal feed; however, their use declined by 57% between 2012 and 2019 as government incentives shifted focus toward renewable bio-energy production. Utilising these co-products for feed – either in their fresh state or processed into pot ale syrup (PAS) and dried distiller grains with solubles (DDGS) – presents a significant environmental advantage, as they offer medium-to-high protein

content that helps close the UK's feed self-sufficiency gap. Whether these by-products are used in energy production or in livestock feed is a significant trade-off in this action with some conflicting evidence on which is more beneficial (Duffy et al., 2023; Saget et al., 2022; Gandy and Hinton, 2018).

Gandy and Hinton (2018) concluded that using distillery/brewery by-products in energy production had a better climate impact than using it for livestock feed when they excluded liquid by-products and so the energy required to dry it. However, more recent studies, found deforestation resulting from imported feeds leads to greater emissions than using the by-product as a local feed source (Duffy et al., 2023; Saget et al., 2022). The impact of this action will vary in these modelled studies depending on multiple variables including, the geographical scope considered (local vs. global), the types of by-product (dry grains vs. liquids), distances and infrastructure between brewery/distillery, feed processing, and farms.

Extending the grazing period – keeping cattle at pasture for longer parts of the year – reduces dependence on manufactured and imported feeds by maximising utilisation of locally grown grass. This option leverages existing pasture resources and widely used grazing systems in Scotland, increasing circularity by reducing reliance on external feed inputs. It is technically feasible with good grassland management (e.g., rotational grazing, forage planning) (Farm Zero C, n.d.) and several sources indicate it is effective in reducing feed requirements In Ireland. Cahill et al (2025) found that grazing extended by 60 days increase grazed grass utilisation and milk and milk solids production, reducing supplementary feed requirements in dairy herds with savings of around 2 Euros per day depending on the season (Farm Zero C, n.d.). Teagasc (2021) reported that better grassland management and shorter grazing rotations can increase grass growth, leading to additional grass utilisation and increased income of around Euro 100 or Euro 175 per hectare for beef and dairy farmers respectively. Fielding (2022) highlighted that rotational grazing can extend the annual grazing period, reducing the need for straw and feed production or purchasing.

Additional benefits for animal health and reduced need for pasture reseeding could also bring productivity benefits and reduce resource requirements. Weaknesses include weather dependency, especially in wetter/colder seasons common in Scotland, which may limit grazing extension and increase soil damage risk during wet periods. Ensuring sufficient high-quality forage into autumn/winter may require investments in pasture species mixes and stock management. Scottish Rural University Consulting (SRUC) have provided guidance on different approaches to outwintering and the topic has been discussed on Farm Advisory Service (FAS) podcasts (SRUC, 2022; FAS, n.d.).

Genetic selection and performance improvement aimed at enhancing feed efficiency is a long-term circular approach that can reduce the total feed required per unit of beef produced. Numerous studies demonstrate moderate heritability for traits such as residual feed intake (RFI), indicating that genetic selection can gradually produce cattle that require less feed for the same growth performance, lowering feed costs and farm GHG footprints. Research programmes have developed genomic tools and selection indices that help breeders incorporate feed efficiency traits into breeding objectives. While these feed indices are more advanced in dairy farming (e.g. Feed Advantage and Maintenance Index), research is ongoing to publish similar indices for beef cattle such as through AHDB's National Beef Evaluations (AHDB, n.d.).

Lower feed cost for farmers is potentially an economic benefit across any action that aims to reduce consumption or waste of animal feed. However, there are also other factors to consider. With novel actions, such as insect feed, where there are limited real-life examples to base analysis on, the economic impact is less clear-cut. Evidence on the potential economic impacts of insect feed are mixed and depend on a variety of factors including feedstock for insect rearing and scale of supply/demand (Gao *et al.*, 2024; Jensen et al., 2021; DEFRA, 2025).

Of the actions discussed here, extending the grazing period and using distillery/brewery by-product are more short-term, compared to genetic improvements in beef and insect protein which due to various barriers are longer term solutions.

5.2.1.2 Livestock feed circular options evaluation

Livestock feed options fall into two key categories – reducing the feed requirements, through measures which improve feed-use efficiency by animals and substitution of existing feed sources with circular options (such as the examples assessed here – spent grain from brewing or insects reared on food waste). We assessed likely GHG emissions reductions and other benefits for these four options (see Table 6).

Measures to increase feed use efficiency usually would achieve a GHG emissions saving by reducing inputs and their associated GHGs to the system. For genetic improvements, we found it would generate an emissions saving, as expected, but the predicted saving is relatively small. Efficiency measures also typically achieve a cost saving for farmers, due to lower feed costs per output. In the Scottish dairy sector, genetic improvement has a much greater current uptake rate than the beef sector, and so this action has greatest potential for impact by expanding uptake in the beef sector (Jenkins et al., 2025). Additional environmental benefits are unlikely as the product system is largely unchanged. Genetic improvements are emerging but may be slow to be adopted across the sector.

Substitution of feed for alternative circular feeds comes with a lot of uncertainty in terms of emissions savings: there are diverse feeds currently in use but data on emissions from alternatives is limited. For brewery by-products, a well-established local source of feed, a moderate emissions saving is likely (around 18,000 tCO_2e per year), whereas for insect-based feed it is less clear. Whilst there is potential for insects as a livestock feed source with relatively low emissions, a recent study by Defra (2025) indicates emissions are higher than many other feed sources). This study found that, per kilogram of protein, soybean meal caused 2.23 $kgCO_2e$, compared to 12.9, 16.0, and 30.2 $kgCO_2e$ from insect meal from food waste, from chicken manure, and traditional feed, respectively. There may also be differences in terms of environmental co-benefits: for brewery by-products, there are likely limited environmental co-benefits whereas with insect-meal, the by-product from insect rearing may provide organic fertiliser, with potential soil health benefits and potential to reduce emissions by substituting for synthetic fertilisers.

The emissions mitigation impact of extended grazing is highest of the options we assessed (at around 37,000 tCO_2e). There may be economic benefit due to reduced feed costs, although there is potential for costs associated with additional grassland management. Wider environmental co-benefits would depend on the grassland management approach – with regenerative or ecologically sensitive management practices there may be soil and biodiversity benefits, but with intensive grazing there would not.

5.2.2 Straws and other crop residues

5.2.2.1 Circular actions for straw and residues

Scottish arable and mixed farms generate substantial quantities of straw and other crop residues, primarily from barley, wheat and oats with smaller amounts of potato haulms and vegetable and fruit crop residues, such as carrot tops. New technologies may provide opportunities for these materials to have their value increased. However, the volume of straw available to alternative circular uses is constrained by established demands in livestock bedding and use for retaining residues on cultivated land to maintain soil organic matter, structure, and erosion protection. Availability of straw at specific locations and times is likely to vary depending on these additional demands. Circular actions for this material must be evaluated with these considerations in mind. For example, if straw starts to be funnelled into one of the actions discussed below and not into bedding, a different stream will have to replace straw that once went to bedding. This shift will have consequences that may off-set any benefit from the action the straw is now used for.

There are a variety of options for chemical extraction and biorefining of straw and residues, to yield high-value materials, such as bioethanol, organic acids, and other chemicals (Stewart, Undated). There is technical potential for these processes but most of the evidence identified came from laboratory or demonstration-scale systems. A Scottish example includes CelluComp who extract nano-cellulose fibres from root vegetables (CelluComp, n.d.). While the European example Inbicon is a technology solution that converts plant dry matter (primarily wheat straw) to highly decarbonised biofuels and biochemicals (Zech et al., 2016).

Scottish Government is encouraging the emerging biorefining sector, which could utilise agricultural residues, by supporting conversion of Grangemouth refinery to biorefining (Majid A., 2025). As well as the novelty aspect of this action being a barrier (technologies and practices are relatively new and not yet widespread in Scotland) other issues may be high capital costs and general complexity of processes. Furthermore, while these high-value products likely offer the highest economic benefit to farmers, the uncertainty around price and market competition complicates this.

Conversion to bio-based materials for use in the construction industry, such as straw bale insulation and construction may provide long-term, stable carbon storage and thereby is an attractive option from a climate mitigation perspective (Bennett, 2022). Scottish case studies demonstrate feasibility of this option, for example, Strawbale Bothy built in Skye in 2017 from straw, wood, clay and lime and is currently used as a rented holiday cottage (Strawworks, n.d.). Uptake remains niche and limited by supply-chain coordination, quality standards, and market demands. The benefit to farmers is unclear as demand and costs are uncertain.

Using straw and crop residues in biochar production has a significant UK evidence base, with multiple field trials showing improvements in soil carbon, nutrient retention and yield response, amongst other impacts (UKCEH, 2024). An evidence gap in long-term, large-scale, commercial or real-life use cases leaves some uncertainty over this practice. It is worth noting that variability in impact is inherent to biochar production and use caused by time and temperature of production process, feedstock used, weather during application, soil type, and others. There may be a logistical barrier in connecting sources of straw with

processing facilities and then biochar with points of application. ClimateXChange is currently conducting research into the potential for biochar in a Scottish context, the results of which were not available to include in this report (Watkins, et al, 2026).

Another, technically-mature, circular action for straw and crop residues in Scotland is their use as a feedstock in anaerobic digestion (AD). There can be technical challenges in using straw as AD feedstock due to low biodegradability and often requiring pre-treatment or co-digestion.

5.2.2.2 Straws and residues options evaluation

There are multiple existing uses of straw and residues, meaning so solutions need to focus on the unused portion, but in reality, the picture is unlikely to be simple and influenced significantly by local supply and demand dynamics. When some straws and residues are diverted to a new use there is potential for an increased demand for a different material e.g. if the straw is used for horticulture, it may be less available for livestock bedding and feed, and so new materials are brought into replace these. e.g. saw dust or shavings, which are then not available for bioenergy production. There are complexities in this dynamic when attempting to calculate potential emissions mitigation potential. There are also uncertainties about emissions from different upcycling end uses – we did not find applicable publicly available data on the difference in emissions from chemicals and other materials derived from agricultural residues and so have not been able to estimate emissions from these options.

However, there are still useful options. Growing the bioeconomy in Scotland, utilising agricultural wastes and residues has potential to provide additional revenue for farmers. This arises from materials – such as straws – which currently have limited value but have new or increased uses in multiple sectors.

In farming, the need to increase soil organic matter may lead to increased demand for these materials for use on land, alongside increased demand from industry for raw materials. Biochar is seen as a good option for increasing soil carbon storage, more effectively than addition of fresh organic matter. This is because it creates a longer-term carbon store. However, emissions from production of the biochar have not been included in the assessment yet and so in real terms this option may be less favourable, depending on the production method used.

Stakeholders highlighted the potential benefit of a cascade-type approach, for example where a high-value chemical has been extracted, the remaining residue can then find a next use, such as composting or use as a bulk raw material.

Overall, Scottish agriculture produces vast quantities of straw and there are a range of both established and emerging options for its use in high value products, with clear climate and potential economic benefits. However, balancing these circular options with current uses of straw is essential to maximise benefits – it cannot be assumed that sufficient residues will be available for significant expansion of new emerging practices, such as biorefining, without giving consideration to other beneficial uses.

5.2.3 Food loss and waste

5.2.3.1 Circular actions for food loss and waste

In line with the food waste hierarchy, circular strategies should emphasise avoiding losses at source as a priority, followed by redistributing unavoidable surplus for human use, animal use and only after this considering disposal options, preferably generating energy and other useful by-products (DEFRA, 2024).

Improved on-farm storage, particularly through shared or cooperative facilities, offers a practical option to reduce food loss in Scotland's agricultural sector – preventing losses from occurring in the first place. Evidence suggests that globally a significant proportion of primary production losses occur due to inadequate temperature, moisture and pest control during storage, especially for fruit, vegetables and potatoes (FAO, 2019). In the UK WWF (2022) and WRAP (2021) highlight post-harvest product handling and storage as a cause of food loss and waste, alongside variations in demand and failure to meet market specification. Pre-harvest factors are also an issue, including localised conditions on farms, such as weather, and such as variety or breed selection, crop management, livestock and crop diseases.

Shared cold or controlled-environment storage hubs allow farms, including smaller holdings, to pool capital and operational costs, improving access to modern infrastructure without requiring individual investment. Scottish research highlights that improved storage can extend marketing windows, reduce spoilage, and support higher farm-gate prices, particularly in years with market disruption or climatic variability (SRUC, 2021). The main strengths of shared storage include reduced waste, improved supply chain resilience and alignment with circular economy objectives by maximising the value of food already produced. Trade-offs include transport to centralised facilities and ensuring storage does not incentivise over-production. Overall, shared storage can strengthen climate resilience by reducing loss during increasingly variable weather conditions.

Other technologies have potential to be deployed on farms to prevent food loss and waste occurring, for example in Scotland, dairy parlour technologies such as automated testers and sensor-based monitoring systems are increasingly applied to reduce milk loss at source (AHDB, 2017). Evidence from UK primary production indicates that milk losses arise from infrastructure and handling inefficiencies, with measurable losses occurring between the Parlor and bulk tank and additional rejections at processing, alongside losses associated with mastitis management and veterinary withdrawal periods (WRAP, 2021). Technologies including real-time milk flow sensors, automated teat-end detection, and inline quality monitoring support early detection of abnormal flows and contamination, improving hygiene and milk quality outcomes (Eastwood et al., 2019). However, high capital costs and training requirements can limit effectiveness without strong herd health and management practices (AHDB, 2017). When integrated effectively, these technologies improve resource efficiency and reduce emissions per litre of milk by avoiding indirect waste, supporting climate resilience in dairy systems (Poore and Nemecek, 2018; FAO, 2019).

General improvements in livestock health management and resource efficiency can reduce herd mortality, as shown at the Woodhead Farm[3].

Food redistribution networks such as FareShare's 'Surplus With Purpose' divert edible farm-level surplus to social and community organisations, reducing food waste and improving food security (FareShare, 2022; WRAP, 2021). This approach aligns with the food waste hierarchy by prioritising redistribution for human consumption over feed or energy recovery and supports circular food system models (European Commission, 2017; FAO, 2019; Ellen MacArthur Foundation, 2019). FareShare Scotland works with farmers in Scotland (with some previous government funding for aspects of their work) and estimate, based on their experience, that there is significant scope for further uptake for example in fruit and vegetable surplus, but detailed data on current uptake of food redistribution from farms in Scotland as a whole is not known (FareShare, n.d.).

Redistribution is particularly effective where food losses result from cosmetic standards, market timing mismatches, or logistical barriers, ensuring safe surplus food is consumed rather than wasted and avoiding unnecessary environmental impacts from production without consumption (FAO, 2019; Porter et al., 2018; Poore and Nemecek, 2018). Evidence indicates that redistribution, alongside improved measurement of loss drivers, is an important element of broader strategies to reduce on-farm food waste globally (FAO, 2019).

However, redistribution faces challenges at scale, including coordination between producers and rescue organisations, seasonal variability in surplus supply, and the need for robust food safety and traceability systems (Alexander and Smaje, 2008; European Commission, 2017; WRAP, 2021), and costs – farmers in Scotland suggested they would redistribute more, but it was not worth their while financially (Stakeholder Insights). As it does not address the causes of surplus generation, redistribution is most effective when combined with preventative measures such as improved storage, farm management, and market forecasting (FAO, 2019; Porter et al., 2018; WRAP, 2021).

Evidence was limited on the current practice and applicability of other options on the waste hierarchy for on-farm food waste in Scotland. WRAP (2021) indicate some surplus dairy is fed to livestock, for example at Woodhead farm. And our own data analysis, utilising data from Zero Waste Scotland (2022) showed that around 35% of post-harvest surplus of fruit and vegetable crop waste is already fed to livestock. Data on composting of on-farm wastes was not found.

Channelling on-farm food loss to AD may be an option in Scotland where facilities are located close to the source of food wastes. The feasibility would be closely tied to development of facilities for manure and slurry treatment, as well as development food waste collections from other parts of the food system and cannot be assessed as a stand-alone solution for on-farm food loss. We also found an evidence gap on whether there is any scope to prevent food loss and waste through more closely matching production volumes to market requirements, and so preventing overproduction and resulting waste.

[3] https://www.fas.scot/article/climate-change-focus-farm-woodhead-ayrshire/

5.2.3.2 Food loss and waste circular options evaluation

Assessment of key food loss circular options focused on a number of options to either prevent food loss and waste, or redistribute edible food surplus to feed people.

Prevention of food waste in the first place is preferable in the waste hierarchy. Whilst our assessment showed that when applied to Scottish agriculture, this had lower scope for emissions mitigation than redistribution of edible food waste from farms, this is a reflection of the smaller scope of the assessment which considered improved storage only. Other methods to prevent food waste, for example improvements in supply chain specifications and ordering practices, may also deliver benefits in Scotland, but happen largely off-farm as so the emissions associated with this were not captured in this study.

Both food waste prevention practices and food surplus redistribution have potential to deliver significant emissions reductions. Redistribution of surplus food and prevention of food waste both avoid the need for food production and will generally create wider environment co-benefits because all environmental impacts associated with primary production (for example pesticide use impacts on biodiversity, land-use, water pollution) are avoided. Economic benefits are also typical because farmers are getting revenue from the produce, although there may be costs associated with the technical solutions – storage facilities or sensor installation – to take into account to assess full costs and benefits.

With redistribution of surplus food from farms, the wider environmental co-benefits are unclear – there may be some emissions from transport, but these would vary depending on the distances travelled. Currently, this option would often cost a farmer more because of costs associated with harvesting, handling and transporting the goods, which would typically be donated, rather than generate revenue. Many redistribution channels provide food to people experiencing food insecurity – creating wider social benefit, aligned to one of the Scottish Government's First Minister's four priorities – tackling poverty.

All the options assessed are technically feasible, but not well established in Scotland with some barriers to uptake – costs to cover logistics and handling can prevent farmers and redistribution networks from rescuing more food. Upfront costs, knowledge and skills and other practical considerations may also limit uptake.

Overall, evidence suggests that the most effective pathway to more circular on-farm food systems combine prevention and redistribution. Priority actions should therefore focus on improved grain and crop storage to address losses at source, strengthened redistribution networks to manage unavoidable surplus for human consumption, and targeted investment in new dairy parlour equipment to reduce milk losses. Further research may highlight other specific technologies applicable for preventing food loss and waste in other cropping or livestock enterprises. Together, these measures maximise the value of food already produced, enhance resilience to climate and market variability, and deliver environmental and social benefits.

5.2.4 Agricultural Plastics

5.2.4.1 Circular actions for agricultural plastics

Types and uses of agricultural plastics vary greatly meaning actions that make this stream more circular have to be varied and specific. For example, actions suitable for plastic wrap

for silage bales are likely not suitable for pesticide containers due to them being made of different types of plastic, with different availability of processing facilities and potential end uses. Actions discussed here strive to cover the range of actions in the waste hierarchy and the variation inherent in this stream.

Reducing plastic use can cut costs for farms from purchase of plastics, such as silage wrap, which since 2022 may have increased due to the Plastic Packaging Tax[4], and by avoiding disposal or recycling costs.

On farm management measures to reduce and reuse plastic film crop covers achieved a reduction of around 20% at Jersey Royal (LEAF, 2022) – similar approaches could be feasible in Scottish horticulture.

One innovative approach being piloted in Scotland is BaleSafe preservative (a mix of food-grade preservatives and organic acids suppresses yeasts and moulds). This enables farmers to reduce use of plastic wrap for hay and haylage bales by allowing bales to be stored unwrapped or lightly covered, resulting in stable, high-nutrient bales that can be stored unwrapped under cover (Kelvin Cave Ltd, n.d.). While this can save on costs from plastic wrap it does introduce the cost of the preservative and application and how this compares to plastic is not known.

A system of intermediate bulk container (IBCs – containers used for transport of liquids in bulk primarily between business users) refurbishment could be introduced to enable pesticide container reuse. Facilities exist in Scotland for chemical IBCs to be safely reconditioned for reuse; a process which involves cleaning, pressure-testing, and refurbishment if required, to meet original safety standards. This circular approach keeps these IBCs in use for longer, reducing the volume of containers sent to landfill and cutting demand for new materials by extending life span through reconditioning (Perella M., 2024). Currently this practice is used in the chemical supply chain and does not yet seem to be deployed for farm chemical containers.

Increasing the level of recycling of agricultural plastics may be challenging due the different types (such as hard containers and flexible films) and contamination from things like soil or hazardous chemicals (EA, 2020). The Waste (Scotland) Regulations 2012 require businesses to separate plastics for recycling where collection services are reasonably available. Current recycling infrastructure in Scotland and the rest of the UK can handle plastic waste generated through agriculture to a certain extent (at specialist facilities), however the geographical scope may be fragmented or limited (Zero Waste Scotland, 2023). The low volume of plastics available for recycling on smaller farms may make collection logistics uneconomic. Legislation in England and Wales, which requires collection and recycling of plastics from households from 2027, may lead to wider changes in the infrastructure availability for flexible plastics recycling in the UK, but any new facilities are unlikely to be close to the majority of Scottish farms.

[4] The tax applies to plastic packaging produced in, or imported to, the UK that does not contain at least 30% recycled plastic – as of April 2025 the tax is ~£223.69 per tonne.

Aside from plastic film and containers which become waste on farms, some single use plastic items such crates and packaging for fruits and vegetables, originate on farms but travel along the supply chain to be a challenge for other businesses. Several actions relating to agri-food chain plastics were identified. Reusable crates are relatively well established in retail now, such as from Sainsbury's and packaging manufacturer Schoeller Allibert (IPL Schoeller, 2014) and the pooled, reusable-container service operated by IFCO Systems targeted to fruit and vegetable producers supplying UK supermarkets (IFCO, 2024) where containers are cleaned, inspected and redistributed. These actions can reduce virgin plastic demand and waste, but require coordinated procurement, standardisation and reliable cleaning/inspection infrastructure.

Solutions for small sources of agricultural plastics are also available: several non-plastic options for plastic tree guards are available or being trialled including cardboard, surplus or unsold wool, cornstarch, pine resin and reusable mesh (Woodland Trust, 2022; Protect Earth, Undated). A Woodland Trust study (2022) found durability was found to be a challenge for cardboard, with pine and wool options faring better, and showed that with careful handling guards could be reused up to three times. Plastic twine replacements include sisal twine (Innovative Farmers, 2024) and wool (Drury and Crotty, 2022).

As described in Section 8.1.98.1.9 data on use of different types on plastics on farms could not be sourced. This means that while the evaluation of actions here strived to cover the range of types and uses of plastics, it is difficult to distinguish which are most important for farms. This is a barrier in evaluating and prioritising actions here. To better understand how to tackle this significant material stream, a breakdown by plastic type is essential. Another gap, perhaps less essential to fill, is a breakdown in plastic use and waste by geography; to understand what regions are under-served and potential 'hot-spots'.

5.2.4.2 Plastic wastes options evaluation

Options for reduced use of plastic, reuse of farm plastics, and recycling were evaluated.

Innovative solutions such as BaleSafe, which reduce the need for plastic silage wrap, are experimental and feasibility of widespread adoption is uncertain so, whilst it may contribute to GHG emissions reduction, it is not considered a feasible option for widespread adoption in the short-term.

The best feasible option of those assessed for plastic wastes appears to be increasing the practice of re-using plastic crop covers and containers – this achieves the highest GHG mitigation and offers potential for financial savings as farmers need to buy fewer plastic covers and pay less disposal costs for either material. Wider environmental benefits may derive from reduced plastic production and transport. This option is relatively straight forward to adopt but may require significant behaviour shift.

Increasing recycling may also deliver emissions reductions but is limited by the constrained availability of services – we found some examples, but they are not available to all Scottish farms and crofts. Economic and environmental benefits are unclear, depending on costs of services and how carefully the recycling process is managed.

Overall, solutions which avoid and reduce the need for farming to use plastics, particularly single or short-term use plastics, are not well established. However, prioritising these could deliver emissions savings, cost savings and wider environmental benefits including reduced

plastics contamination of soils, water courses and the food chain. Legislation is driving forward solutions to single use plastic across the wider economy, but the needs of agriculture are slightly different so additional efforts by the sector and government are likely to be needed to develop and adopt of solutions in farming.

5.2.5 Cross cutting actions

As achieving circularity requires whole-system changes, it is important to cover cross-cutting actions that are not isolated to one material stream or sector.

A recent study on farmers' decision-making and behaviours towards adopting circular actions in agriculture highlighted that farmers have positive attitudes to a circular approach (Evans, 2025). Despite this, the need for intervention to enhance uptake of circular actions was also identified. Both knowledge (i.e. awareness and understanding of circular actions) and skills (i.e. being equipped to implement the actions) were identified as barriers. Inclusion of education on the full range of circular farm actions and their relevance for Scottish farmers could be integrated into existing farming advice programmes. Given the alignment of many circular actions on farms with sustainable and regenerative farming practices which are already addressed in farming advice programmes, it may not be necessary to label actions as 'circular' actions. The focus could be on identifying and filling any gaps where circular actions are not already addressed in advice.

Increasing the uptake of broader agricultural transition actions set out in the Vision for Agriculture and Code for Practice for Sustainable and Regenerative Agriculture, which improve resource efficiency, improve nutrient cycling and reduce emissions, is another important cross-cutting action. Circular actions for specific materials do not take place in isolation on farms but need to form part of a whole farm management approach which is already being encouraged in Scottish agriculture. More inclusion of circular actions in farming advice programmes, including training and awareness raising as part of the whole farm management approach, could help increase resource efficiency and circular actions across a variety of farm types and materials.

Better data is also needed on the generation of wastes on farm and the opportunities for reducing inputs and material use, to help farmers better prioritise action and also policy makers prioritise policy or practical support for actions.

5.2.6 Summary evaluation of circular actions

Table 6 summarises the assessment of GHG emissions savings associated with each of the circular actions proposed, the relevance to different categories in the national GHG inventory, other benefits (e.g., economic or environmental) and the feasibility of implementation.

It should be noted in relation to the assessments that, due to limitations in data availability and project constraints, these assessments are relatively high level, intended only to give a general indication of scale of potential emissions savings. A more thorough life-cycle assessment would be needed to fully understand the scale and type of emissions (e.g. inventory category) associated with these circular actions. As has been flagged above, there are multiple complexities associated with different options – most materials can be utilised in several beneficial circular actions, and yet the availability of materials is finite and a quantity for widespread uptake of all actions is unlikely be available.

In terms of GHG emissions, there is a wide range of emissions reduction potentials across materials and actions. These are addressed in order below.

5.2.6.1 Waste from food production and demand

Overall, actions that prevent food waste and reduce demand for food production, which can be a source of high emissions, deliver the greatest emissions reductions with the largest total mitigation potential coming from redistribution of edible on-farm food waste (~145,000 tCO_2e/yr), reflecting the potential for significant uptake. This action focuses on fruit, vegetables, and potatoes that would otherwise be wasted and reflects avoided emissions from food production, as less food would need to be produced. As these savings largely occur in supply chains, the emissions reductions are attributed to both Scotland (primarily the waste and agriculture inventory categories) and outside the Scottish inventory.

After food waste prevention, a series of straw-based biomaterial use and feed interventions rated highly in terms of emissions mitigation potential. However, it should be noted for both straw and use of surplus materials for livestock feed, the limitations in terms of supply in the face of competing demand for materials are potentially significant.

5.2.6.2 Straw-based actions

The second largest mitigation potential was identified for conversion of straw to biochar and application to soils, delivering around 101,000 tCO_2e/yr. This increase in soil carbon stock would occur entirely within Scotland but is not currently estimated for the Scottish (or UK) GHG inventory. A key limitation of our assessment was that emissions from biochar production were not able to be assessed, so in practice the mitigation potential of biochar may be lower – further assessment following forthcoming CXC research (CXC, in press) should be conducted.

A second straw-based action, using straw as a horticultural growing medium to replace peat, delivers around 16,000 tCO_2e/yr. This would be reflected in national GHG inventories for the countries where the peat is extracted, through decreased emissions from peat extraction (and associated degradation). There are several possible scenarios for former peat extraction sites – ceasing use of peat may cease expansion into new areas which would prevent emissions, or may lead to abandonment of existing exposed peat areas with continued emissions. In addition, there may be peatland restoration or palludicultural use, both of which would reduce but not eliminate emissions. This leads to significant uncertainty over likely emissions.

5.2.6.3 Feed-related actions

Feed-related actions make a moderate but important contribution. Extending the grazing period for beef cattle was assessed as having emissions mitigation potential of around 37,000 tCO_2e/yr, the largest feed-related saving. Reuse of distillery and brewery by-products as animal feed delivers 18,021 tCO_2e/yr, while the mitigation potential for genetic improvements in beef cattle is around 5,000 tCO_2e/yr. All feed measures reduce demand for feed inputs (from local and imported sources) and therefore have potential to create emissions reductions both within Scotland and internationally.

5.2.6.4 Agricultural plastics

The circular actions assessed for agricultural plastics all showed emissions mitigation potential based on our high-level assessment, with options for re-use (a combination of crop cover and container reuse, both of which reduce need for primary plastic production and disposal of waste plastic) showing the biggest mitigation potential for plastics of around 62,000 tCO_2e/yr.

5.2.7 Conclusion

Alongside GHG emissions, the evaluation also considered economic benefit, environmental co-benefits and feasibility to increase uptake. Results for each option are presented in Table 6. Extended cattle grazing is the only option assessed as having high feasibility, with economic benefits to farmers and some potential for GHG mitigation.

The wider environmental benefits are unclear, because they would vary a lot based on management practices but there is potential scope for biodiversity and water management benefits if conservation grazing practices where utilised. Options with medium feasibility, economic benefit and GHG emissions mitigation potential include using spent grains from breweries for livestock feed, preventing waste food through improved storage and reuse of plastic crop-covers and containers.

Table 6. Table summarising impact assessment results by material stream, action, and impact category

Material	Waste hierarchy	Action (for full assumptions see Appendix ?)*	Total emissions reduction for Scotland (tonnes CO_2e/yr)	Emissions reduction location	Climate mitigation potential				Outside inventory	Economic benefit	Environmental co-benefit	Feasibility to increase uptake
					Agri (Cat 3)	LULUCF (Cat 4)	Energy (Cat 1)	Waste (Cat 6)				
Feed	Reuse (animal feed)	Supplementing animal feed with brewery/distillery waste (assuming an increase in the amount of waste used as feed by 50% of the reduction in this stream since 2012)	18,000	Both Scotland and outside	likely mitigation	mitigation unlikely	mitigation unlikely	likely mitigation	Supply chain (upstream)	Benefit	Benefit not identified	Medium
	Reduce consumption	Genetic improvements in beef for feed efficiency to reduce feed demand by 0.03 t DM $animal^{-1}$ yr^{-1}	4,840	Both Scotland and outside	likely mitigation	mitigation unlikely	mitigation unlikely	mitigation unlikely	Supply chain (upstream)	Benefit	Benefit not identified	Low
	Reuse (animal feed)	UK-produced insect protein reared on food-waste as feed to meet 13% of total pig and poultry feed demand	-42,200	Both Scotland and outside	-	mitigation unlikely	mitigation unlikely	likely mitigation	Supply chain (upstream) – increase	Benefit not identified	Benefit	Low
	Reduce consumption	Extending grazing period for 50% of beef cattle population by 30 days (replacing bought feed with grass)	37,200	Both Scotland and outside	likely mitigation	likely mitigation	mitigation unlikely	mitigation unlikely	Supply chain (upstream)	Benefit	Unclear/multi-direction	High
Food loss	Prevent waste	Shared grain storage facilities to reduce loss from spoilage and contamination (reduces grain loss by 40%)	18,700	Both Scotland and outside	likely mitigation	mitigation unlikely	likely mitigation / mitigation unlikely[5]	likely mitigation	Waste (exports)	Benefit	Benefit	Medium
	Reuse/ redistribution	Saving 22% edible on-farm food waste of fruit and vegetables (from specification grade-outs and supply-demand mismatch) and redistributing in for human food	145,000	Both Scotland and outside	likely mitigation	mitigation unlikely	mitigation unlikely	likely mitigation	Waste (exports)	Unclear/ multi-direction	Benefit	Medium
	Prevent waste	New equipment (sensors/testing) in dairy parlours to prevent milk loss from spillage/contamination by 50%	13,000	Both Scotland and outside	mitigation unlikely	mitigation unlikely	mitigation unlikely	likely mitigation	Waste (exports)	Unclear/ multi-direction	Benefit	Medium
Plastic	Reduce consumption	BaleSafe: spray that prevents requirement to wrap bales in plastic: assumes a 20% reduction in farm plastic use	15,300	Both Scotland and outside	mitigation unlikely	mitigation unlikely	mitigation unlikely	likely mitigation	Supply chain (upstream) Waste (exports)	Unclear/ multi-direction	Benefit	Low
	Reuse	Refurbishment and re-use of crop-covers and containers leading to a 56% reduction in these plastics	62,700	Both Scotland and outside	mitigation unlikely	mitigation unlikely	mitigation unlikely	likely mitigation	Supply chain (upstream) Waste (exports)	Benefit	Benefit	Medium
	Recycle	Increase in plastic recycling based on ZWS report that reported 35% of farmers do not have plastic recycled	45,100	Both Scotland and outside	mitigation unlikely	mitigation unlikely	mitigation unlikely	likely mitigation	Supply chain (upstream) Waste (exports)	Unclear/ multi-direction	Unclear/multi-direction	Medium

[5] There was no literature identified that covered the emissions from powering small facilities on farm - there is likely a change in energy emissions, but it is unclear if this is positive, negative, or significant.

Material	Waste hierarchy	Action (for full assumptions see Appendix ?)*	Total emissions reduction for Scotland (tonnes CO_2e/yr)	Emissions reduction location	Climate mitigation potential				Outside inventory	Economic benefit	Environmental co-benefit	Feasibility to increase uptake
					Agri (Cat 3)	LULUCF (Cat 4)	Energy (Cat 1)	Waste (Cat 6)				
Straw	Recycle: biomaterial	Using straw as a horticultural growth medium, replacing peat by 80%	16,100	Scotland inventory	likely mitigation	mitigation unlikely	mitigation unlikely	likely mitigation	Waste (exports)	Unclear/ multi-direction	Benefit	Medium
	Recycle: biomaterial	Conversion of straw to biochar and applied to 50% of arable land (instead of retaining straw on soil)	101,000	Scotland inventory	likely mitigation	likely mitigation	mitigation unlikely	mitigation unlikely	-	Unclear/ multi-direction	Benefit	Low
	Recycle: biomaterial	Upcycle high value materials (e.g. chemicals, antioxidants)	Unclear	Both Scotland and outside					Supply chain (upstream)	Benefit	Unclear/multi-direction	Low
	Recycle: biomaterial	Upcycle bulk materials (e.g. construction materials)	Unclear	Both Scotland and outside					Supply chain (upstream)	Benefit	Unclear/multi-direction	Low

5.3 Challenges and barriers

Challenges or barriers to achieving circularity in Scottish agriculture vary depending on action, material stream, and the perspective (i.e. the farmer, Scottish Government, other sectors), but they can be broadly grouped into financial, regulatory, technical, information, and social. Several actions discussed in preceding sections would require significant capital investment from farmers, such as anaerobic digestors (Evans, 2025). Insect protein also faces financial barriers in becoming an established sector, although once established, costs may be lower for the implementation by the farmer.

The range of technical and logistical barriers include weather dependency (extending grazing), technological gaps (alternatives for silage wrap), and resources trade-offs (distillery/brewery by-product in livestock feed, straw/crop residues actions).

A significant logistical barrier relevant across many actions, and a barrier to circularity in general, is in connecting farms with each other, and with facilities to make use of the resources from these farms. According to the Scottish Agricultural Census there are around 31,000 smallholdings across Scotland, accounting for 65% of all farms but only 151,689 hectares or 3% of total farmed area (Scottish Government, 2024). While the quantity of any one material relevant to these farms may be limited, when aggregated, they likely account for non-trivial quantities. However, gathering and pooling resources across small farms which may be geographically dispersed may be challenging, offering a barrier to optimising circularity. Greater reporting on material streams of interest, and where they are generated, could help to identify where there may be hot-spots of materials that could be utilised.

Implementing more circular actions on farms may require a collaborative approach (for example collaborating with other farms or supply chain partners). While farmers are aware of this (Evans et al., 2025), it is considered difficult although the reason is unclear. It may be a lack of trust, a preference for independence, and viewing other farmers as competitors. Further work with farmers to unpack this issue could help enable more circular use of resources.

Whilst some farmers perceive circularity in agriculture to be common sense and a win-win solution offering multiple benefits, Evans et al (2025) identified knowledge and awareness, as well as the confidence to implement circular actions, as barriers for wider uptake by farmers. They found farmers may not be familiar with the term circularity or circular but could quickly understand its principles and how circular practices align to some long-standing practices. Despite possessing relevant knowledge to understand circularity principles, a lack of practical skills to implement actions on farm can still be a barrier, for example arable farmers may not have the skillset to introduce livestock to improve nutrient circularity.

Lack of accessible evidence of effectiveness of more novel solutions, may discourage farmers from adoption. For example, with Balesafe or technologies to prevent food loss and waste, there are limited examples of on-farm adoption and without these to demonstrate effectiveness, farmers may have limited confidence to adopt these solutions.

5.4 Implementing change

Several factors could help implement a shift towards more circular actions in Scottish farming:

- Improve primary data on farm material and product flows
  - our assessment is relatively high level and often based on limited or potentially out of data information on material flows and volumes. A clearer picture of material and product flows in Scottish farming, which can demonstrate regional and year-on-year changes is important to underpin further developments in the sector.
- Increase confidence in effectiveness of circular options
  - farmers, policy makers and industry need confidence in order to change behaviour or to invest. Several actions can support this. High quality research into emerging solutions, such as methods to reduce flexible plastics used in agriculture or reusable containers for agricultural inputs, could provide evidence of effectiveness (or otherwise) and accelerate adoption. Knowledge transfer, including on-farm demonstrations through peer-to-peer learning and schemes like Scottish Farm Advice Service (FAS), can also increase confidence and support further adoption.
- Integration of circular solutions into the wider farming transition agenda and support package
  - education and awareness for farmers (for example through peer-to-peer learning and other knowledge transfer methods) will be important to support implementation, particularly to see how circular actions can benefit them and fit within their wider farm management goals.
- Financial incentives and support for farmers and for the wider sector
  - funding could be targeted to individual farmers for example in relation to food waste, to cover costs associated with redistribution of surplus food and/or to distribution networks that may otherwise struggle to fund the logistical operations needed.

5.5 Limitations/gaps

Some key evidence gaps include the lack of data on material and product flows – good quality information is not available for all flows that are relevant for Scottish farming. For example, there is limited reported farm data on major materials flows, such as food loss and waste, fuels, plastics, and feed – this had to be estimated from other credible data sources and so is subject to uncertainty. There is no routine quantification available of some other flows, such as on-farm un-sold wool, chemicals and horticultural growing media.

In our assessment the timeframe of data use is also a possible limitation. Key data for several materials is from 2022 and due to variations in farming context, such as market prices for produce or input costs there can be changes in production volumes and farming practices. For example, since 2022 beef cattle numbers have declined slightly in line with the long-term trend, whilst dairy cattle and poultry have increased, pigs decreased and sheep remain below a 5-year average. These changes may influence slurry and manure generation slightly, and whilst it will remain a key material flow considering current livestock numbers, the volume may vary over time (See Appendix D for full methodology and

assumptions). Fertiliser prices have also varied significantly in recent years, which influences farmers' decisions about how much to apply year-to-year. We used a 3-year average where possible in this study, but this was not always possible due to data availability.

Data on effectiveness of solutions, cost implications and associated emissions reductions is uncertain for many materials and solutions. For example, redistribution of surplus food from farms ranks highest in terms of effectiveness at reducing GHG emissions, but there is some uncertainty over available foods and the costs and emissions for distribution, and so further data and research could give a clearer picture of costs and benefits. Biochar also ranked highly in terms of potential GHG emissions reductions, but full assessment of production process was not possible in the scope of this study – this could be investigated through other research.

6 Conclusions

Our research shows clear opportunities to make Scottish farming more circular, delivering benefits for farmers and contributing to GHG reductions. However, the picture remains complex. Some materials already have several competing uses. For other materials, uncertainty remains around environmental and economic implications, and challenges in implementation.

6.1 Key material and product streams

6.1.1 Nutrient flows

Nutrient flows include fertilisers and livestock feed inputs and manure, slurry, and crop or food waste such as straws, residues and food loss. Together, these represent the largest material flow in Scottish agriculture. Nitrogen-related flows, including synthetic fertilisers, other organic nitrogen fertilisers, manure and slurry create the greatest emissions impact because they generate nitrous oxide. Other critical nutrients, such as phosphorous, ranked lower against the criteria used in this study. However, they should still be considered when developing of circular economy actions, particularly given the potential for future constraints on supplies.

Increasing the adoption of practices that improve the circularity of nutrient flows is a critical step for these interconnected material streams. To a certain extent, key nutrient flows are addressed by existing and planned efforts to improve sustainability and efficiency in agriculture, such as measures included in the Agriculture and Rural Communities (Scotland) Act 2024 and the associated Agricultural Roadmap and Future Farming Support Programme. Alongside integrating circular economy principles into the wider agricultural transformation programme, we identified several actions with the potential to reduce emissions from the nutrient flows we prioritised in this study.

6.1.2 Food

For food, the priority should be to prevent loss and waste through better crop storage, technologies to prevent waste in the first place, and redistribution of surplus food that would otherwise go to waste. This should be part of wider actions to tackle food loss and waste across the food system.

6.1.3 Livestock feed

For livestock feed, key actions include reducing feed requirements through extended grazing and building on existing practices that use suitable by-products.

6.1.4 Straw and crop residues

For straws and crop residues, the picture is complex. Farmers already use these materials in several ways, many of which compete with each other. There is uncertainty about whether new uses for these materials could increase emissions if they compete with existing uses.

While there are opportunities for farmers to gain economic benefits from new, higher-value markets for these materials, there is increasing recognition of the value of these materials on farm for improving soil health and for existing uses such as animal bedding. It is key to focus on genuinely surplus materials and consider the material 'cascade' to gain multiple uses from this organic material.

6.1.5 Agricultural plastics

Plastics include soft films for silage wrap and horticultural use, and containers for feed, fertilisers and agro-chemicals. These are already recycled to a certain extent, but collection logistics, contamination and costs make recycling challenging. Innovative solutions such as Balesafe to store silage without plastic, and the potential adoption of reuse systems for chemical containers, could reduce plastic use. However, further feasibility assessment is needed.

Simpler approaches, such as re-using horticultural plastics on farms, could reduce emissions and costs. Farmers could adopt these approaches more quickly with appropriate support and suitable behaviour change programmes.

6.1.6 Fuel

Fuel use is another key material flow in agriculture, particularly because it contributes significantly to GHG emissions. We did not assess fuel use in detail because of data limitations and ongoing research. However, it remains an important area for action.

6.1.7 Other materials

Other material streams also potentially warrant attention. Wool waste and chemical waste may be significant, but data availability to confirm this was limited. Clarifying the quantities and causes of these materials is a necessary first step before exploring potential circular solutions. End-of-life equipment was not investigated in detail in this study, as existing waste management channels and regulation were assumed to address this issue. However, this assumption could be checked and potential opportunities to introduce circular practices explored, if specific challenges were identified.

Materials which are similar to those arising from households, such glass and metals, were relatively insignificant for the agriculture sector and therefore not a priority for sector-specific action. Developments in these materials could be considered for households and other economic sectors.

6.2 Summarising options for improving circularity

There are options to improve circularity across the waste hierarchy. The greatest opportunity is to prevent waste from occurring. Farmers can also generate economic benefit from avoiding waste and creating more value from previously wasted materials. Findings from across these material and product streams assessed in this study identify the following key opportunities:

- **Reducing material inputs and preventing waste by:**
  - improving livestock feed-use efficiency and extended grazing
  - reducing food waste through technological solutions and better storage
  - reducing plastics use through new management practices.
- **Reusing materials** such as plastic containers, tree guards and surplus food.
- **Increasing recycling** of agricultural plastics, through better collection services and, where there is sufficient demand, treating some materials through anaerobic digestion.
- **Expanding the use of circular materials**, such as brewery waste for livestock feed to replace existing materials used. There are also opportunities to use farm waste as a more sustainable feedstock for emerging industries, such as biorefining.

6.3 Priorities for action by Scottish Government

Scottish Government can play a key role in supporting development and uptake of circular options that could benefit farmers, reduce emissions, and generate wider environmental benefits. Potential actions for government include:

- Support for further reporting and data collection into farm material use, flows and waste, prioritising getting better data on more significant materials volumes and those responsible for higher emissions, alongside filling data gaps where there is no or limited data.
- Support for research and development of new and emerging circular solutions. This could focus on those targeting the priority material and waste streams identified here, or others that emerge because of further research.
- Integrating circular economy actions into wider farming transition programmes, including potential for incentives for action where it is aligned to government goals.
- Support for food waste redistribution from farms, connecting into systems being developed for other parts of the food system where appropriate.
- Mapping the potential actions for other stakeholders in relevant material and product value chains, which could support adoption of circular principles on farms for example roles of the food retail sector or emerging biorefinery sector.
- Considering the unique needs of the agricultural sector when developing systems and services for other sectors of the economic and households, for example any synergies for plastics or food waste collections.

6.4 Barriers and challenges

There are a number of barriers and challenges which hinder uptake of circular solutions in Scottish agriculture including:

- Need for greater knowledge and awareness of opportunities amongst farmers. Although some circular economy actions align well with general resource efficiency and regenerative agriculture, both of which are addressed through existing agricultural knowledge transfer schemes, there is still a challenge in driving behaviour change. Farmers may need new skills, such as new grazing practices, plastics reuse or to deal with new customer requirements for any surplus or waste going to new end destinations.
- Distribution and types of materials: agriculture has some unique materials, such as contaminated and hard to recycle plastics. The unique waste types and distribution of farms across a wide area presents a practice challenge for recycling services.
- Financial challenges are present for some solutions, due to challenging economies of scale or need for upfront investment in infrastructure or equipment, for example costs associated with food redistribution discourage farmers.
- Data availability and evidence base for solutions are also barriers. Better data availability could help to refine priority streams and actions, allowing farmers, government, and researchers to streamline efforts.

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8 Appendices

Appendix A – Rapid Evidence Assessment

8.1.1 Scope

The REA focused on:

- **Key material and product streams:** types and quantities of waste generated on Scottish farms, current destinations and associated environmental impacts, including characteristics of waste generated and resource needs in typical Scottish farm types/crofts farm-types.
- **Circular economy opportunities and related practical actions for farmers and crofters:** in general, taking into consideration the whole waste hierarchy, including opportunities to reduce consumption and specific guidance on environmentally preferential reuse options such as food waste hierarchy statutory guidance for the UK.
- **General applicability, benefits and challenges**: of circular opportunities for Scottish farms and crofts.
- **GHG Emissions reduction potential**
- **Other benefits:** such as economic, environmental or efficient improvement of identified circular opportunities or specific material or product streams.

8.1.2 Method

The REA methodology used for this project aligned with NERC methodology (Collins et al., 2015) and comprised of the following steps.

1. **Define the search strategy protocol, identify key search words or terms, define inclusion/exclusion criteria.** This step helped to focus the review on the most relevant sources. Inclusion and exclusion criteria were also defined. For example, studies that had no relevance to Scotland were excluded.

Searching for evidence and recording findings. Due to the short timescales of this REA, we searched for literature using Google Scholar, utilising our accounts with Science Direct and Research Gate to access restricted pdfs where required**.** For each search, we recorded the date, search string and number of results found, each search string was assigned a reference number. The search protocol is presented in Table 7.

Table 7: The keywords and specific words used in search strings in this REA

Keyword	Including
Fuel	diesel, fuel, biofuel, biomass, biogas
Feed	animal feed, compound feed, bagged feed
Plastics	mulch film, plastic sheets, greenhouses, plastic sacks, plastic bags
Agri-chemicals	fertiliser, pesticides, plant protection products, fungicides, insecticides, rodenticides, bactericides, nutrients, nitrogen, phosphorus, potassium
Manure	manure, slurry, excreta, digestate
Climate	greenhouse gases, GHGs, carbon, carbon dioxide, nitrous oxide, methane, CO2, N2O, CH4, climate change
Cost	economy, financing, funding, cost, price, profit
Other environmental	water, biodiversity, nature, natural capital, ecosystem services, eutrophication, pollution, contamination, soil degradation, environmental
Waste hierarchy	waste valorisation, reuse, reduce, recycle, disposal, treatment, recovery, waste hierarchy
Circular economy	circular economy, circular, resource efficiency, closed-loop, zero waste, bioeconomy, value chain
Opportunities	opportunities, strategies, interventions, practices, actions
Agriculture	arable, cropping, grass/land, pasture, dairy, beef, sheep, pigs, poultry, horticulture, livestock, greenhouse, farming

2. **Screening.** Evidence was then screened, initially by title and a selection of sources were screened by the abstract, applying the criteria developed in step 1. This step ensures the relevance and robustness of the evidence that was included in the study.
3. **Extract and appraise the evidence.** Evidence was then extracted from the papers after screening.

8.1.3 Results

Key results:

- 17 searches carried out
- Approximately 311,000 results (including > 200,000 from a wide google search, most of which were duplicates or not relevant)
- 10 searches brought forward to screening
- The most relevant papers were systematically identified using the following approach:
    - Date range – papers pre-2015 were excluded
    - Papers were sorted by relevance and the titles reviewed
    - Titles of papers relating to materials with no relevance for Scottish farming were excluded
    - Titles of paper relating to studies which were not directly relevant to the study or not applicable in the short-medium term were also excluded.
    - The first approximately 5 pages or search results were reviewed – the review of papers was stopped once it was clear that remaining papers were of very limited relevance.

- 63 papers brought forward to screening
- 15 additional sources included (from reference lists of other papers, evidence from stakeholders, other targeted searching to fill gaps)
- 51 papers fully screened (16 excluded at this stage due to accessibility issues, irrelevance, or poor quality research)

Appendix B – Circular Economy (Scotland) Act 2024 definition

Section 1 (3) of the Act requires in preparing the Circular Economy Strategy, Scottish Ministers must give "regard to the desirability of the economy being one in which—

(a)processes for the production and distribution of goods, products and materials are designed so as to reduce their consumption and their whole life-cycle carbon emissions,

(b)the delivery of services is designed so as to reduce the consumption and whole life-cycle carbon emissions of goods, products and materials,

(c)goods, products and materials are kept in use for as long as possible to reduce their consumption, their whole life-cycle carbon emissions and their impacts on the environment,

(d)the maximum value is extracted from goods, products and materials by the persons using them,

(e)goods, products and materials are recovered or, where appropriate, regenerated at the end of their useful life,

(f)waste is managed in Scotland if it is appropriate to do so,

(g)due diligence in relation to environmental protection and human rights is exercised in supply chains."

Appendix C – Material and Product Stream Summaries

8.1.4 Slurry and manures

Slurry and manure[6] are generated on all livestock farms but are not collected on farms where the livestock are solely grazed outdoors – the excrement is directly deposited on land in this circumstance and not available to be further utilised. In Scotland, slurry and manure are two of the biggest material streams due to the large numbers of livestock. A majority (97%) is spread on land, for fertiliser with around 3% being used in Anaerobic digestion (after which the digestate will also be spread on land).

Slurry and manure contain valuable nutrients (nitrates, phosphate and potash) and other beneficial components for improving soil health and supporting crop growth. They can, however, create significant air and water pollution. Ammonia (NH_3) emissions contribute to

[6] Slurry - Excreta, including any liquid fraction, produced by livestock whilst in a yard or building. This includes any mixtures of excreta with bedding, feed residues, rainwater and washings from dungsteads, middens and any buildings or yards used by livestock. Manure is solid animal excreta. (Farming and Water Scotland, Know the Rules Factsheet 1)

poor air quality with harmful health impacts and nutrient pollution in water harms aquatic habitats and affects drinking water quality. Nitrous oxide (N_2O), a powerful GHG, is released from slurry and manure spread on land, although on a life cycle basis the GHG emissions from using slurry and manure are lower than using synthetic fertilisers.

On farm, slurry and manure must be securely contained (in tanks or lagoons) and its use is carefully managed in Scotland (Farming and Water Scotland, 2025). Slurry is often combined with effluent from silage clamps, yard scrapings and parlour washings. Farmers are required to consider all these in their Farm Slurry and Manure Management Plan for the purposes of calculating how much storage is required. Field heaps of manure are permitted in limited circumstances, where risk of water pollution is low (Farming and Water Scotland, 2025). Management practices (e.g., covered storage) and the timing and method of manure or slurry spreading influence the emissions to air and water.

Limitations and evidence gaps:

- Key data use is from 2022, since then beef cattle numbers have declined slightly in line with the long-term trend, whilst dairy cattle have increased, poultry have increased, pigs decreased and sheep remain below a 5-year average - these changes may influence slurry and manure generation slightly, but it will remain a key material flow considering current livestock numbers (See Appendix D for full methodology and assumptions).

Uptake of management practices during spreading, such as injection, are not accounted for in the emissions data – these may reduce emissions. Uptake of these practices in Scotland was not identified in our research. A legal requirement for precision spreading commences in 2027 under the General Binding Rules on silage and slurry - Farming and Water Scotland.

8.1.5 Livestock feed

On Scottish farms, livestock are typically fed a combination of grassland grazing, silage made from harvested grass/forage crops, straw and supplementary feeds, which are either grown on the farm, bought in from local sources or imported (from other UK nations or further afield). Some cattle and sheep are grazed on rough grazing land (classified as 'less favoured areas'[7]) whereas others will be grazed on lowland grassland which may be improved through additional fertilisers and management practices. Supplementary feed includes wheat, barley, soya meal, rapeseed, maize grain – with the largest portions from wheat and soy in Scotland. Many farmers will use compound feeds with a mixture of ingredients.

We assessed the volumes and emissions associated with grass and straw, locally sourced feed and imported feed separately, which showed grass and straw was by far the largest quantity, but emissions associated with this are unclear, so a figure was not allocated. Grassland is a significant carbon store, and so rather than an emission, there may be a net reduction depending on management practices. Emissions from other feeds come from

[7] Land with severe limitations – either steep, poorly drained or with shallow soils that would mostly be suitable only for low intensity farming e.g., rough grazing sees https://www.gov.scot/publications/economic-report-scottish-agriculture-2016/pages/6/

growing (including land management practices and land-use change where relevant) and transport which would vary significantly depending on the location of feed. The quantity of locally sourced feed in Scotland is almost 10 times more than imported feed (see Section 8.1.5), so emissions from transport of the feed will already be relatively low.

Livestock feed is a key cost for many farmers and therefore is a key variable in profitability. On farm decisions about feed sources will depend on cost, availability and weather conditions.

Limitations and evidence gaps:

- A single GHG emissions factor for imported and local feed was used. It was not possible to analyse the various geographical sources of imported feed within the scope of this study and therefore apply a different emissions factor to feed from different locations. In practice the emissions will vary between different ingredients and sourcing locations (e.g. soya from a recently deforested area versus a locally grown wheat crop). This suggests a conservative approach has been taken as we have not factored in emissions from land-use change and transport of feed to Scotland. These emission sources will be outside the Scottish inventory (See Appendix D full methodology and assumptions in data analysis).
- Detailed data on types and sourcing locations of feed was not available – our analysis used information from literature and the Scottish Nitrogen Balance sheet to make some assumptions (See Appendix D full methodology and assumptions in data analysis).

8.1.6 Fertilisers and pesticides

Fertiliser and pesticide use in Scottish agriculture is concentrated in cropping sectors, alongside more limited use on lowland pastures for livestock rearing. Slurry and manures are a key source of organic fertiliser in Scotland but have been quantified in the slurry and manure category, so are excluded here to avoid double counting. Synthetic nitrogen fertiliser is the largest farming input in this category, followed by potassium fertilisers (K) and phosphates (P) and then a smaller amount of other organic fertilisers including sewage sludge, digestate, and compost. There is an important linkage from a circular economy perspective - effective and efficient slurry and manure use should reduce fertiliser input.

When it comes to GHG emissions, nitrogen fertilisers are even more significant because, alongside emissions from fertiliser manufacturing they are also significant source of GHGs due to nitrous oxide (N_2O) emissions from soils and emissions from water run-off from fields and from soils where volatilised nitrogen is deposited. Other environmental impacts of fertilisers are similar to those associated with slurry and manure – air and water pollution with potential harm for aquatic life and air quality. Rathbone and Ullah, (2024) assessed that ammonia emissions in the UK from synthetic N fertilisers may be more significant than previously thought, with up to 77% of applied nitrogen in the fertiliser lost to air as ammonia.

Fertiliser prices have been volatile in recent years, with some periods of significantly high prices which is a challenge for farm profitability and driven more precise fertiliser use, compared to when fertiliser is cheaper and farmers are more likely to use more fertiliser to secure yields.

Limitations and evidence gaps:

- Method and timing of application and use of inhibitors can have an impact on emissions from fertilisers, but has not been taken into account fully in our applications due to unavailability of robust data to make credible assumptions about this for Scottish agriculture.

8.1.7 Straw and crop residues

Straw and crop residues include all the parts of crops which are not edible or the primary product, for example cereal straw or fruit and vegetable leaves and stalks (such as carrot tops) and potato leaves and stalks – knows as haulms. Surplus or wasted harvested products are excluded from this category as they are incorporated in the food loss and waste category below.

Many farms already use straw and other crops residues for animal feed and incorporate them into soils. Other uses may include use for animal bedding, mushroom production, protection for carrot crops, energy generation in biomass boilers or anaerobic digestion (typically green parts, as straw is less effective although sometimes used alongside slurry and manure to create a balance feedstock. The data shows that despite this, a significant portion remains unused, and a waste product from agriculture.

Emissions from straw and residues in general would be classed as zero under IPCC rules, which treat CO_2 from biogenic sources (including crop residues, straw and other plant biomass) as part of the short-term carbon cycle i.e. because the carbon in residues was recently removed from the atmosphere during plant growth, its release on decomposition is assumed to be net-zero over a short timescale. For straw and residues that are utilised – they may be a net emissions reduction by displacing other materials, such as animal feed, but we have not quantified this emissions reduction due to uncertainties. For materials applied to land, there may also be an increase in soil carbon sequestration, and potentially a net GHG emissions reduction. We had no information on end disposal of unused straw and residues, and therefore did not assign an emission reduction to these beneficial end destinations. In landfill, composting or simply left in a field these waste materials would likely represent lost monetary value to farms, but farms are increasingly recognising benefits of crop residues in improving soil health. As well as potentially contributing to soil carbon sequestration, straw and crop residues can improve soil texture, structure and water retention all of which contribute to more resilience production during variable weather (for example better water retention helps protect crops in the event of prolonged dry periods and better soil structure helps with increased infiltration and reduced soil erosion during heavy rainfall).

Limitations and evidence gaps:

- Data sourced is from 2022 and is based on earlier industry insights, updated to reflect agricultural production volumes. The data source included data on carrot stalks and leaves, potato haulms, brassica tops, other stalks and straw from cereals, oilseeds rape, vegetables, and strawberries (See Appendix D full methodology and assumptions in data analysis).
- Limited primary data on both the quantity and end destination of straws and residues is available.

- Agricultural practices are changing with the increasing adoption of direct drilling techniques and farmer awareness of the benefits of incorporating organic matter, such as straws and residues into soils. Current uptake of these practices may not be reflected in the available data, and therefore this is some uncertainty around the end destination of some straw and residues.

8.1.8 Food loss and waste

Food loss and waste in agriculture examples can include in-field waste such as unharvest products due to lack of market, milk spilt during milking, out graded products not meeting market specifications and post-harvest wastes such as animals rejected from a slaughterhouse, fruit and vegetables harvested but not sold due to last minute order changes (WWF, 2022). Our estimate of food loss and waste in Scottish agriculture showed it was the 8th most significant material flow, behind livestock manure and slurry, feed and straw/crop residues.

In terms of GHG emissions food loss and waste ranked much more highly (2nd) due to significant methane emissions from decomposition of waste in landfill or other disposal routes. On-farm food loss and waste is estimated to be 16% of the total agricultural-related greenhouse gas emissions globally (O'Connor et al 2023), and in the UK represents around 10% of UK agricultural GHG emissions (WWF, 2022). As with straws and crop residues, under IPCC rules, CO_2 emitted from biogenic sources (including crop residues, straw and other plant biomass) is allocated zero emissions as it forms part of the short-term carbon cycle i.e. because the carbon in residues was recently removed from the atmosphere during plant growth, its release on decomposition is assumed to be net-zero over a short timescale. Methane emissions from decomposition in landfill and emissions associated with additional production of food (e.g. fertiliser applications during crop production; or enteric fermentation during cattle rearing) are the drivers of excess emissions from food loss and waste which are reflected in our calculations. There are wider implications of land being used to produce food that isn't eaten: that land could have provided food and/or biodiversity, sequestration and climate adaptation.

The volumes and reasons for food loss and waste vary across different agriculture sectors. March et la (2019) assessed milk losses and emissions in Scotland - across all farms, an average of 98.2% of total milk produced was sold, 0.66% was purposely retained, 0.55% was rejected due to antibiotic residues, 0.5% was lost from parlour to bulk tank infrastructure, a further 0.09% was rejected by the processor. This seems like a relatively small volume but represents a significant GHG emission due to the relative emissions intensity of milk production. Beausang et all (2017) qualitatively assessed soft fruit waste challenges in Scotland, finding that waste levels were high, with causes of loss including short-term order volume changes from retailers and that farmers were interested in finding ways to add value through better use of this waste. Stakeholders we spoke to confirmed that food loss /and waste is a challenge in Scotland and indicated that it is most significant in fresh produce, such as potatoes, fruit and vegetables.

Limitations and evidence gaps:

- Primary data on food loss and waste in agriculture in Scotland is very limited with only a few specific studies, and therefore to understand the overall quantity we relied on UK wide data which we then apportioned to Scotland based on economic

output from relevant agriculture sectors. This only gives a broad sense of the likely scale of the issue, rather than an accurate picture of the on-farm realities in Scotland – although our stakeholder consultation confirmed that food loss and waste is significant on Scottish farms (See Appendix D full methodology and assumptions in data analysis).

8.1.9 Plastics

Plastic waste on farms typically comprises plastic silage wrap, flexible plastic used to cover poly tunnels or on the ground for horticultural production, plastic containers from agricultural chemicals and inputs (e.g. pesticides, sheep dip, feed supplements) and plastic sacks for other inputs such as compound feed and fertilisers (EA, 2020; FAO, 2021; EIA, 2023). Most data is available on plastic film – a Zero Waste Scotland (2023) study estimates total farm film waste of just under 22,000 tonnes with 9% of this from the horticultural sector and 91% from livestock comprising 82% from silage bale wrap, 9% from silage clamp cover and the remainder from crop covers. Stakeholders we spoke to also highlighted agricultural twine, products such as tree guards and polymer coatings of agrochemicals as sources of plastic waste. Some plastic packaging is bought in by farms for packaging products for onward sale – it has not been possible to quantify this.

GHG emissions from agricultural plastics arise during the supply chain associated with their production from raw materials extraction, through manufacturing and transport and also during disposal. In our assessment we use average UK Government emissions factors (Defra, 2025) for plastic material production (from virgin plastic, which includes the extraction, primary processing, manufacture and transportation of materials to the point of sale) and disposal.

Recycling of agricultural plastics is estimated at around 20% for this study – SEPA data indicates a majority of plastics are recycled in Scotland overall but agricultural plastics are typically harder to recycle because of contamination (for example with chemicals, dirt and silage residues); varied types of plastics, some of which less widely recycled (plastic films) and farms being spread over a wide area making the economics of collection services more challenging. Therefore based on stakeholder insights, and data published by Agriculture Plastics Environment[8] a lower estimate (20%) was adopted for the purposes of GHG emissions calculations.

Plastics are associated with additional environmental challenges, alongside GHG emissions, including environmental contamination, particularly where disposal methods do not properly contain the risk (EIA UK, 2023) and given agricultural land is often close to water courses (EA, 2020), contamination of soils and water from micro plastics is an emerging challenge (Gerassimidou and Lacovidou, 2024).

Limitations and evidence gaps:

- Primary data on plastic use and waste in Scotland is limited – the data for this study are drawn from Scottish Environmental Protection Agency (SEPA) published waste

[8] Which claims less than 30% of agricultural plastics are recycled in the UK.

data, but these are estimates due to lack of reported data for this waste category – the estimates use an Agricultural Waste Estimates Model which is not publicly available (See Appendix D full methodology and assumptions in data analysis).

- There is limited data on the volumes of individual types of agricultural plastics waste – a UK wide 2001 report (EA, 2001) indicated that flexible plastics including silage wrap, mulch film and crop covers were the biggest portion of waste by weight, and plastic feed and fertiliser packaging was also significant but did not specify what type of plastics (bags or other containers), or polymer type and farming practices have changed since this study. Zero Waste Scotland (2023) provides data on quantity, type and distribution of plastic films in Scotland, but not other types such as containers (See Appendix D full methodology and assumptions in data analysis).
- Estimates of recycling percentage are based on stakeholder insights and non-peer reviewed sources, and so may have limited accuracy.

8.1.10 Machinery and equipment

By far the largest portion in this category is end-of-life agricultural vehicles, with a much smaller volume of other equipment. Combined these ranked towards the bottom by volume and are covered by the end-of-life vehicle disposal regulations so are mostly recycled.

Limitations and evidence gaps:

- Data reflects only vehicles which are collected for disposal and therefore reported via official statistics – any un-used vehicles on farms are not included, nor are second hand sales.

8.1.11 Chemicals

Chemicals waste in agriculture is primarily sheep dip and unused pesticides – the quantity is taken from SEPA estimates based on an Agricultural Waste Data Model, because there is no reporting requirement for this specific waste stream.

GHG emissions are relatively low compared to other material flows, taking into account both the emissions associated with chemical supply chain and disposal.

Limitations and evidence gaps:

- Primary data on chemical waste in Scotland is limited – the data for this study are drawn from Scottish Environmental Protection Agency (SEPA) published waste data, but these are estimates due to lack of reported data for this waste category – the estimates use an Agricultural Waste Estimates Model which is not publicly available (See Appendix D full methodology and assumptions in data analysis).

8.1.12 Fuel

Fossil fuel use on farms is a significant input, particularly for arable farms for crop cultivation and harvesting. GHG emissions from fuel combustion on farms is a key source of GHGs, resulting in fuel being ranked the most significant source of emissions, from the materials and products we considered in this study. Alternative fuels from renewable and circular sources are associated with lower emissions, for example biodiesel from use cooking oil, tallow (waste animal fat) or other common natural oils such as vegetable soils generates

emissions of around 0.1675Kg CO_2e per litre, and hydrotreated vegetable oil (HVO) biodiesel even less at around 0.03558kgCO_2e. compared to typical diesel sold in the UK which causes 2.54kg CO_2e per litre (Defra, 2025). Biomethane derived from anaerobic digestion of biogenic wastes (such as crop waste and slurry) is also emerging as a potential source of fuel, with lower emissions than fossil fuels. Data on uptake of these fuels in agriculture was not identified during this research so data on emissions from fuel is all derived from standard UK diesel blend.

Limitations and evidence gaps:

- Data on fuel usage is limited, and sources are not available to show uptake of alternative fuels such as bio-fuels from waste materials in Scottish agriculture (See Appendix D full methodology and assumptions in data analysis).

8.1.13 Horticultural growing media

A variety of growing media are used in horticultural production, including peat-based materials, wood and bark chips, coconut fibre (coir), compost, spent mushroom compost, and mineral based substrates.

GHG emissions associated with peat-based growing media are significantly higher than other materials, due primarily to the release of carbon stored in peatlands once the peat is extracted for use. This means peat growing media emissions ranked much higher for GHG emissions than for quantity. Defra (2023) reports that proportion of peat in growing media across the UK is declining – reduced from 36% in 2021 to 24% of total volume in 2022.

Limitations and evidence gaps:

- Data used were for UK as a whole – various factors may influence current use in Scotland, such as availability of peat in Scotland and pressures to reduce peat use from government and retailers – therefore the estimates of peat use versus other materials may not be accurate. The emissions associated with replacements for peat also need to be considered – we considered a limited number of alternative materials, but may not have fully considered all associated emissions for example transport emissions for transporting materials from overseas. Ongoing research by CXC is looking into what alternatives to peat can be used in the horticulture industry and their potential for commercial adoption (CXC, 2024). The results from this CXC fellowship have recently been published but were not available for use during this study so are not reflected in the calculations. This new study should contribute to filling the gap we have identified in the assessment carried out here (See Appendix D full methodology and assumptions in data analysis).

8.1.14 Other wastes

Other wastes, which are less specific to agriculture, were quantified based on the data from SEPA. These waste sources include glass, metallic wastes, mixed and undifferentiated materials, rubber wastes, used oils, and wood wastes. SEPA data report these waste streams apportioned to agriculture based on economic value of the sector. No further data was available to allow a more accurate estimation.

These waste streams were amongst the lowest in terms of quantity in agriculture and also for emissions.

Appendix D – Data Analysis Methodology

A dashboard was prepared for all agriculture, and one for each of the 5 key agricultural sub-sectors; dairy, beef, sheep, cereals, and horticulture.

Each dashboard lists major product material streams classed as either inputs or wastes.

8.1.15 Estimation of volumes/quantities of product/material streams:

8.1.15.1 Inputs

Detailed description of data sources and rationale for choice of data, calculations for volume, GHGs, other parameters, allocation to farming sectors, assumptions, limitations.

For material and product streams as per Section 4.

The following section covers the methodology employed for the estimation of volumes/quantities of product/material streams completed as part of Task 1 of this project. The findings are presented in Section 4. This section is broken down into each product/material stream covered in the data analysis. Each sub-section covers the raw data sources used, intermediate calculations (e.g. to allocate a value for total agriculture in Scotland between the various sub-sectors) and data sources used for these intermediate calculations, data limitations, and any other notes to consider for each value.

Animal Feed:

- Animal feed was split into two different categories: Feed (imported) and Feed (local)
- The source for total animal feed consumed was Leinonen I. et al. (2019). The raw data from this source is presented in Table 8.

Table 8: Quantities of livestock feed used in Scotland by feed and livestock types taken from Leinonen I. et al (2019)

Feed type	Unit	Chicken	Pig	Sheep	Cattle	Total
Wheat grains	kt yr-1	264	119	0	71	454
Barley grains	kt yr-1	9	27	85	478	599
Soya meal	kt yr-1	67	23	24	28	143
Rapeseed	kt yr-1	45	33	4	128	210
Maize grain	kt yr-1	11	7	26	129	173
Grass and straw	kt yr-1	0	0	1962	4287	6249
Other	kt yr-1	30	9	4	98	141
Total	kt yr-1	427	218	2104	5219	7968

- These values are total feed consumed in Scotland. They were split into locally grown and imported feed using the percentage split of locally grown and imported nitrogen from the Scottish Nitrogen Balance Sheet (Scottish Government, 2025b).
- The cattle category value was split into values for beef and dairy based on the percentage split of the total cattle population by beef and dairy animal. The source

of the raw data provided values by livestock category for sheep and so no allocation/disaggregation was required for the sheep value.
- Grass and straw consumption was excluded from both imported and local feed categories, and was presented as a distinct material stream.

Synthetic N, P_2O_5, and K_2O:
- The three main synthetic nutrients applied in agriculture (N, P_2O_5, and K_2O) were all calculated using the same raw data set and approach as follows.
- Synthetic nutrient use data was sourced from the British Survey of Fertiliser Practice (DEFRA, 2025b). Table AA1.7 in this report provides values for fertiliser use for Scotland (and England and Wales, NI, and UK) in kilotons of nutrient.
- This was allocated to each subsector based on the land-use area and livestock population from the Scottish Agricultural Census (Scottish Government, 2024). The percentage of total agricultural area covered by arable, horticultural, and grass land was calculated. These values were applied to the total nutrient use for Scotland.
- The grassland value was then split into beef, dairy, and sheep by the relevant percentage of total livestock units, also from the Census (Scottish Government, 2024).

Pesticides:
- Pesticide use data was sourced from Scottish Government Pesticide Usage reports (Scottish Government, n.d.). The most recent report for each land-use type was included in the data analysis.
- Specifically, the following reports were used:
    - Pesticide Usage in Scotland: Outdoor Vegetable Crops 2023 (Scottish Government, 2024b)
    - Pesticide Usage in Scotland: Soft Fruit Crops 2022 (Scottish Government, 2023b)
    - Pesticide Usage in Scotland: Arable crops and Potato stores 2022 (Scottish Government, 2023a)
    - Pesticide Usage in Scotland: Rodenticides on Grassland and Fodder Farms 2021 (Scottish Government, 2023c)
- These provided weights by pesticide group in either kilograms or tons depending on the report. For values provided in kg conversion to t was required.
- Outdoor vegetables, soft fruits, and potato were included under the horticulture sub-sector.
- Arable and fodder crops were included under the arable subsector.
- Grassland only was included in the three livestock categories. The total value for usage on grassland was split into the three livestock categories based on the percentage of total livestock units against livestock type.

Fuel:
- There was limited fuel use data identified.
- The 'Total final energy consumption at regional and local authority level: 2005 to 2022' data from the Department for Energy Security and Net Zero was used here (DESNZ, 2024).
- This presented petroleum used for agriculture in Scotland in ktoe for 2022.

- The total for agriculture was split across each sub-sector based on economic output. Data on economic output was sourced from 'Total income from farming in the UK in 2024' published by DEFRA (DEFRA, 2025c).

Other organic fertiliser (N):

- This category covers sewage sludge, compost, and digestate (manure-based, crop-based, food-based, and other), that is applied to soil.
- The source for this data is the Scottish Nitrogen Balance Sheet (Scottish Government, 2025b).
- The unit is kilotons of N, not kilotons of material.
- The values provided for these materials are the total applied to soil in Scotland. This required allocation to each of the 5 sub-sectors. This allocation was based on the land area and livestock population from the Scottish Agricultural Census (Scottish Government, 2024).
- The total was split between arable, horticulture, and grassland, based on the area covered by each of these land use types.
- The derived value for grassland was split between livestock types based on the LUs of each type also taken from the Census (Scottish Government, 2024).

Medicine:

- No data on medicine use was identified for use in the data analysis.
- It is expected that this stream is not very significant in either quantity of medicines or emissions associated.
- It is also thought that there is limited opportunity for making this more circular.

Slurry and Farmyard Manure (FYM):

- Data from Zero Waste Scotland's BioResource Mapping Tool (2022 update) provided by Zero Waste Scotland (Zero Waste Scotland, 2022). was used as the source for quantity of slurry and FYM generated on farms. (Similar data is available in Zero Waste Scotland's 2017 report)
- In this source the fate of these streams is all to land. However, to estimate a value for the quantity of these materials that go to AD, it was assumed that these values represent the entire quantity of slurry and FYM generated on farms.
- The split between these streams that go to land and to AD was based on data from the SNBS (Scottish Government, 2024). According to the SNBS, 55.77kt N livestock excreta is used as manure for spreading, while 1.63kt N livestock excreta is used in AD. This works out at 97% going to land and 3% going to AD.

Growing Media:

- Data on use of growing media was sourced from the Growing Media Monitor Report (HTA, 2022).
- This report provided volumes of peat and other growing media. Other growing media consists of wood-based materials, bark, coir (coconut-fibre), composted green waste, other organic, other mineral, spent mushroom compost, and soil/loam. Quantities of these materials were also provided in the aforementioned report.
- The values were in volumes and for consistency in the dashboard presentation, conversion to mass was required. Densities for each material were sourced from an ADAS report (ADAS UK Ltd, 2016).

- All growing media was allocated to the horticultural sub-sector.

8.1.15.2 Outputs and wastes

Where categories were deemed to overlap between the two waste data sources (SEPA and Zero Waste Scotland), the Zero Waste Scotland data was opted for and the SEPA waste category excluded. The reason for this was the Zero Waste Scotland data had disaggregated waste streams into different destinations which is more useful for this task.

Food loss:

- Quantity of food loss was sourced from the WWF Hidden Waste Report: The Scale and Impact of Food Waste in Primary Production (WWF-UK, 2022).
- This source had a value for total farm stage food loss for the UK of 2.9 million tonnes.
- As well as an overall value for agriculture, this report also provided sector specific data and so no allocation between sectors was required.
- This was disaggregated to Scotland using Scotland's share of total UK utilised agricultural area (12%). This was based on the economic output of Scottish agriculture compared to economic output of agriculture for the entire UK, with data taken from the Total Income from Agriculture reports by DEFRA (DEFRA, 2025c).
- This values includes all material intended for human consumption lost at the farm stage.

Wool:

- Wool waste was investigated as a potentially important waste stream from sheep farms. Results from the REA, where searches were carried out targeting scientific literature on wool waste, yielded no relevant results. Of the approximately 2700 papers returned, only 1 was pulled through for full a screen. The key reasons for exclusion was that the research focused on waste wool and textile from the textile industry rather than the farm stage. The one paper identified was looking at valorisation of wool waste for building materials but did not provide any information on quantity of wool waste (Csaki, S., 2025). None of the papers provided an indication of quantity of wool waste in Scotland.
- A, seemingly discontinued, research project at Glasgow Caledonian University identified that wool waste is an issue on Scottish farms and anaerobic digestion could be a potential solution (Glasgow Caledonian University, 2024). However, no outputs from this project could be identified and from the limited information available on it no indication of quantity of wool waste could be gleaned.
- A targeted search strategy on wool waste identified a study looking at wool waste on Italian sheep farms (Parlato, M.C.M. et al., 2022). This paper cited 95% of wool produced in Italy as being wasted and not used in the textile industry. This assumption was not clearly evidenced in this paper.

Straw and crop residues:

- Quantities of straw and crop residues were sourced from the Zero Waste Scotland (2022).
- Sources of straw in this databased are oilseed rape, oats, wheat, barley, and fruit and veg straw, stalks, tops, haulms, and non-food residues.

- The fates of these materials are animal feed, landfill, land, animal bedding, unused, and horticulture.
- The unit of data in this source is tonnes so no conversion was required.
- The Zero Waste Scotland data was split into different crop types. Therefore, no disaggregation between sectors was required. Straw and residues from fruit and vegetables data was attributed to the horticulture sector dashboard. Straw from arable categories data was attributed to the arable dashboard sector.

Other waste categories:

- Other waste categories are chemical wastes, discarded equipment, discarded vehicles, glass wastes, metallic wastes (ferrous, non-ferrous, and mixed ferrous), mixed and undifferentiated materials, paper and cardboard wastes, plastic wastes, rubber wastes, used oils and wood wastes.
- The source for all of these streams was Scotland's Environment Waste Discover Data tool from SEPA (SEPA, 2025).
- The unit for all of these categories in this source is tonnes.
- The total values were allocated by sub-sector based on economic output by sub-sector, or emissions by sub-sector, depending on what was deemed most relevant for each stream.

Excluded waste categories:

- There were several categories of waste from the SEPA data (SEPA, 2025) that were excluded as they were of minimal quantities or of little relevance to agriculture.
- The excluded categories are presented in Table 9.

Table 9: SEPA waste data categories and quantities in tonnes that were excluded from this analysis

Waste Material	Quantity (tonnes)
Acid, alkaline or saline wastes	1
Batteries and accumulators wastes	1,128
Household and similar wastes	13,925
Industrial effluent sludges	73
Mineral waste from construction and demolition	n/a
Other mineral wastes	1
Sorting residues	n/a
Spent solvents	n/a
Textile wastes	1
Common sludges	n/e
Dredging spoils	n/e
Waste containing PCB	n/e

n/a: Output totals are insufficient to include
n/e: No values outlined in SEPA tool

8.1.16 Estimation of GHG emissions from product / material streams

To calculate emissions of greenhouse gases, emissions factors were sourced and applied to the volume of each material. The sources used for emission factors are primarily the UK Government GHG Conversion Factors for Company Reporting (DESNZ, 2025) and the Renewable Transport Fuel Obligation (RTFO) and Sustainable Aviation Fuel (SAF) Mandate Standard Data (DfT, 2024).

Where a suitable emissions factor was not available via these sources, alternative emissions factors were sourced from credible data bases and literature.

Some product streams could not have emissions factors applied directly to quantities of materials to estimate emissions, due mostly to lack of robust emissions factors or a complexity of required calculations. In these cases, a “top-down” approach was taken. This involved a more general emissions value (e.g. from the national inventory) being disaggregated based on intermediate data such as land-use cover and livestock population.

A “mixed” approach was used where both emissions factors and a top-down approach were required to estimate emissions across different stages of a material or product’s lifecycle. For example, an emissions factor may be applied to estimate emissions associated with the manufacture of a product, while a top-down approach is used to estimate emissions associated with its use. The approaches applied to each of the materials and product streams are listed in Table 10.

Table 10: Greenhouse gas emissions factors for each material and product stream

Material/ product stream	Approach	GHG Emissions factor source (and specific factor choice)	Notes on selection
Feed (imported)	Emissions factor	1.147kgCO_2e/£ - UK and England's carbon footprint to 2022 (Prepared animal feeds, SIC Multiplier)	
Feed (local)	Emissions factor	1.147kgCO_2e/£ - UK and England's carbon footprint to 2022 (Prepared animal feeds, SIC Multiplier)	
Feed (grass and straw)	n/a	n/a	
Synthetic N	Mixed	Manufacture: (Ammonium nitrate) – 3,420.7gCO_2e - RTFO and SAF Mandate Use: Top-down using N_2O from synthetic fertilisers from NAEI	
Synthetic P (P2O5)	Mixed	Manufacture: (Triple superphosphate) – 542.2gCO_2e - RTFO and SAF Mandate Use: Top-down using N_2O from synthetic fertilisers from NAEI	
Synthetic K (K2O)	Mixed	Manufacture: (Muriate of potash) – 413.76gCO_2e - RTFO and SAF Mandate Use: Top-down using N_2O from synthetic fertilisers from NAEI	
Other organic fertiliser	Top-down	Emissions from other organic fertiliser taken for all UK from NAEI and allocated to Scottish agriculture based on Census data	
Pesticide	Emissions factor	11,991.07gCO_2e – RTFO and SAF Mandate	
Fuel	Top-down	UK Government Greenhouse gas reporting: conversion factors 2025 (fuels category) - Fuel use (diesel - average biofuel blend): 3,087.9kgCO_2e/tonne	
Slurry (to land)	Top-down	Emissions from slurry applied to land taken for all UK from NAEI and allocated to Scottish agriculture based on Census data	
Slurry (to AD)	Top-down	n/a	
Farmyard Manure (to land)	Top-down	Emissions from FYM applied to land taken for all UK from NAEI and allocated to Scottish agriculture based on Census data	
Farmyard Manure (to AD)	Top-down	n/a	

Material/ product stream	Approach	GHG Emissions factor source (and specific factor choice)	Notes on selection
Chemical wastes	Emissions factor	UK Government GHG Conversion Factors for Company Reporting Combustion: 6.41 $kgCO_2e/t$ Incineration: 520.33 $kgCO_2e/t$	
Discarded equipment	Emissions factor	UK Government GHG Conversion Factors for Company Reporting Disposal: 4.69 $kgCO_2e/t$ Production: 3,473.13 $kgCO_2e/t$	
Discarded vehicles	Emissions factor	UK Government GHG Conversion Factors for Company Reporting 4.69 $kgCO_2e/t$	WEEE and Scrap metals have the same EF so this was used as a proxy for 'Discarded vehicles'
Glass wastes	Emissions factor	UK Government GHG Conversion Factors for Company Reporting Disposal (open-loop): 4.69 $kgCO_2e/t$ Disposal (landfill): 8.98 $kgCO_2e/t$ Production: 1,402.77 $kgCO_2e/t$	
Metallic wastes	Emissions factor	UK Government GHG Conversion Factors for Company Reporting Disposal (open-loop): 4.69 $kgCO_2e/t$ Production: 3,824.09 $kgCO_2e/t$	
Mixed and undifferentiated materials	Emissions factor	UK Government GHG Conversion Factors for Company Reporting Incineration: 4.69 $kgCO_2e/t$ Landfill: 497.24 $kgCO_2e/t$	No production EF included as material are not known
Paper and cardboard wastes	Emissions factor	UK Government GHG Conversion Factors for Company Reporting Production: 1,288.5 $kgCO_2e/t$ Disposal (closed-loop): 4.69 $kgCO_2e/t$	
Plastic wastes	Emissions factor	UK Government GHG Conversion Factors for Company Reporting Production: 3,172.5 $kgCO_2e/t$ Landfill: 8.98 $kgCO_2e/t$ Closed-loop: 4.69 $kgCO_2e/t$ Incineration: 4.69 $kgCO_2e/t$	Disposal EFs were applied to the proportion of total plastic waste that goes to each disposal route.
Rubber wastes	Emissions factor	UK Government GHG Conversion Factors for Company Reporting Production: 3,335.57 $kgCO_2e/t$	

Material/ product stream	Approach	GHG Emissions factor source (and specific factor choice)	Notes on selection
		Closed-loop: 4.69 $kgCO_2e/t$	
Straw and crop residues	n/a	n/a	
Used oils	Emissions factor	UK Government GHG Conversion Factors for Company Reporting Production: 1,401 $kgCO_2e/t$ Disposal: 3,219.38 $kgCO_2e/t$	
Wood wastes	Emissions factor	UK Government GHG Conversion Factors for Company Reporting Production: 269.50 $kgCO_2e/t$ Disposal: 4.69 $kgCO_2e/t$	
Food loss	Emissions factor	WWF total UK emissions figure (6 $MtCO_2e$) apportioned to Scotland based on economic output with fish and seafood % deducted	
Peat	Emissions factor	Horticultural Trade Association/DEFRA Offsite emissions from removed peat: 0.235 tCO_2e/m^3	
Other growing media	Emissions factor	Combined from Climatiq and UK Government GHG Conversion Factors for Company Reporting 7.25 $kgCO_2e$/tonne	Different EFs were combined to reflect different materials that may be included in 'Other growing material'

8.1.17 Sectoral breakdowns

Method for sectoral breakdowns of material and product flows

The sectoral breakdown for material and product flows and associated GHG emissions considered a number of data sources and factors including economic output per sector and other factors, such as whether a material flow is relevant for the sector. For example, livestock feed for example was excluded from the arable and horticulture sector and pesticides were split across sectors using government published data on pesticide use on different crops.

Fuel use was excluded from the sector breakdowns as no data was available to inform assumptions about fuel use distribution across sectors and as decarbonisation options for fuel are being considered by other Scottish Government research, it was not a priority for this study to explore it further.

Table 11 Scottish agriculture sectors by economic output

Sector	% Economic Output (2021-2023 adjusted average)
Arable (including potatoes)	30%
Dairy	21%
Horticulture	16%
Sheep	9%
Poultry	7%
Pigs	4%
Other	1%

The results of the breakdown are down below, showing the key flows of relevance to agriculture. General waste types such as glass or undifferentiated wastes were excluded from these tables due to uncertainty of data and lower relevance for the study.

8.1.18 Beef

Table 12: Key material and product streams for the beef sector in Scotland ranked by quantity and GHG emissions

Material/product flow	Quantity		GHG emissions	
	Tonnes/yr	Rank	Tonnes CO2e/yr	Rank
Manure (To Land)	6,360,000	1	179,000	4
Slurry (To land)	2,390,000	2	125,000	5
Feed (local)	616,000	3	114,000	6
Manure (To AD)	186,000	4	No data	n/a
Feed (imported)	74,900	5	13,900	10
Slurry (To AD)	70,000	6	No data	n/a
Food loss (All destinations)	34,300	7	200,000	2
Synthetic N Fertiliser (Input)	26,600	8	221,000	1
Synthetic K Fertiliser (Input)	11,900	9	4,920	11
Chemical wastes (All destinations)	7,830	10	93,900	7
Synthetic P Fertiliser (Input)	6,750	11	3,660	12
Plastic wastes (All destination)	5,040	12	16,000	9

8.1.19 Dairy

Table 13: Key material and product streams for the dairy sector in Scotland ranked by quantity and GHG emissions

Material/product flow	Quantity		GHG emissions	
	Tonnes/yr	Rank	Tonnes CO2e/yr	Rank
Slurry (To land)	2,720,000	1	131,000	5
Manure (To Land)	509,000	2	187,000	3
Feed (local)	215,000	3	39,900,000	1
Slurry (To AD)	79,600	4	No data	n/a
Food loss (All destinations)	26,400	5	154,000	4
Feed (imported)	26,200	6	4,860,000	2
Manure (To AD)	14,900	7	No data	n/a
Synthetic N Fertiliser (Input)	9,280	8	97,000	6
Chemical wastes (All destinations)	6,020	9	72,300	7
Synthetic K Fertiliser (Input)	4,150	10	1,720	9
Plastic wastes (All destination)	3,880	11	12,300	14
Synthetic P Fertiliser (Input)	2,360	12	1,280	10

8.1.20 Sheep

Table 14: Key material and product streams for the sheep sector in Scotland ranked by quantity and GHG emissions

Material/product flow	Quantity		GHG emissions	
	Tonnes/yr	Rank	Tonnes CO2e/yr	Rank
Feed (local) (Input)	2,090,000	1	388,000,000	1
Manure (To Land)	523,000	2	16,600	6
Slurry (To land)	59,100	3	11,600	7
Synthetic N Fertiliser (Input)	22,500	4	110,000	3
Feed (imported) (Input)	15,500	5	2,880,000	2
Manure (To AD)	15,300	6	No data	n/a
Food loss (All destinations	14,000	7	81,600	4
Synthetic K Fertiliser (Input)	10,100	8	4,170	10
Synthetic P Fertiliser (Input)	5,730	9	3,110	11
Chemical wastes (All destination)	3,190	10	38,300	5
Plastic wastes (All destinations)	2,050	11	6,530	8
Other organic fertiliser (Input)	1,950	12	7,460	9

8.1.21 Horticulture

Table 15: Key material and product streams for the horticulture sector in Scotland ranked by quantity and GHG emissions

Material/product flow	Quantity		GHG emissions	
	Tonnes/yr	Rank	Tonnes CO2e/yr	Rank
Straw and crop residues (To Land)	208,000	1	No data	n/a
Food loss (All destinations)	127,000	2	48,700	4
Peat growing media (Input)	45,600	3	80,600	2
Other growing media (Input)	41,100	4	298	14
Synthetic N Fertiliser (Input)	36,200	5	112,000	1
Chemical wastes (All destinations)	4,950	6	16,900	6
Plastic wastes (All destinations)	4,600	7	55,100	3
Synthetic K Fertiliser (Input)	2,960	8	9,400	7
Synthetic P Fertiliser (Input)	2,210	9	916	9

8.1.22 Arable

Table 16: Key material and product streams for the arable sector in Scotland ranked by quantity and GHG emissions

Material/product flow	Quantity		GHG emissions	
	Tonnes/yr	Rank	Tonnes CO2e/yr	Rank
Straw and crop residues (animal bedding)	753,000	1	No data	n/a
Straw and crop residues (animal feed)	380,000	2	No data	n/a
Straw and crop residues (Unused)	294,000	3	190,000	2
Straw and crop residues (To land)	225,000	4	2,020	9
Straw and crop residues (Horticulture use)	161,000	5	No data	n/a
Straw and crop residues (Other uses)	161,000	6	No data	n/a
Food loss (All destinations)	88,400	7	529,000	1
Synthetic N Fertiliser (Input)	28,900	8	48,700	3
Synthetic K Fertiliser (Input)	12,900	9	18,000	6
Chemical wastes (All destinations)	11,800	10	13,400	8
Plastic wastes (All destinations)	7,550	11	45,300	4
Synthetic P Fertiliser (Input)	7,360	12	1	10
Other organic fertilisers (Input)	2,510	13	44,800	5
Pesticide (Input)*	1,200	16	14,400	7

*Included due to high GHG rank, despite lower quantity rank.

8.1.23 Methods for prioritising options for action

8.1.23.1 Economic impact

Where possible a qualitative assessment of the economic scale of each material/product stream was completed. This was completed by applying a cost in £/tonne of a material to the volume/quantity in tonnes. The cost values came from the Scottish Farm Management Handbook. Where a cost was not available for a product stream a likely cost implication was estimated based on team industry knowledge

Where cost data was available a quantitative assessment of the farm economic impact was carried out. The main source of cost data used was the Scottish Farm Management Handbook. In cases where robust cost data was not available a qualitative approach was applied using expert judgement within the research team and findings from the REA.

8.1.23.2 Scope for action

Qualitative assessment, based on research for this study and expert judgement showing the degree to which circular actions are understood, well established and adopted in Scotland.

8.1.23.3 Policy need

Qualitative judgement on whether further policy intervention could potentially play a role in driving adoption of circular actions.

8.1.23.4 Prioritising options for action

Table 17 shows the results of the prioritisation process, which considers the quantity of material flowing through the Scottish agriculture sector each year, each material's GHG emissions, and then economic impact, potential to become more circular, and need for policy support.

Table 17: Results of prioritisation of materials and product streams within the system annually (key provided in Table 18).

Material	Significant quantity (rank)?	Significant GHGs (rank)?	Economic impact?	Scope for action?	Policy need?
Farmyard manure (Waste, To Land)	1	4			
Feed (grass and straw) (Input)	2	25			
Slurry (Waste, To Land)	3	6			
Feed (local) (Input)	4	5			
Straw and crop residues (Waste, Other uses)	5	25			
Straw and crop residues (Waste, To land)	6	25			
Straw and crop residues (Waste, Animal Feed)	7	25			
Total food loss (Waste, All destinations)	8	3			
Straw and crop residues (Waste, Unused)	9	25			
Fuel (tonne oil equivalent)	10	2			
Farmyard Manure (Waste, To AD	11	25			
Feed (imported)	12	10			
Slurry (Waste, To AD)	13	25			
Synthetic N Fertiliser (Input)	14	1			
Synthetic K Fertiliser (Input)	15	11			
Peat growing media (Input)	16	8			
Other growing media (Input)	17	21			
Chemical wastes (Waste)	18	23			
Synthetic P (P2O5)	19	14			
Plastic wastes	20	9			
Other organic fertiliser	21	7			
Undifferentiated materials	22	18			
Metallic wastes	23	12			
Discarded vehicles	24	24			
Used oils	25	15			
Pesticide	26	13			
Rubber wastes	27	17			
Paper and cardboard wastes	28	19			
Wood wastes	29	22			
Glass wastes	30	16			
Discarded equipment	31	20			

Table 18: Colour coding key for Table 17.

Colour meaning	Significant Quantity?	Significant GHGs?	Economic impact	Scope for action	Policy need?
Green indicates the materials that are the highest priority for action.	Above 100,000 tonnes	Above 50,000 tonnes	Significant cost/impact on profitability	Circular practices not common	Yes – not already addressed and policy could help.
Yellow indicates materials that are a moderate priority for action, with some potential for intervention but less significant opportunities than those shown in green.	10,000 to 100,000 tonnes	10,000 to 50,000 tonnes	Some costs e.g. waste disposal cost	Some circular practice or unclear.	Partial or planned policy
Red indicates materials with the lowest priority for action.	Below 10,000 tonnes	Below 10,000 tonnes or uncertain GHGs		Well established solutions/ uptake.	No – existing policy, or not suitable for policy intervention.
			Not rated	Not rated	Not rated

Appendix E – Impact Assessment Methodology

This Appendix contains a breakdown of the methodologies and assumptions used to calculate the emissions impact of each circular action.

8.1.24 Feed

8.1.24.1 Waste material

Table 19. Background data, calculations, and sources used for assessing the impact of using waste material as animal feed

Value	Unit	Description	Source
47	%	The use of by-product in animal feed reduced by 47% between 2012 and 2019	Optimising sustainability: Circular pathways for Scotch Whisky distillery co-products
53	%	Percentage of the by-product used for animal feed in 2012 that is still used for animal feed	Calculation (derived from value above)
685,140.74	tonnes	Current volume of by-product going to feed	ZWS Scotland Database, tab 'By-Products - Updated', sum of columns C, I:K
1,007,156.89	tonnes	Volume of by-product that can go to feed	Calculation
32%	% (CP in DM of by-product)	This is an average of the crude protein content of the 4 by-products looked at in this study, Table A1	Optimising sustainability: Circular pathways for Scotch Whisky distillery co-products

Value	Unit	Description	Source
322,290.21	tonnes of CP in by-product	This is the CP in the by-product that could go to feed based on historical value	Calculation
50%	%	Feasible percentage of total CP from by-product that might go to animal feed	
161,145.10	tonnes CP	Feasible quantity of CP from by-product that may go to animal feed	
1,719,000.00	tonnes of animal feed (non-grass)	This is total non-grass animal feed	Applying a process-based livestock model to predict spatial variation in agricultural nutrient flows in Scotland
18%	% (CP in animal feed (non-grass)	The average CP content of different animal feeds	fas.scot/downloads/farm-management-handbook-2024-25/
309,420.00	tonnes CP in animal feed (non-grass)	Total crude protein fed to animals (non-grass)	Calculation
52%	%	Percentage of total CP requirement that could be fulfilled by waste product	

To get an estimate of the quantity of by-product that may be used for feed we used Duffy et al. (2023), which reported that it decreased by 47% between 2012 and 2019. We increased the current quantity of by-product used in feed to get an estimate of what this could be increased to. However, we also employed a factor of 50% to this estimated value as it was assumed that there would not be a complete return to the 2012 scenario.

8.1.24.2 Performance improvements

Table 20. Background data, calculation and sources used for assessing the impacts of performance improvements in beef in Scotland

Value	Unit	Source
557,700	suckler bred animals per year (from study)	Ryan et al., 2025
16,290	tonnes of DM per year (from the study)	Ryan et al., 2025
0.03	tonnes of DM per animal per year	Calculation
29.21	kg feed per animal per year	Calculation
891,484	number of beef cattle	Census
26,039,581.07	kg feed per year	Calculation
26,039.58	tonnes feed per year	Calculation

This action is based on the potential of genetic improvements to reduce feed requirements in livestock. The assessment of this action was based Ryan et al. (2025). This paper reported a reduction of 16,290 tonnes of dry matter per year for a herd of 557,700 sucklers due to genetic improvements. This works out at 0.03 tonnes of dry matter animal^{-1} year^{-1}. When

this is scaled up based on the heads of beef cattle in the Scottish Agricultural Census (Scottish Government, 2024) (891,484 heads), there is a potential saving of 26,038 tonnes of feed. This action is only relevant to beef due to availability of data suitable for including in this assessment. Furthermore, genetic improvement is relatively advanced in dairy systems, while it is very difficult to implement this in sheep systems.

8.1.24.3 Insects

Table 21. Background data, calculation and sources used for assessing the impacts of using insect protein in livestock feed

Value	Unit	Description	Source
378,000	tonnes	poultry feed demand by 2040 in tonnes	The_future_of_feed_July_2021.pdf
92,000	tonnes	pig feed demand by 2040 in tonnes	The_future_of_feed_July_2021.pdf
470,000	tonnes	total pig and poultry demand	Calculation
13%	%	estimate of total demand met by UK production	The_future_of_feed_July_2021.pdf
61,100	tonnes	tonnes of insect protein produced in the UK for pig and poultry	Calculation
13%	%	Percentage of total UK pig and poultry production in Scotland	Dashboard file (using UK and Scottish Census data)
7,943.00	tonnes		Calculation

The basis for this assessment was data presented in 'The Future of Feed: A WFF Roadmap to Accelerating Insect Protein in UK Feeds'. This estimated that by 2040 demand for insect protein for the pig and poultry sectors in the UK will reach 470,000 tonnes.

WWF reported that 13% of the demand could be produced within the UK, based on a projection that 48 production facilities will be operational by 2040. Applying this percentage to the projected value of 470,000 tonnes of insect protein, results in 61,100 tonnes of insect protein for the UK pig and poultry sectors, produced in the UK.

This value was scaled down from the whole UK level to the Scotland. The percentage of total UK pig and poultry production based in Scotland was calculated based on the livestock numbers from the Scottish Agricultural Census and the UK National Inventory Report. Scottish pig and poultry account for 7 and 6% of total UK production, respectively. Therefore, the Scottish portion of the UK demand for UK produced insect protein is 13% or 7,943 tonnes.

This report focuses on demand for insect protein with the pig, poultry, and aquaculture sectors. This is because there is anticipated change in legislation that could allow for insect protein being fed to these sectors, while this change is not anticipated for ruminants currently. It is also noted in this report that pigs and poultry have higher dietary protein requirements compared to ruminants.

8.1.24.4 Extending the grazing period

Table 22. Background data, calculation and sources used for assessing the impacts of extending the grazing period in the Scottish beef herd

Value	Unit	Source
30	days extra grazing per year	Rotational grazing systems for cattle | AHDB
15	kg dry matter a day	Rotational grazing systems for cattle | AHDB
450	kg DM saved per cow per year	Calculation
891,484	number of beef cattle	Scottish Agricultural Census
50%	% of cattle applicable	Expert judgement
445,742	number of applicable beef cattle	Calculation
200,583,900	kg DM saved per year	Calculation
200,584	t DM saved per year	Calculation

The Agriculture and Horticulture Development Board (AHDB) reported an example of extending the grazing period for beef production of 30 days. In this example there was a saving of 15kg DM per day per cow. Therefore, DM intake could be reduced by 450kg per cow per year.

This was then scaled up to the Scottish herd. However, it was assumed that due to land quality or accessibility issues etc. that it was feasible to extend the grazing period for only a portion of the Scottish herd. The value of 50% was applied as an estimate, in lieu of a published figure for this portion. This left 445,742 cattle to considered feasible for this action, and that the impact value of 450 kg DM per cow per year was applied to.

Not having a robust value for the area of land suitable for extended grazing in Scotland is a key limitation to this methodology.

8.1.25 Food

8.1.25.1 Storage

Table 23. Percentage of grain rejections by each rejection reason

Reason	Percentage of total grain rejected by each reason
N Level	26%
Moisture Level	26%
Specific Weight	23%
Infestation	4%
Impurities	6%
Temperature	4%
Other	11%

The table above contains the percentage breakdown of grain rejected by reason based on a survey carried out by Aberdeen Grain (Aberdeen Grain, n.d.). Rejections due to moisture level, infestation, impurities, and temperature were considered as having the potential to be mitigated through better storage facilities. This resulted in 40% of total grain rejections being relevant to this action.

Table 24. Presents the calculation of reduced grain loss due to improved storage

Scenario	Quantity (tonnes)	Unit	Source
Baseline (All food)	353,689	tonnes	WWF Hidden Waste Report
Lost grain percentage	7%	%	WWF Hidden Waste Report
Baseline (Lost grain)	25,487	tonnes	Calculation
Possible to reduce lost grain by	40%	%	https://www.aberdeengrain.co.uk/membership/crop-storage-survey?
New (Lost grain)	10,195	tonnes	Calculation

Total food loss is estimated as 353,689 tonnes. Grains account for 7% of total food loss, which equates to 25,487 tonnes. It is assumed that 40% of rejected grain can be mitigated by improved storage, based on the data reported by Aberdeen Grain. This results in 10,195 tonnes of grain being saved.

8.1.25.2 Redistribution

Table 25. Total production of potato, fruit, and vegetables in Scotland

Food type	Production value	Unit	Source	Link
Potato	1,161,244.64	tonnes	ERSA, Table A4	Scottish Government, 2020
Vegetables	432,796.64	tonnes	ERSA, Table A4	Scottish Government, 2020
Fruit	44,301.30	tonnes	ERSA, Table A4	Scottish Government, 2020
Total	1,638,342.58	tonnes	Calc	n/a

Table 26. Volume Availability Assumption – Grade-outs

Crop	Over-plantings as % of Total Crop	% of Overplantings Useable	% of Useable Over-plantings available to SFI
Carrots	15%	66%	33%
Onions (dry bulb)	10%	50%	40%
Leeks	10%	40%	50%
Broccoli + Cauliflower	8%	40%	50%
Cabbages	10%	25%	50%
Lettuce	15%	20%	66%
Tomatoes	15%	33%	66%
Apples (desert)	20%	66%	25%
Strawberries	15%	50%	66%
Average	13%	43%	50%

Table 27. Volume Availability Assumption – Over-plantings

Crop	Over-plantings as % of Total Crop	% of Over-plantings Useable	% of Useable Over-plantings available to SFI
Carrots	5%	80%	33%
Onions (dry bulb)	3%	90%	40%
Leeks	5%	80%	45%
Broccoli + Cauliflower	6%	80%	50%
Cabbages	6%	80%	50%
Lettuce	8%	75%	50%
Tomatoes	6%	75%	50%
Apples (desert)	3%	85%	50%
Strawberries	10%	80%	50%
Average	6%	81%	46%

Table 28. Volume assumptions for potato production available for redistribution

Description	Value	Unit	Source
Total potato production (England)	3885	000 tonnes	https://fareshare.org.uk/wp-content/uploads/2024/05/FareShare-Food-SFI.pdf
Total for redistribution (over-plantings)	36.5	000 tonnes	https://fareshare.org.uk/wp-content/uploads/2024/05/FareShare-Food-SFI.pdf
Total for redistribution (grade-outs)	92.2	000 tonnes	https://fareshare.org.uk/wp-content/uploads/2024/05/FareShare-Food-SFI.pdf
Percentage of total for redistribution (over-plantings)	1%	000 tonnes	Calc
Percentage of total for redistribution (grade-outs)	2%	000 tonnes	Calc

Table 29. Quantities of potato, vegetables, and fruit available for redistribution

Food type	Value	Unit	Source
Potato	38,469.03	tonnes	Calc
Vegetables	37,192.64	tonnes	Calc
Fruit	3,808.20	tonnes	Calc
Total	79,469.87	tonnes	Calc

This action focuses on saving edible on-farm food waste and redistributing it in the food supply chain via organisations such as FareShare. The basis of this assessment was a report completed by The Andersons Centre, for Fareshare. This report contained percentages of total production of fruit, vegetables and potatoes that would be available for the redistribution action. These are presented here in Table 26, Table 27 and Table 28. The

percentages in these tables are applied to the total Scottish production values for each of these three food categories sourced from the Economic Report for Scottish Agriculture that are presented in Table 25. Table 29 presents the results of this; the quantities of potato, vegetables, and fruit that could be redistributed instead of going to waste.

The emissions impact of this is calculated as the emissions avoided in sending this quantity of food to landfill.

8.1.25.3 New dairy equipment

Table 30. This table contains the background data, calculation and sources used for assessing the impacts of new dairy equipment on on-farm food loss

Description	Value	Unit	Source	Link
Percentage lost	1.1%	%	Food Waste in Primary Production: Milk Loss With Mitigation Potentials	March et al., 2019
Produced	1,311,000,000	litres	Economic Report on Scottish Agriculture, Table A6	Scottish Government, 2020
Lost	13,765,500	litres	Calculation	n/a
Lost	13,766	thousand litres	Calculation	n/a
Milk density	1.03	g/ml	University of Guelph	Goff et al., n.d.
Lost	14,178	tonnes	Calculation	n/a
Efficacy of technology	50%	%	Food Waste in Primary Production: Milk Loss With Mitigation Potentials	March et al., 2019
Impact	7,089	tonnes	Calculation	n/a

According to March D., et al. (2019), 0.5 and 0.55% of milk produced in Scotland is lost due to bulk infrastructure and antibiotic residue, respectively. It was therefore assumed here that of total milk production, 1.1% is lost due to reasons that could be mitigated with advanced equipment. See Section 5.2.35.2.3 for more detail on this action.

From the ERSA, it was determined that 1,311,000,000 tonnes of milk is produced in Scotland in a year, and when converted to weight in tonnes, using a density of 1.03g/ml, it was determined that 14,178 tonnes of milk is lost due to the two reasons mentioned above. This was the value that was considered relevant to this action.

The efficacy of this action (which considered both the technology itself and also the uptake rate) was set as 50%, which was based on a scenario in the paper by March D., et al. (2019).

This resulted in 7,089 tonnes of milk saved from loss and retained in the food system.

This 7,089 tonnes of milk saved, equates to a 2% reduction in the total food loss value of 353,689t.

The emissions savings was calculated as the avoided emissions from this milk going the waste of this milk as the alternative route. Total food loss emissions were estimated as

647,077tCO_2e, and the saving in milk loss accounted for 2% of total food loss. Therefore, total food loss emissions were reduced by 2%. This resulted in an estimated emissions saving of 12,970tonnes CO_2e.

8.1.26 Plastic

8.1.26.1 BaleSafe

BaleSafe has been used on 45% of bales by a farmer in Scotland (Kelvin Cale, n.d.). There is no technical limitation on this action and so 100% of straw/hay bales could have BaleSafe applied. The plastic quantity was reduced by 20%. This is lower to offer a conservative estimate while also accounting for the plastic quantity not being entirely applicable.

8.1.26.2 Re-use of crop covers and containers

Table 31. Background data, calculation and sources used for assessing the impacts of re-using crop-covers and containers

Value	Unit	Description	Source
75%	%	Farmers not re-using any LDPE	https://cdn.zerowastescotland.org.uk/managed-downloads/mf-ndywketi-1680012009d
0.75	no.	Purchases per year in re-use scenario (1 in 3 years)	https://cdn.zerowastescotland.org.uk/managed-downloads/mf-ndywketi-1680012009d
56%	%	Plastic reduction	Calculation

The basis of this assessment was data reported in the Zero Waste Scotland report 'A Market Analysis of Farm Film Plastics'. This reported that 75% of farmers are not reusing any LDPE film. It also reported that farmers who do reuse film typically do so twice – meaning they purchase new film 1 in 3 years (or 0.75 purchases a year). We assumed that the 75% of farmers not currently reusing any film could start to reuse at this rate. This equates to a 56% reduction in plastic.

The emissions impact was modelled as the avoided production and disposal emissions from the quantity of plastic that is saved.

8.1.26.3 Plastic Recycling

Table 32. Background data, calculation and sources used for assessing the impacts of recycling agricultural plastics

Value	Unit	Description	Source	Link
24,037.00	tonnes	Total plastic waste	SEPA	
35%	%	This value is number of farmers who responded that their plastic is not collected, assumed that this 35% of farmers reflects 35% of plastic - which may not be the case.	Zero Waste Scotland Report	Zero Waste Scotland, 2023
8,412.95	tonnes	Plastic waste that could be recycled		

In the Zero Waste Scotland report, 35% of farmers responded that their plastic is not collected. Therefore, it was assumed for the *'Recycling'* action that there was 35% of plastic that could be recycled that is not currently.

Plastic collectors (Table 33) and processors (Table 34) were checked across Scotland and are summarised in Tables below. This verification suggests that while there is broad coverage of plastic collection and processing facilities, there is scope to broaden this; perhaps, in more frequent or further reaching collections.

This resulted in 8,413 tonnes more recycled plastic.

The emissions impact was calculated by increasing the quantity of plastic waste that is disposed of through recycling, and applying the emission factor for this route of 4.68568 $kgCO_2e$/tonne of material.

The assumption that 35% of plastic was not recycled because 35% of farmers responded that their plastic was not collected is a limitation of this method. The amount of plastic waste created on a farm will vary based on size and farm type, so 35% of farmers do not necessarily create 35% of plastic waste.

Table 33: Collectors of Agricultural Plastic Operating in Scotland

Collectors:	Link:	Location/Reach:	Coverage:
Solway	Farm Plastic Recycling | Recycled Plastic Products | Solway Recycling	Based in Dumfries - seems to have quite wide reach - states UK wide - a lot of local collection hubs across Scotland	Covers most plastics I can think of (bale wrap, crop cover, feed bags, bilk bags, drums, buckets, bottles, wrap)
Wyllie	Wyllie Recycling	Aberdeenshire, Angus, Clackmannanshire, Dundee, Highland, Moray and Stirling Councils	various films and polytunnel, 5L containers up to 1000L IPBCs
Farm Waste Recycling	Farm Waste Recycling » The first choice for agricultural and equestrian waste recycling	Based in Dundee, offers drop-off or collection, unsure of reach for collection	most types of farm waste including cardboard, chemical drums, fertiliser bags, and silage wrap'
Caledonian Recycling	Caledonian Recycling | Forth Resource Management Ltd	Drop-off at site in Galashiels, or collection, unsure of reach of collection, and they operate collections three times a year	Among others: Fertiliser and seed bags, Silage wrap, Net wrap and string (collected separately), Crop cover Not sure on hard plastics
Binn Group	Agriculture - Binn Group	Based in Perth	collection and recycling service for all agricultural waste

Table 34: Plastic Recycling Processors in Scotland Which May Take Agricultural Plastics

Processor:	Link:	Location:	Coverage:
RPC bpi recycled products	can't find the right one - but seems to be still open according to Google/Co-pilot	Dumfries	Unsure
Plaswood	Sustainable Plastic Wood UK | Recycled Products by Plaswood	Dumfries	Unsure
WRC Recycling	WRC Recycling: Waste Management - Skip Hire - Scotland	Glasgow area	LDPE film, among others but unsure of coverage
Agri.Cycle	Specialist Farm Plastic Waste Recycling | Agri.Cycle	UK wide network - collection service that can cover Scotland depending on collection schedule	Wide range of farm plastics (silage wrap, fertiliser bags, tree guards)
Solway	Farm Plastic Recycling | Recycled Plastic Products | Solway Recycling	Based in Dumfries	Solway collects waste and recycles it but unsure of how /what they reprocess it. They see to have recycled plastics for sale so they must do it

8.1.27 Straw

8.1.27.1 Replacement for peat in horticultural growing medium

Table 35. Summary of results of the impact of replacing peat in horticultural growing medium

Scenario	Quantity Used (tonnes)	Emissions (tCO2e)
Baseline	45,628	80,633
New	9,126	16,127
Absolute Impact	36,502	64,506
Relative Impact	80%	80%

The impact of using straw as a horticultural medium was to replace peat. The peat quantity was reduced by 80% based on two UK companies that sell horticultural media; one selling 100% peat-free mixes (ICL Growing Solutions, 2025) and the other selling 60% reduced peat mixes (Sinclair, n.d.). Therefore, the mid-point was assumed and the quantity of peat used was reduced by 80%.

The emissions were reduced by 80% also, in line with this.

Whilst sufficient straw is theoretically available to replace 80% of peat, as noted in Section 5.2.2, there are a variety of materials that could potentially be used along with straw to produce horticultural growing medium. In practice growers may use a composite product, including straw, composted straw and other materials. It was assumed for these calculations that the materials used to replace 80% of peat in growing medium would all be other waste

materials sourced in Scotland, and so would have relatively low emissions. Therefore, these emissions were not considered here.

It was assumed that there would be transport required, and therefore associated emissions, whether peat or alternative materials were used for the medium. This is practically based on the assumption that the replacement materials will all be locally sourced, waste materials. Therefore, transport emissions were not considered in this calculation.

8.1.27.2 Conversion to biochar

Table 36: Soil organic carbon sequestration rate under different soil management scenarios

Scenario	SOC-2014 (gC/kg)	SOC-2021 (gC/kg)	SOC-ST (kgC/ha)	SOC-SR (kgC/ha/yr)
Conventional tillage	7.45	7.89	1154.5	164.9
Wheat straw	7.45	8.74	3348.4	478.3
Straw biochar	7.45	9.84	6205.0	886.4

Table 36 shows the soil organic carbon sequestration rate under different soil management scenarios, including wheat straw retention, and application of biochar made from wheat straw. These values were sourced from Chang *et al.* (2025). The difference between the sequestration under wheat straw (3,348.4kgC/ha) and biochar (6,205.0kgC/ha) scenarios was calculated as 2,856kgC/ha. This was the impact value that was used in the calculations detailed below (Table 37).

Table 37: Data points for calculations

Value	Unit	Source	Description
408.10	kgC/ha/yr	Chang *et al.* (2025)	The increase in SOC sequestered through using straw biochar compared to just straw
3.67	n/a	n/a	C to CO_2 conversion
1,497.73	kgCO2/ha /yr	Calculation	The SOC sequestered is converted to a CO_2 saving (emission reduction)
1.50	tonnesCO2 /ha /yr	Calculation	Conversion between kg and tonnes CO_2
473,259.00	hectares	Scottish Agricultural Census	Area of combined crops
29%	%	ZWS Database	% of total arable straw that is sent to land or unused Assume that this is the max amount of straw that can be used for conversion to biochar and applied to soil
135,452.11	hectares	Calculation	Area of combined crops that can have the straw produced on it converted to biochar and applied to soil
50%	%	Expert judgement	Feasible potential uptake of straw conversion to biochar and application of soil
67,726.06	hectares	Calculation	Hectares of arable land that may have biochar applied
101,435.14	tonnesCO2	Calculation	Emission reduction due to increased SOC sequestration

In this study, straw was applied at 8t/ha while biochar was applied at 5t/ha. 5t of biochar was produced from 8t of wheat straw so the quantity of straw used is the same.

These values have been checked against other research papers and are considered a reasonable application rate (Vijay *et al.*, 2021). However, it is worth noting that that impacts of biochar are vary variable as a direct result of the variation possible in feedstock, process, application, and environmental factors.

A limitation of this method is the uptake rate of 50%. While biochar is extensively researched in lab and field trials, commercial uses are still limited and so determining an accurate projection for uptake is difficult.

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