A Review of Solutions to Reduce Reliance on Soy-Containing Feed and Synthetic Fertilisers in the UK

The Co-op Foundation

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Report For

The Co-op Foundation

Research Team

Rebecca Mason

Hugo Bennetts

Helena Connors

William Fitter

Technical Leads

Daniel Stunell

Rebecca Mason

Prepared By

Rebecca Mason

Hugo Bennetts

Helena Connors

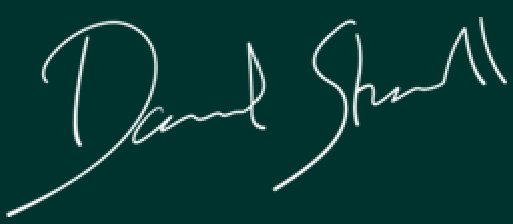
William Fitter

Isabelle Williamson

Quality Review

Daniel Stunell

Approved By



Daniel Stunell

Project Director

Eunomia Research & Consulting Ltd
37 Queen Square
Bristol
BS1 4QS
United Kingdom

Tel +44 (0)117 9172250
Fax +44 (0)8717 142942
Web www.eunomia.co.uk

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Executive Summary

Reducing reliance on soy-containing animal feed and synthetic fertilisers are two of the key environmental challenges facing farmers today. Recognising the challenges, Co-op Foundation in partnership with the Co-op dedicated the second round of the Carbon Innovation Fund to decrease farmers' reliance on soy-containing feed and synthetic fertilisers through funding projects and trials, while encouraging collaboration that further test and scale up innovative solutions.

This study aims to contextualise Carbon Innovation Fund Round 2 (CIF2) within the field of reducing the reliance on soy-containing feed and synthetic fertilisers in the UK and internationally. The research explores a range of solutions to reducing farmers' reliance and maps organisations that work in these areas.

Globally, the expansion of agricultural land is the primary driver of deforestation. Notably, soy production is expanding into the Amazon Rainforest and Cerrado, with potentially disastrous consequences for the global climate. Over 90% of all soy produced is used to feed livestock,[1] which is much less land use efficient than feeding it directly to humans. Finding alternatives to soya used for animal feed with a lower land requirement will be a key component in halting the expansion of global agricultural land, and ultimately reducing overall land demand to facilitate natural regeneration.

Synthetic fertilisers cause a range of environmental problems, including greenhouse gas (GHG) emissions (both during fertiliser production and following application to soils), water pollution (from nutrient leaching), and air pollution (from soil ammonia emissions). There are two main categories of 'solutions' to reduce reliance on synthetic fertiliser. Firstly, there are those that reduce the need for fertilisers (whether these are synthetic or organic alternatives), and secondly there are alternatives to synthetic nitrogen. Reducing the need for fertilisers overall reduces all of the environmental impacts listed above. Fertiliser alternatives may only reduce the manufacturing GHG emissions, except for those that also improve soil structure and therefore reduce leaching. Therefore, the optimal approach is to primarily reduce the overall *demand* for fertilisers, whilst *substituting* the remaining demand (as far as possible). Demand reduction is a win-win for both farmers and the environment as it lowers input costs whilst reducing emissions and pollution.

This report assesses four potential 'solutions' to reduce reliance on soya used for animal feed and seventeen potential 'solutions' to reduce reliance on synthetic fertiliser. These solutions are each assessed in terms of their: transformation potential and scalability; wider environmental impact; development stage; barriers to uptake; strength of evidence; and applicability to the UK context. This analysis shows that there is no silver bullet solution to reducing the reliance on either soya used for animal feed or synthetic fertilisers. The food system is too diverse for a one-size-fits all approach and so both challenges will likely need a mix of solutions.

For soy, there are possibilities with all four solutions looked at. Domestic production of grain legumes (of which soy is one) can onshore production of a valuable crop and diversify cropping, but will not reduce global land use. Food waste offers two distinct solutions. It can be fed directly to animals in some circumstances, or become feed via the use of insect farming to generate an alternative feed. These are attractive options for the medium term, but ultimately reducing food waste is a greater environmental priority, so the volume of food waste is limited and should fall over time. Microbial protein using inedible crop residues is an approach still in its development phase but its potential to radically reduce global agricultural land use is significant.

For synthetic nitrogen fertiliser, the aim should primarily be to reduce the demand for fertilisers whilst swapping the remaining demand from synthetic to other sources of reactive nitrogen (as far as possible). A sustainable system is likely to be characterised by a diverse application of the solutions reviewed here, applied according to local circumstances.

The solutions reviewed included a combination of both low- and high- tech solutions. Approaches ranged from reinstating historical farming techniques, to implementing technologies that are market ready but not yet in widespread use, to accelerating R&D to bring developing technologies to market. Typically, lower-technology and more natural techniques can have the greatest overall environmental benefit, especially when it comes to improving soil health, which is a fundamental component of all sustainable food systems.

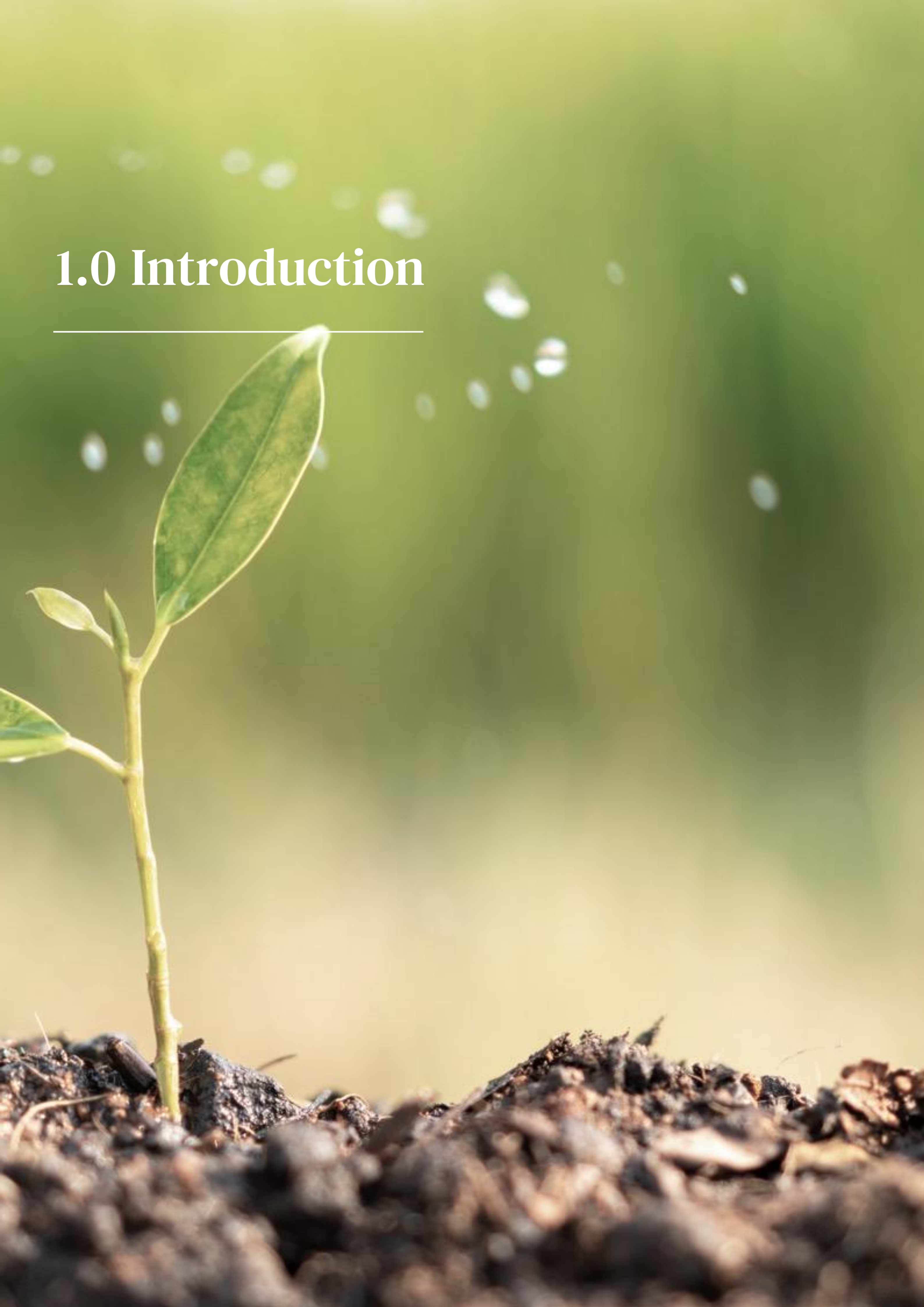
Table of Contents

List of Tables

Acronym Table

Acronym	Definition
AD	Anaerobic digestion
ABP	Animal by-products
BSF	Black soldier fly
CRF	Controlled release fertilisers
DAC	Direct air capture
ELM	Environmental land management
GHG	Greenhouse gas
GM	Genetically modified
MSS	Multi-species swards
NI	Nitrogen inhibitors
R&D	Research and development
TRL	Technology readiness level

1.0 Introduction



1.1 Introduction

1.1.1 About the Co-op Foundation

The Co-op Foundation is Co-op's charity. It co-operates for a fairer world. The charity believes co-operation is at the heart of strong communities, and this makes them a different kind of funder. The charity works closely with communities, by listening and learning. The charity unlocks communities' power by focusing on those who have most at stake.

1.1.1.1 About the Carbon Innovation Fund

In 2021, the Co-op Foundation and the Co-op partnered in a three-year £3.5m Carbon Innovation Fund. This is funded through Co-op donations raised from the sale of compostable carrier bags in the UK, as well as Co-op Foundation funds.[2]

The pilot year of the Carbon Innovation Fund supported initiatives working to reduce the environmental impact of the food and farming sector. Upon reflection and advice from experts in the field, it was decided that round two should take a more focused approach. This will allow for deeper impact, better synergy between partners, and a wealth of learning that could be openly shared.

As a result of a consultation process to test out different focus areas with a panel of industry experts, the second round of funding is going towards initiatives which help to reduce the UK's reliance upon:

- Soy-containing animal and fish feed; and
- Synthetic fertilisers.

The aim of the second round of the Carbon Innovation Fund is therefore to decrease farmers' reliance on soy-containing feed and synthetic fertilisers through funding projects and trials, while encouraging collaboration that further test and scale up innovative solutions.

1.1.2 Why Focus on Feed and Fertiliser?

Crop and livestock production in the UK depends upon a sustainable nutrient cycle; there needs to be a reliable supply of key nutrients such as nitrogen, phosphorus, and potassium to produce the food we eat. Protein-rich animal feed and fertiliser are two of the key sources of these nutrients for UK agriculture. Currently, much of these are imported from outside the UK, for example, the majority of phosphorus used in the UK food system is contained within imported feed and fertiliser.[3] These key nutrient inputs have spiralled in financial cost in recent years, and at the same time generate significant negative impacts, posing both environmental and economic challenges. Understanding how we source and use nutrients, and how this impacts the global and national nutrient cycle to manage surpluses and deficits will be a major factor in moving towards a sustainable food system.

To address these challenges, there has been an influx of interest and innovation in affordable and sustainable alternatives to traditional feed and fertiliser, as well as ideas which help reduce reliance on them altogether. Some techniques use cutting-edge technology, while others bring back the increasingly well-understood benefits of traditional techniques. While eliminating soy and synthetic fertilisers overnight is not viable, and may not even be desirable, changes to the current approaches are necessary, and these new ideas and alternatives aim to reduce deforestation rates, greenhouse gas emissions, help farmer livelihoods and protect biodiversity.

One approach to reducing reliance on soy-containing feed and synthetic fertiliser would be to decrease the intensity of agricultural production. For both inputs, decreasing intensity by a) rearing more livestock on forage/grazing than feed, or b) growing the same amount of crops over a larger area, would reduce the food system's reliance on soy-containing feed and synthetic fertiliser. However, without changes to more resource efficient consumption and diets, both these approaches would increase overall land use. Given that agricultural already uses half of habitable land globally,[4] there is little opportunity to expand agricultural land without significant environmental and social consequences. Where these approaches do become possible is if they are combined with a reduction in demand due to dietary shifts and reductions in food waste, as this will reduce demand for agricultural produce opening up the opportunity for lower-intensity production with lower costs, greater resilience, and less reliance on inputs and imports. Against this background, the scope of this report is to analyse a distinct list of measures that can be implemented at the farm-level to reduce reliance on soy and fertiliser, rather than global shifts in consumption.

1.1.2.1 What is the Need to Reduce Reliance on Soy-containing Animal Feed?

By far the greatest environmental problem with soy-containing animal feed is land use, as occupying land for agriculture has a huge impact on climate and nature.[5] It is estimated that 6,655m^2 land per tonne of protein is required for the production of soybean meal concentrate.[6] Existing agricultural land use prevents carbon sequestration and nature recovery through natural regeneration (which can be seen as an ‘opportunity cost’ of the status quo), while agricultural expansion drives land use change, such as deforestation, which causes greenhouse gas (GHG) emissions and biodiversity loss. When it comes to soy, research has estimated that 96% of the climate impact of soybean production is associated with these land use requirements and only 4% is associated with production emissions.[Error! Bookmark not defined.] Reducing agricultural land use globally will be key to reducing the climate impact of agriculture.

1.1.2.2 What is the Need to Reduce Synthetic Fertiliser Inputs?

The manufacturing emissions associated with synthetic fertiliser production are substantial. These are often overlooked in an agricultural context because they are included under industrial – not agricultural – emissions in carbon accounting. The manufacturing emissions associated with nitrogen fertiliser (one of the primary types of synthetic fertiliser) used on UK farms are ~3 Mt CO_2e per year.[7] To provide a sense of scale, this is more than UK emissions from wastewater treatment (2.7 Mt CO_2e per year) and peat extraction (2.0 Mt CO_2e per year), but less than agricultural machinery (4.2 Mt CO_2e per year).[8] Furthermore, over-use of fertilisers (both synthetic and organic) also increases emissions of nitrate and nitrous oxide from the soil to which they are added. Additionally, excessive use of fertilisers (both synthetic and organic) and/or poor application techniques can cause nutrient leaching into waterways which in turn causes eutrophication and thus negatively impacts aquatic habitats and biodiversity.

1.2 This Study

1.2.1 Aim and Objectives

The aim of this study is to contextualise Carbon Innovation Fund Round 2 (CIF2) within the field of reducing the reliance on soy-containing feed and synthetic fertilisers in the UK and internationally. Specifically, the study has the following objectives:

- to explore a select range of solutions to reducing farmer’s reliance on soy-containing feed and synthetic fertiliser, to assess their feasibility, implementation potential, strength of evidence, and extent of impact; and
- to map the UK organisations that work in these areas and highlight examples of their practices.

This study is a standalone research project, but is also a first phase in the delivery the second round of CIF funding, in which Eunomia will be working collaboratively as a learning partner with both the Co-op Foundation, and funded projects, over the next two years. This first phase is a landscape analysis and evidence review, to both inform discussions about funding award, and to locate the funded projects in the wider context. In the second phase, Eunomia will be working to support funded projects to measure, assess, and share learning as they develop specific project ideas, and support the Co-op Foundation and Co-op to explore the effectiveness of their funding approach.

1.2.2 Methodology for this Review

This review has been conducted by consultants at Eunomia Research & Consulting Ltd.

1.2.2.1 Identifying Solutions

The research process began with an initial longlisting of solutions. This involved a review of solutions, followed by discussion with agricultural specialists within Eunomia to assess the global suite of solutions that are being developed. This was also followed by discussions with the Co-op Foundation who wanted to ensure that all the solutions represented by CIF2 applicants had been captured within the longlist. The solutions were then shortlisted in collaboration with the Co-op Foundation based upon their estimated applicability to the UK, development stage, and potential for transformation. This estimation was achieved through pre-existing technical knowledge within the Co-op and Eunomia teams.

The final shortlist of solutions included four which aim to reduce reliance on soy feed, and seventeen which aim to reduce reliance on synthetic fertiliser. These are listed in Table 1.

Table 1 List of Solutions

Reducing Reliance on Soy for feed	Reducing Reliance on Synthetic Fertiliser
1. Insect protein 2. Microbial protein 3. Growing alternative grain legumes 4. Pre-consumer food and organic waste	1. Precision fertiliser technology 2. Controlled release fertilisers (CRF) 3. GM Nitrogen fixing arable crops 4. Cover crops: legumes in crop rotations 5. Solid compost 6. Liquid compost/ compost tea 7. Manure 8. Seaweed 9. Shellfish by-product for wastewater nutrient recovery 10. Fish waste (fishery and aquaculture by products) 11. Rotational grazing 12. Digestate from anaerobic digestion 13. Human urine as fertiliser 14. Adding biochar to soils 15. Nitrification inhibitors (NIs) 16. Perennial crops 17. Multi-species swards

1.2.2.2 Refining Research Questions

A set of research themes and questions against which each potential solution would be assessed were developed through liaison between researchers at Eunomia and representatives from the Co-op Foundation based upon the initial project requirements project. These questions are presented in Table 2.

Table 2 Research Questions

	Research Theme	Research Questions
1	**Background**	**1a.** How does this solution work?
2	**Transformation potential**	**2a.** What is the extent of reduction per unit area/per animal?
		2b. How widely applicable is it to farms / is it scalable?
3	**Environmental impact**	**3b.** What are the wider environmental benefits?
		3c. Are there possible unintended environmental consequences?
4	**Development stage & barriers to uptake**	**4a.** What stage of development is it at?
		4b. If it's market ready, why is it not yet in widespread use? What are the key barriers to uptake?
5	**Strength of evidence**	**5a. Amount of evidence** *for whether the solution works/has unintended consequences (including key evidence gaps)*
		5b. Agreement of evidence *for whether the solution works/has unintended consequences*
6	**Relevance to the UK**	**1.** Is it *applicable* to UK farming? If not, why not? **2.** Is it already being implemented/trailed in the UK? If yes, please provide detail. If not, why not? **3.** Are the UK Government supportive of this solution and if so how/ if not why? **4.** If applicable, are UK-based organisations developing/promoting/ implementing this? If so, who are they?

1.2.2.3 Evidence Gathering

The Eunomia research team developed a set of solutions and compiled evidence for each solution into a comprehensive data collection instrument. All solutions were collated together to enable cross-comparison and ensure consistency of research approach between team members.

Evidence was drawn from 170 academic papers, research studies, websites and books, and are referenced according to Chicago style. Predominantly, online searches using Google were conducted to identify grey literature, which was supplemented by direct searches in databases and common academic journals. Table 3 lists a selection of the most common sources used in research.

Table 3 Key Sources used in Research

Databases	Academic Journals	Other
• National Atmospheric Emissions Inventory (NAEI) • ELMS payments database • WRAP Compost Calculator	• Nature Food • Plant Biotechnology Journal • Annals of Applied Biology • European Journal of Agronomy • Global Change Biology • Agriculture, Ecosystems & Environment • Environmental Science & Technology • Plants • Journal of Cleaner Production • Nature Microbiology • Applied Soil Ecology • Waste, Air and Soil Pollution • Advances in Agronomy • Agricology • Frontiers in Marine Science • Science Advances • Sustainability • Waste Management • Water Research • Microbial Biotechnology	• WRAP • WWF UK • ELMS (Defra) • Defra Farming Blog • Government's Agricultural Transition Plan 2021 to 2024 • Farmers Weekly • Delivering Clean Growth Through Sustainable Intensification - SCF0120 (Defra) • Farm Advisory Service • The Land Institute • Animal and Plant Health Agency • Morrisons Blog • Deep Branch • The Guardian • Innovative Farmers • Business Wales • King's College London

The methodological quality of sources identified was assessed through the:

- Reputability of the source and/or paper.
- Extensiveness of citations used in the paper.
- Reputability of the author.
- Comprehensiveness and rigour of the research from an entire lifecycle perspective.

- Robustness of the methodology and analysis.

Sources which were excluded from the research were those which:

- Where multiple sources were found for data and information, we preferentially selected the most recent sources, with an overall aim of maximising the % of sources from the last five years. The rationale for this focus was that the research topic was on new and evolving solutions, and so recent studies were prioritised to ensure that findings would be consistent with current knowledge.
- Demonstrated a bias or vested interest of certain organisations.
- Were written in a foreign language.
- Demonstrated a lack of relevance to the research questions in this evidence review.

While some research papers were identified directly through searching the databases outlined in Table 3 Key Sources used in Research, evidence was also identified through using search strings in Google. Table 4 provides some examples of the terms used.

Table 4 Example Terms Used in Search Strings

Soy-containing animal feed	Synthetic Fertiliser
• Protein diversification • Cropping strategies • Alternatives to soy-containing animal feed • Land sparing • [names of the specific measures]	• Synthetic fertiliser • Chemical fertiliser • Fertiliser • Fertiliser consumption • Fertiliser demand • Fertiliser application • Fertiliser requirement • Fertiliser reduction • UK/England/Great Britain • Nutrient use efficiency (NUE) • Nitrification/de-nitrification • Nutrient loss • Nutrient leaching • Biodiversity • Ammonia emissions • Nitrogen oxide emissions • (names of the specific measures)

1.2.2.4 Identification of Organisations

The final research theme 'Relevance to the UK', included the question "If applicable, are UK-based organisations developing/promoting/ implementing this? If so, who are they?". Organisations were identified predominantly through Google to identify actors who:

a) Are developing (or have developed) products associated with the solution.
b) Have written research reports, blogs, or articles on the solution.

c) Are actively promoting the solution, through blogs for example.

In addition to Google, organisations were identified through Government funding competitions, press releases, and references in research reports and academic studies. Note, that these organisations were not assessed with regards to their approach to solutions, but simply identified to provide an indication of the type and number of actors visibly working within this space currently. No criteria was used to say their work is particularly representative of the sector.

1.2.2.5 Scoring & Analysis

Once all evidence had been collected, a Red Amber Green (RAG) scoring system was developed and applied to research questions where this was appropriate, to aid high-level comparison between solutions. These questions included: transformation potential; development stage; strength of evidence; and applicability to the UK context. Environmental impact was the only research theme excluded from scoring given that quantification is more difficult for complex and synergistic nature and climate impacts, especially where there may be trade-offs between incommensurable harms. It should be noted that this scoring aimed to provide a rough indication of the status of each solution to enable comparison. This was not a vigorous process with an inevitable element of subjectivity involved, hence why the information behind the scoring is provided in the Appendix.

1.2.2.6 Synthesis and Reporting

Once all research and analysis was complete, key findings were collated and synthesised under each of the research questions in the form of tables and short narratives. Full explanations were collated in an Appendix document which correlates with the structure of the main report.

1.2.2.7 Limitations

This research has several limitations which include:

1. Limited scope of solutions and evidence sources used due to bias towards sources published in the **English language only**. Setting criteria in this way excluded potentially useful and relevant literature. It also meant that the organisations identified were more UK-centric.
2. Lack of **consultation with industry experts** such as farmers, scientists, NGOs and Agritech companies, whose insights could have improved the technical understanding of solutions and assessment and scoring of solutions, which was due to the time and resource constraints of the work. This lack of external engagement may also have limited the range of organisations identified as active or working in the field.
3. Researcher bias towards **accessible and documented evidence** of solutions with some solutions being commercially sensitive, not publicly available, behind a paywall, or not available online. Bias towards evidence sources which had clear findings and succinct conclusions was partly inevitable given the nature of this study as a landscape analysis and rapid evidence assessment.

1.3 Structure of the report

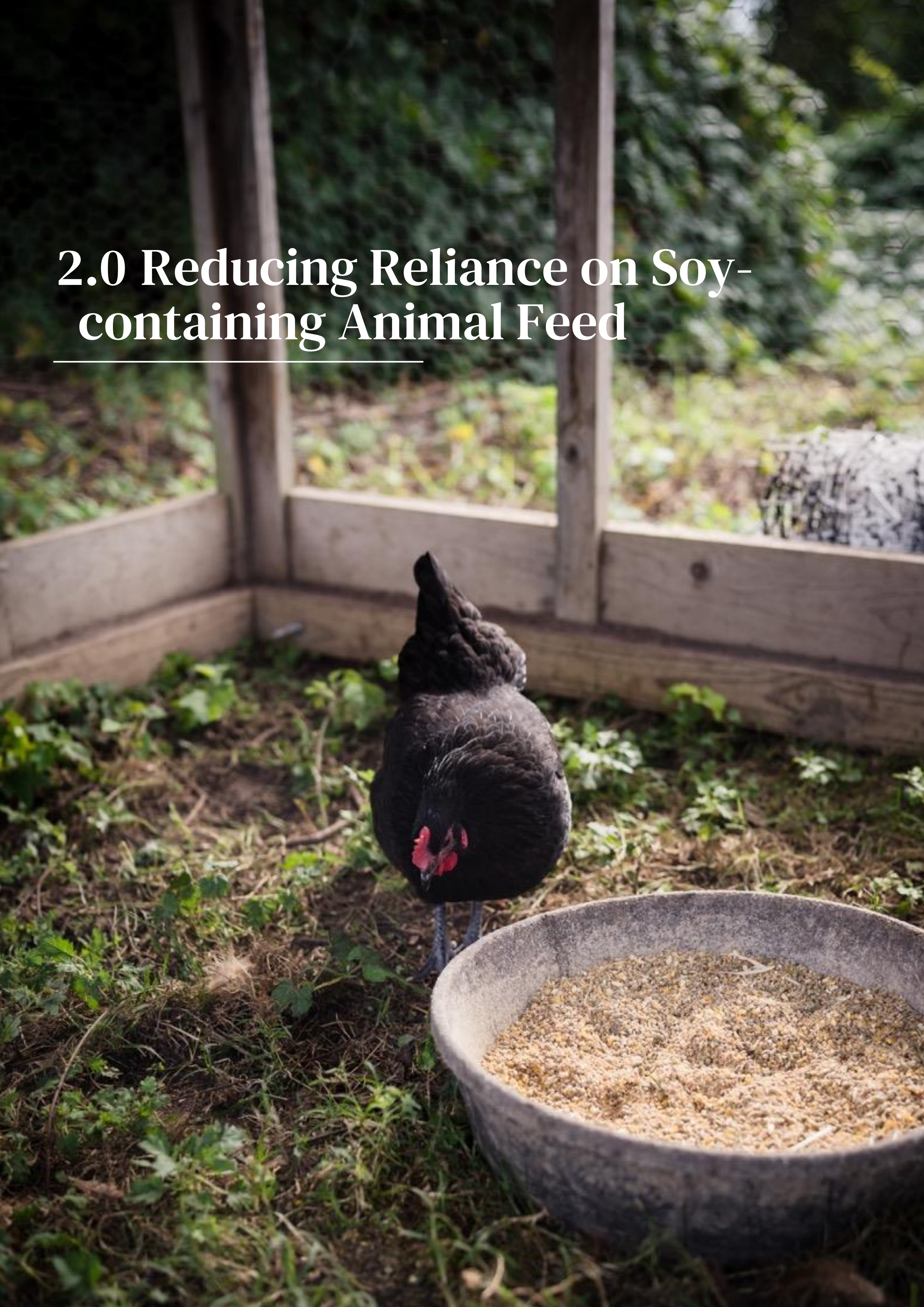
This report is split into two. The first Section (2.0) explores solutions which aim to reduce reliance on soy-containing animal feed, while the second Section (**Error! Reference source not found.**) covers solutions which aim to reduce synthetic fertiliser inputs. Both Sections are structured in the same format, which includes:

- A short description of how the solutions intend to reduce reliance on soy-containing feed/synthetic fertiliser.
- An assessment of the transformative potential of the solutions.

- A summary of the environmental benefits and risks of the solutions to assess the overall net environmental benefit.
- An assessment of the development stage of each solution, and the key barriers to uptake.
- A review of the strength of evidence for each solution, and any obvious evidence gaps.
- An assessment of the applicability of solutions to the UK context.

While short summaries have been provided within the main body of the report, supported by key references from the landscape analysis and evidence review, **additional detail from the research process, as well as full references, are included in an Appendix,** which follows a similar structure.

2.0 Reducing Reliance on Soy-containing Animal Feed



2.1 Solutions Summary

At a global level, four broad approaches for reducing reliance on soy-containing animal feed have been identified. These are listed in Table 5 alongside a brief explanation of how the solution would reduce reliance on soy-containing feed.

Forage feed (i.e., feed, such as grass, that is grazed by animals in situ) was not considered in the list of solutions as this report is primarily concerned with fodder feed (i.e., feed that is harvested and transported to animals). Specifically, the fodder feed of interest in this report contains soy, the majority of which is fed to monogastric animals like chickens, pigs, and fish.[9]

Also out of scope was increasing livestock feed efficiency, which although relevant to this topic area, was excluded from this review given the lack of available literature on its readiness, limitations, and transformation potential. Livestock tend to be oversupplied with protein in concentrate feed so reducing the intensity of feeding, for example through precision feeding[10] or genetic improvements,[11] would in turn decrease reliance on all animal feed, including soy-containing varieties.

Table 5 Summary of Solutions to Reduce Reliance on Soy

Solution	How it Works
Insect protein	Food waste can be fed to insects, particularly black soldier fly (BSF). This recycles amino acids contained in food waste into new protein. Although BSF are far more efficient at converting feed to protein than livestock, they still produce less protein than they are fed because they do not synthesise new amino acids. Nevertheless, insects as feed can avoid some of the challenges of using pre-consumer food and organic waste as animal feed directly (see solution 4). There may additionally be other organic wastes (including sewage) that can provide a feedstock for insects, which could increase potential further, but these have not been a focus in this study.
Microbial protein	Microbial protein is the edible, dried biomass of microbial cultures (i.e., bacteria, yeasts, filamentous fungi or microalgae) that can contain up to 83% protein. Microbial protein is produced through fermentation using sources of oxygen, hydrogen, nitrogen and carbon. Oxygen can be provided from the air; green hydrogen can be produced by electrolysis of water using renewable electricity, and bio-available nitrogen can be produced by extracting nitrogen from air and then converting it to green ammonia. Carbon, however, is more challenging because it makes up such a tiny proportion (0.03%) of air. There are a range of possible sources of carbon being considered, including Direct Air Capture (DAC) of CO_2, flue gas, plants (woody biomass and crop residues) and sewage.
Growing alternative grain legumes	There are grain legumes that offer an alternative to soy that are easier to grow in the UK, such as pea and faba bean. However, most alternatives require a similar amount of land (if not more) than soy. Therefore, replacing imported soy with grain legumes grown locally, without increasing land use efficiency will not have a net global benefit. This is because it will likely displace production of other crops elsewhere and this may ultimately lead to deforestation overseas, particularly when these other crops are very high yielding in the UK. Land use efficiency could be increased by replacing non-grain legumes (e.g., clover) used as cover crops with grain legumes. This may provide a nitrogen-fixation benefit for the subsequent crop while simultaneously producing an animal feed.

Pre-consumer food and organic waste	Some pre-consumer food and organic waste streams can be fed directly to livestock where it can be guaranteed that no restricted foodstuffs will be in the waste stream. Foodstuffs that are currently restricted include catering and kitchen waste, meat or fish, unprocessed eggs or milk, collagen and gelatine from ruminants (animals that chew the cud), and mouldy foodstuffs that were intended for human consumption. It is difficult to summarise the legislation around these waste streams in a high level manner without missing key nuances. Therefore we list below what animal by-products (ABPs) Defra do permit and in what context. Foodstuff by-products that can be used as livestock feed include pre-consumer bakery and confectionary products not containing meat, fish or shellfish, as well as some low risk category 3 ABPs. These ABP's include processed milk or egg products, animal fats and fish oils, hydrolysed proteins, gelatine and collagen from non-ruminant sources, and glycerine from approved biodiesel sites. Fishmeal and blood products may be fed to non-ruminants only, whilst processed animal proteins (e.g. bonemeal) from poultry and pigs may be fed to farmed fish only.[12] Other farm and food system by products that can be used to feed livestock include crop processing by-products, brewers grains and crop residues.[13]

2.2 Transformation Potential

This section aims to distinguish which solutions have the potential to radically reduce reliance on soy-containing animal feed inputs, compared to those which are likely to make a more marginal difference – though these latter cases may still have many useful applications in a diversified food system. Transformation potential has been split into two key aspects:

1. **Extent of reduction per animal**: this refers to the extent to which a solution could replace soy in an animal's diet (i.e., how nutritionally similar is it to soy).
2. **Scalability**: this refers to the extent to which a solution could replace all soy used as animal-feed globally. Note that this only considers the biophysical limits to scalability (e.g., feedstock availability), rather than manmade limits such as legislation and cost which are considered under *Barriers to Uptake* in Section 2.4.

Error! Reference source not found. Table 6 presents Red Amber Green (RAG) ratings for both extent of reduction per animal and scalability and is followed by a narrative discussion of these. The RAG rating scoring criteria are listed below.

Scoring criteria for extent of reduction per animal

- **Red:** could only replace a small fraction of soy in animal's diet
- **Amber:** could replace large proportion but not all soy in animal's diet
- **Green:** could replace soy in animal's diet

Scoring criteria for scalability

- **Red:** some notable biophysical limits on production (e.g., feedstock availability), meaning could only replace small amount of soy globally. Non-biophysical limits such as cost and legislation are considered under *Barriers to Uptake* in Section 2.4.
- **Amber:** some biophysical limits on production but could still replace a substantial quantity of soy globally. Non-biophysical limits such as cost and legislation are considered under *Barriers to Uptake* in Section 2.4.
- **Green:** potential to replace all soy-used in animal feed globally.

Table 6 Transformation Potential of Solutions to Reduce Reliance on Soy

Solution	Extent of reduction per animal	Scalability
Insect protein	● (Green)	● (Amber)
Microbial protein	● (Green)	● (Green)
Growing alternative grain legumes	● (Green)	● (Amber)
Pre-consumer food and organic waste	● (Amber)	● (Amber)

Extent of reduction per animal

Soy is used as animal feed because it is high in easily accessible protein (around 30-50% dry weight).[14] Growing alternative grain legumes, insect protein and microbial protein are all similarly high in accessible protein and therefore could theoretically replace soy in an animal's diet. Black soldier fly larvae are around 50% protein (dry weight)[15] and microbial protein can be almost entirely protein.[16] Grain legumes (of which soy is one) have varied protein contents, with one study finding a range from 20.6% in peas to 34.1% in soy,[17] and this high protein content of soy makes it one of the most land efficient crops to grow in terms of protein. There is a nuance here in that high-yielding-yet-low-protein grain legumes such as faba bean in the UK could yield more protein per hectare of land than soy, however, alternatives will likely require slightly more (or at least the same amount of) land to produce the same amount of protein as soy.

Pre-consumer food and organic waste encompass a wide range of different products with highly variable protein content. The extent to which this could nutritionally replace soy in an animal's diet depends entirely on the exact products they are being fed, and one challenge with using waste and by-product streams is potential inconsistency and unpredictability in the feed received. Another key consideration is whether these feed streams offer the potential for partial but not total replacement of alternatives, implying that they may be a useful part of a mixed feed stream in some contexts. Food nutritional calculators could help to provide more clarity here. However, the displacement potential is certainly real.

Scalability

The scalability of insect protein and pre-consumer food and organic waste is fundamentally limited by the availability of suitable feedstocks. Although a third of all food globally is wasted,[18] not all of this is captured and ultimately the aim is to radically reduce the quantity of food waste produced. For insects, there are also conversion losses and so they produce less protein than they are fed. while the protein and nutritional value of pre-consumer food and organic waste may be variable. For both insects and food waste, uptake is further limited by current legislation. While some legislation will remain for food safety reasons, other restrictions may change once practices can be proven to be safe. Therefore, legislation has been considered a barrier to uptake rather than a fundamental limit on scalability. Within the category of pre-consumer food and organic waste, there is significant theoretical potential to increase the proportion of livestock by-products and fishmeal from fish by-products for use in animal feeds. One research paper estimates that just 4% of livestock by-products and 17% of fishmeal from fish by products are currently used in animal feed, at the global level.[19]

The scalability of alternative grain legumes is limited by land – not just in the UK but globally. Alternatives will require the same amount of land (if not more) than soy. If the overarching aim of replacing soy in feed is to reduce deforestation, then alternative grain legumes will not achieve this in isolation. This is because they will potentially just move demand and supply around in the global market, rather than reducing either overall. In fact, scaling them up could increase global agricultural land use and therefore increase (not decrease) deforestation.

Microbial protein has good potential in terms of scalability. Unlike insects, micro-organisms can synthesise new proteins via fermentation, meaning this solution represents a new source of protein rather than a conversion of existing protein. Proteins are made from carbon, hydrogen, oxygen, and nitrogen. Oxygen can be provided from the air; bio-available nitrogen can be produced by extracting nitrogen from air and then converting it to green ammonia or provided directly from organic matter if a plant feedstock is used; hydrogen can be sourced by electrolysis of water using renewable electricity, or directly from organic matter. Carbon, however, is more challenging because it makes up such a small proportion (0.03%) of air. Direct air capture (DAC) of CO_2 produces a concentrated CO_2 stream, but almost 6,000 tonnes of air needs to be processed to extract one tonne of carbon (for contrast, only 1.28 tonnes of air is required to extract 1 tonne of nitrogen). A cheaper alternative to DAC is to use the CO_2 produced from burning fossil fuels, which can be found concentrated in flue gas. However, the long-term future of this source is limited as the world tries to decarbonise. Finally, carbon could come from plants, notably crop and forestry residues, or cacti that grow in semi-arid area, or even sewage. The scalability potential here may be huge but is still relatively novel.

Summary

Microbial protein is the only solution to have a green RAG rating for both extent of reduction per animal and scalability. Although still an extremely novel solution, the transformation potential of microbial protein to replace soy and therefore release land from agriculture over the medium term is huge. Food waste fed to insects or fed directly to animals is unlikely to ever be able to fully replace soy but could make a substantial difference and is also a highly efficient use of these waste streams for as long as they persist. Growing alternative grain legumes to soy does not fundamentally solve the land use issue and therefore the transformation potential is low, though this transition may be part of a wider transformation in dietary choices and agricultural practices.

2.3 Environmental Impact

This Section aims to understand the environmental impact of the solution beyond just the extent to which it can replace soy-containing animal feed. It has been split into two key aspects:

1. **Environmental benefits:** this research treats the primary benefit of reducing soy-containing feed as the potential to reduce overall land use and land change pressures from growing soy - a change that can have both climate and biodiversity benefits.
2. **Potential unintended consequences**: potential unintended negative impacts of the solutions on the environment.

Table 7 provides a summary of these aspects.

Table 7 Environmental Benefits and Potential Unintended Consequences of Solutions to Reduce Reliance on Soy

Solution	Environmental Benefits	Potential Unintended Consequences
Insect protein	• Reduced demand for agricultural land.[20] • Provides a potentially higher value use for food and organic waste streams. • Potential for insects to be used as high protein ingredient for food products intended for direct human consumption, which could reduce demand for meat.	• Creates an outlet for food waste, thereby disincentivising attempts to reduce the production of food waste. • Management of insect frass (excrement) can be problematic
Microbial protein	• Reduced demand for agricultural land. • No nitrogen or phosphorus loss during this process. Highly efficient nutrient use.[21] • Potential for microbial protein to be used as ingredient for food products intended for direct human consumption, which could reduce demand for meat.	• If using crop residues as carbon source, there is potential for farmers to remove too much crop residue from the field which means that insufficient carbon (and other nutrients) is returned to the soil.

Growing alternative grain legumes	• Legumes fix nitrogen so reduce the need for fertilisers. • Increased diversification of cropping, reducing pests and disease and increasing resilience.[22]	• No reduction (and possibly an increase) in agricultural land use at global scale.[23]
Pre-consumer food and organic waste	• Reduced food and organic waste for waste management of other use-of-by-product processes. The environmental impact will vary depending on the waste management stream effected. • Reduced demand for agricultural land.	• Possible spread of disease if by-products are not stored or treated properly.

The main benefit of reducing reliance on soy – and all protein-rich crops – is to reduce demand for agricultural land, slowing and perhaps even reversing expansion at global scale, and thus reducing deforestation, and even facilitating natural regeneration. All but one of the solutions should achieve this land sparing effect. For example, replacing all soy feed in the UK with insect protein (if it is possible) has the potential to spare 150,000 ha/year of land from conversion to agriculture, limiting habitat destruction and biodiversity loss.[20]

Insect protein and food waste streams

Both insect protein and pre-consumer food and organic waste run the risk of creating a market for food waste and thus disincentivising efforts to reduce the production of food waste in the first instance. This goes against the waste hierarchy; the prevention of food waste should be prioritised over recycling of food waste. This is of increasing concern as biomaterials are already in demand for use in biogas and biomethane production. In addition to this, the use of some pre-consumer food and organic waste as feed is currently legally restricted. The use of post-consumer food waste is banned under UK law due to health risks and the threat of disease outbreaks, as happened with the 2001 UK foot-and-mouth outbreak. [24]Some animal by-products as animal feed are also banned (see Solutions Summary); the BSE crisis of the 1990s was a result of the feeding of meat processing co-products of ruminants to ruminants.[25]. However, the use of pre-consumer waste streams that can demonstrate they are free of animal waste as feed is allowed. Given these concerns with food safety and previous disease outbreaks, the use of food and organic waste as animal feed – regardless of whether it is pre- or post-consumer – should always be considered with caution.

Microbial protein

The key benefit of microbial protein is that there is no nutrient loss in the production process.[21] For insects, there is nutrient loss when rearing the insects (as they recycle proteins from food into new proteins). For food and organic waste, there will have been nutrient loss to grow the crop/animal. In comparison, micro-organisms can synthesise new amino acids via fermentation and are therefore extremely efficient at using nitrogen and phosphorus. However, if crop residues are used as a carbon source, there is a risk that without prior awareness, farmers remove too much residue from the field, serving to reduce the amount of carbon and wider nutrients returned to the soil. It should be noted that all microbes used in fermentation for proteins are wild strains that already exist in the natural environment, so therefore do not present a pollution risk.

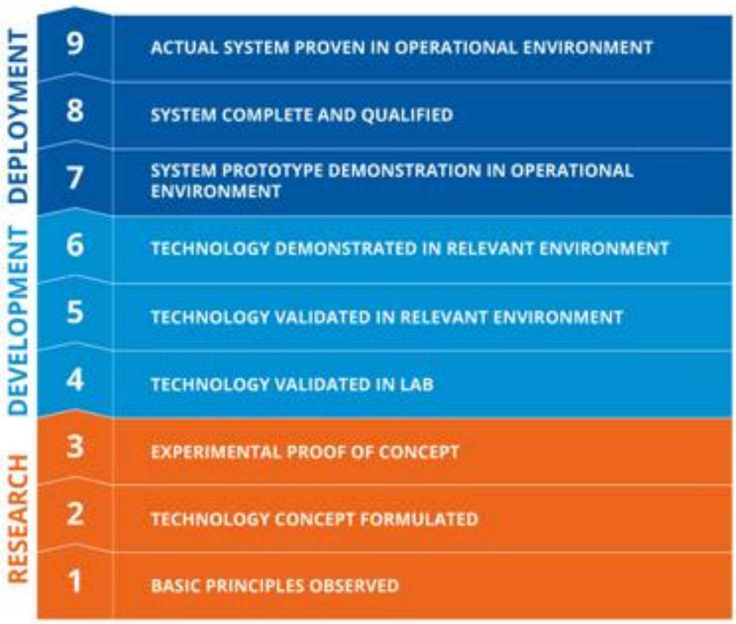
Growing alternative grain legumes

Growing alternative grain legumes requires a similar area of land (if not more) than soy. Therefore, simply replacing imported soy with alternatives grown locally without increasing land use efficiency will reduce global agricultural land use as it will likely displace production of other crops elsewhere, which may ultimately lead to deforestation overseas. The area of farmland required to meet UK demand for soy in 2016-2018 was 1.7 million ha (an area approaching the size of Wales).[23] If this area of land was used to grow alternative grain legumes, the production of other crops would have be offshored. Nevertheless, legumes are nitrogen-fixing crops, and, as discussed in Chapter 3, are often included in cropping sequence cycles to increase the nitrogen content of soil. If grain legumes are used as cover crops within an arable rotation, they can be harvested to produce animal feed and still leave some residual nitrogen in the soil for the subsequent crop, although in some cases, the nitrogen off-take in the grain is more than the crop fixes. This would increase land use efficiency compared to growing non-harvestable cover crops. Furthermore, adding legumes to cereal-dominated European cropping systems would help address biological constraints on cereal productivity such as increasing problems with weeds and diseases. Increased crop diversity can also be beneficial for insect pollinators and other biodiversity.

2.4 Development Stage and Barriers to Uptake

This section assesses the development stage of each solution against the technology readiness level scale (TRL) (Figure 1), and accordingly, references the key barriers to uptake in relation to the UK context. These are presented in Table 8. The TRL provides a method for estimating the maturity of technologies (rather than commercial competitiveness), enabling consistent assessment of solutions of different types.[26] TRLs are based on a scale from 1 to 9, with 9 being the most mature technology.

Figure 1 Technology Readiness Level Scale



Source: TWI

Table 8 Development Stage and Key Barriers of Solutions to Reduce Reliance on Soy

Solution	Development stage	Key barriers to uptake
Insect protein	• TRL9	• **Regulation:** Current UK law does not allow insects to be fed to livestock.[27] The exception is if they are live insects.

Microbial protein	• TRL4	• Not yet market ready.
Growing alternative grain legumes	• TRL9	• **Cost:** In recent times, soy has been the cheapest and most widely available grain legume (in terms of protein) produced globally, making it difficult for alternatives to compete commercially.
Pre-consumer food and organic waste	• TRL9	• **Cost:** Can require infrastructure to prevent microbial degradation. • **Regulation:** Many ABPs and post-consumer food waste is not legislated for use.

Summary

All but one of the soy-replacing feed solutions are market-ready. Microbial protein is still in the research and development (R&D) stage, with some large-scale trials ongoing in pilot plants.[28 29] Despite this, regulatory and financial barriers have so far prevented widespread uptake.

The main barriers to widespread uptake of these solutions fall into two categories: regulation and cost. Regulatory barriers exist for all but one (growing alternative grain legumes) of the solutions. Currently, UK legislation prohibits the use of insect protein as feed for terrestrial livestock that are consumed by humans;[27] it is only approved for use in aquaculture and for use as pet feed. It remains to be seen whether the UK will follow the EU, which approved insect protein as a feed for pigs and poultry in 2021.[27] In the UK, it is considered that *live* insects are permitted to be used in animal feed since they are not considered a processed animal protein. This process is already taking place with live insects being fed to chickens producing eggs.[30] The retailer Morrisons appear at the forefront for insect-fed hens, having launched a line of 'carbon neutral' eggs laid by hens fed on insects reared on food waste.[31]

Regulatory barriers

Microbial proteins are generally permitted as animal feed in the UK.[32] However, businesses must receive approval from the relevant Trading Standards Agency of their local authority before manufacturing or placing microbial proteins on the market as animal feed.[33] The application and fee for approval may represent a barrier to uptake (though this is likely to be relatively minor), and there is a risk that certain microbial products will not gain regulatory approval.

There are numerous regulations that restrict the use of *some* food system by-products and food waste as feeds in the UK and Europe. UK legislation currently bans the use of post-consumer food waste and many animal by-products (ABPs) as animal feed.[1] This restriction is likely to limit investment into solutions based around food waste and by-products (although it should be noted that these regulations do not apply to *all* food and farm system by-products). Pre-consumer plant-based agricultural products (e.g. crop residues), bakery products not containing meat or fish, and certain category 3 (low risk) ABPs such as animal fats and fish oils are permitted for use in livestock feeds (see solution summary in 2.1 for further details). However, some of these by-products, like crop residues, tend to be much poorer sources of protein than those derived from animals and can only provide a proportion of dietary input for a given farming operation. There are also competing uses for food system by-products. For some by-products such as those from oilseed processing, the vast majority are already used in feed. However, for others like livestock and fish by-products, there is significant potential to increase their use in feeds.[34]

Financial barriers

The market for agricultural products is complex, with multiple interacting cost and price factors at any one time. Even in simplified form this can pose barriers to changing crop choices. Growing alternative grain legumes for animal feed in the UK presents some complicated challenges. It may not be cost-effective for farmers to switch production from cereals to grain legumes if their land currently returns high cereal yields. Soy has comparative advantage in regions like South America where many other crops do not grow well, however soy is less competitive in Europe, where average yields are 2.77 tonnes/ha compared to, for example, 5.55 tonnes/ha for wheat.[17] Any UK-grown grain legumes would have to compete with soy-containing feeds on the global market from countries which may have lower production costs (e.g., cheaper land and labour). On this last point, changes to regulation (such as the UK aligning to the EU's commitment to eliminate import of deforestation-linked goods) or global demand (meaning the UK is increasingly competing for soy imports with other countries) could change this cost profile for soy and alternative grain legumes over time.

Microbial protein is still in the R&D phase, and so is likely to be more expensive in the short term as this solution is scaled-up. However, production at scale has the potential to be cost-effective, particularly if the feedstocks used are also competitively priced. Currently, certain feedstocks, such as carbon from DAC and green ammonia are also in the R&D phase, so they remain too expensive to produce commercial quantities of protein.

2.5 Strength of Evidence

This section aims to distinguish the strength of evidence associated with each solution, including whether the solution works, and/or has unintended consequences. To assess this, Table 9 provides a Red Amber Green (RAG) rating for each solution which has been scored against the criteria presented below. In addition, the table lists evidence gaps where applicable.

<u>Scoring criteria</u>

- **Red:** This solution is at an early stage of research with limited evidence to date.
- **Amber:** This solution has a growing body of evidence with some outstanding research areas.
- **Green:** This solution has been thoroughly researched and has few evidence gaps.

Table 9 Strength of Evidence for Solutions to Reduce Reliance on Soy

Solution	Strength of Evidence	Evidence Gaps
Insect protein	● (Amber)	• The future of the food waste supply is highly uncertain. • Would benefit from more research into overcoming barriers of insect feedstocks currently classed as having low potential for use (e.g., sewage, paper sludges).
Microbial protein	● (Amber)	• More research is needed into nutritional content of microbial protein and how this can vary depending on feedstock/production process. • More research is needed into understanding the quantities of various feedstocks available.
Growing alternative grain legumes	● (Green)	• More research is needed on the most effective cropping strategies for optimising yield and minimising land use.[35]
Pre-consumer food and organic waste	● (Amber)	• More research is needed into the replacement potentials of by-products and surpluses from dairy and bakery industries, as well as distiller grains.

Growing alternative grain legumes

Growing alternative grain legumes has the most available evidence, with a considerable body of research conducted both abroad and within the UK and relatively few research gaps. Nonetheless, more research is required on which cropping strategies are most effective for protein diversification, with consideration to yield, land use, and other environmental impacts.[35]

Insect protein and microbial protein

The remaining three solutions have a growing body of evidence, but also have some outstanding research areas and evidence gaps. Pre-consumer food waste and by products are by far the most available, and WWF's Future of Feed report[36] identifies food surpluses from manufacturing that include ABPs, fruit and vegetable surpluses, and bakery surpluses, within this category as the most overall appropriate feedstocks for insects based on a multi-faceted scoring system that incorporates contamination risk, availability, nutritional profile, and cost, among others. Nonetheless, both bakery and vegetable products have low nutrient densities, and it is the advantages they have in areas such as contamination risk and availability that score them higher than others overall. However, it is difficult to predict how much food waste will be available in future, with competing demands for its use and a sustainability vision that seeks to reduce its production in the first instance. Microbial protein can be produced using a range of feedstocks, but again there needs to be more research into understanding the quantities of feedstocks available and potential for unintended consequences, such as crop residues and cacti. There also needs to be more research into how its nutritional content will vary based upon which of these feedstocks and production processes are used.

Pre-consumer food and organic waste

Many studies have investigated the nutrient profiles of food wastes. However, fewer have looked at those of pre-consumer food and organic waste, and fewer still what the overall inclusion potential (i.e., the potential of waste to be included within a feed mix) is, given scalability limitations. Precise inclusion potentials of protein rich by-products and surpluses from dairy or bakery industries, as well as from distillers dried grains, has not been studied and requires further research. [37] One study did however quantify the specific replacement potential of fish oil and poultry oil by products for all oilseed oil feeds – which include soy.[37] However, the paper does not specify what proportion of the oilseed feed that could be replaced is soy specifically.

2.6 Applicability to the UK Context

With some solutions emerging from contexts outside of the UK, this Section aims to distinguish the applicability of solutions to the UK context. To assess this, Table 10 outlines whether the solution is: being implemented or trialled in the UK; provides a Red Amber Green (RAG) rating for the level of Government support; and lists stakeholder types that are currently developing, promoting, or implementing the solution within the UK. Please note that all solutions have been identified to be applicable to the UK farming context.

Scoring criteria

- **Red:** The UK Government has restrictions in place that limit the use of the solution.
- **Amber:** The UK Government has shown interest in this solution but does not provide financial support.
- **Green:** The UK Government provides financial support for this solution.
- **Grey**: The UK Government has no position or involvement in this solution.

Table 10 Applicability of Solutions to Reduce Reliance on Soy to the UK Context

Solution	Is it being implemented / trialled in UK?	Level of UK government support	UK-based organisations involved in this Solution
Insect protein	N	🔴	• Entocycle and Agrigrub (agri-tech start-ups). • Research associations. • Queen's University Belfast.
Microbial protein	Y	🟢	• Deep Branch (agri-tech start-up). • King's College London and the University of Nottingham.
Growing alternative grain legumes	Y	🟢	• Research associations. • Small agricultural NGOs.
Pre-consumer food and organic waste	Y	🟡	• WRAP. • Tesco and Arla Foods. • UK Government in the form of Defra's advocacy for the use of certain animal by-products and bakery waste.

Usage and applicability to the UK

All solutions except for the use of insect protein as animal feed are being implemented or tested in the UK. The use of insect protein from dead insects in animal feed is not currently permitted under UK law, except for use in aquaculture and in pet food, and therefore conforming to RAG criteria, has been rated as a red. Nonetheless, the fact that insect protein is permitted in aquaculture and pet feed, and the fact that the EU has legislated for its use in pig and poultry feed, shows its potential for the UK context. Moreover, it is notable that *live* insects do not qualify as a PAP and are being farmed and fed to egg laying hens already currently. Nonetheless, research organisations are looking into formulating insect feeds and trialling them in fish as part of a wider research process into eventually using them as feed for terrestrial livestock. There is also potential commercial interest. Because regulation does not permit its use, the level of Government support is rated as red, and there is no indication that regulation changes are being considered in the

UK. However, in 2021, the EU Council did vote to authorise their use in poultry and pig feed, potentially setting a future precedent for the UK.[27]

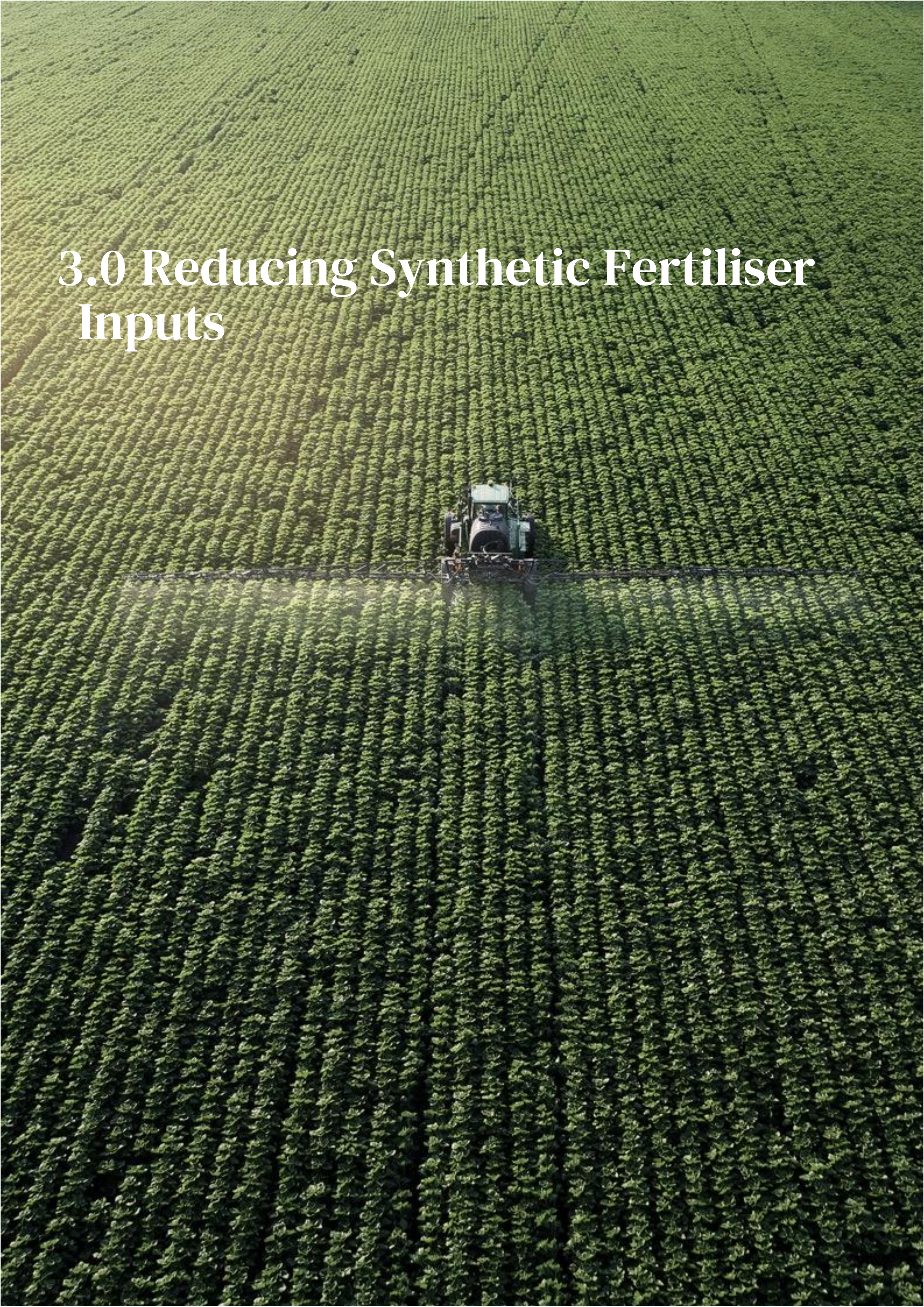
Level of UK Government support

Pre-consumer food and organic waste have been rated as amber because Government does not provide funding for this solution. Still, Defra and the Animal and Plant Health Agency do provide clear guidance for farmers on which animal by-products from food processing can and cannot be used, as well as on the use of bakery products, on the Government website.[38] Microbial protein and the growing of alternative grain legumes both have financial support from Government, one in the form of research, and the other through grants to farmers. The UK Government has provided project funding for the Agri-tech firm 'Deep Branch' which is conducting research into developing microbial proteins for use in livestock feed.[28] Under the Environmental Land Management (ELM) scheme, in which farmers in England are to be paid for nature and climate-positive farming practices, although there are payments for farmers integrating legumes into grasslands and arable rotations, there are no payments for harvesting grain legumes.[39] However, the Welsh Sustainable Farming Scheme does include financial support for growing and harvesting grain legumes (which are referred to as 'protein crops').[40]

UK-based organisations involved in these solutions

Given their high-tech nature, the solutions of insect and microbial protein are both being supported by large and well-funded organisations, such as UK Research and Innovation (UKRI) and the Welsh Government that have funded research institutions to explore these topics as well as NGOs who can advocate for policy change.[20] Given that the growing of grain legumes, as well as their use in animal feed, is well established, those who are involved in increasing their use appear to largely be organic farmer partnerships and agricultural NGOs. Similarly, it is farmer partnerships that are amongst those promoting the use of pre-consumer food and organic waste, although large NGOs are also advocates. WRAP – as well as major UK retailers like Tesco and Arla Foods – are particularly influential in promoting improved supply chain efficiency by using food waste that results from processing.

3.0 Reducing Synthetic Fertiliser Inputs



3.1 Solutions Summary

The nutrient cycle involves inevitable removal of nutrients from the food system. Nutrients are removed through the off-take of nutrients from food products (both animal and plant) and through losses to the environment. Therefore the system requires nutrients to be inputted. Currently, synthetic fertiliser is applied to farmland to increase the nutrient content of soils, which in turn increases yields of crops and forage. Key nutrients that synthetic fertilisers add to soils include nitrogen, phosphorus, potassium, and sulphur. However, as explained in Section 1.1.2.2, their use is linked to many environmental impacts, and there is a need to reduce their usage both locally and globally. At a global level, 17 solutions for reducing the use of synthetic fertiliser – with a focus on nitrogen fertilisers – have been identified. These are listed in

Table 11 Summary of Fertiliser Solutions

Solution	Reduce or Replace?	How it works
Precision fertiliser technology	Reduce	This is an umbrella term for measures which enable farmers to add only the precise amount and/or type of fertiliser required by a specific crop in a particular location at a given time, thus reducing excess use. The term is applied to the management of in-field sppatial variation in particular. Technology such as artificial intelligence and drones can provide data on the spatial and temporal variation in fertiliser needs, as well as the variation in the nutrient content of organic fertilisers. It is important to note that good knowledge of a farm/farming practices can increase fertiliser application "precision" but this study has focused on higher tech solutions.
Controlled release fertilisers (CRF)	Reduce	These are granulated fertilisers encapsulated in coatings which break down slowly when added to soil, and therefore release nutrients at a rate appropriate to the needs of the plant.
GM nitrogen fixing arable crops	Reduce	Research is ongoing into how crops could fix (or capture) their own nitrogen. Legumes already do this by developing a symbiotic relationship with bacteria in root nodules which convert atmospheric nitrogen into ammonia. This is then exchanged with the plant for carbon. Various approaches are being trialled, which include: transferring nitrogen fixing genes into bacteria which typically associate with cereals; adding nitrogen fixing genes to new crops; and genetically engineering the plant to produce biofilms extruding into the soil to house existing nitrogen fixing bacteria.

Cover crops: legumes in crop rotations	Reduce	Cover crops ('green manure') are crops or vegetation that cover soil to protect it within an arable rotation. When used as cover crops, legumes have the added benefit of fixing nitrogen from the atmosphere, making it available for plants. They do this through a symbiotic relationship with bacteria that live in their root nodules, whereby the plant supplies the bacteria with carbon, which the bacteria uses as energy to fix atmospheric nitrogen which it then supplies the plant.
Solid compost	Replace	Compost is made using aerobic digestion of organic materials in a composting system. It is typically made from green waste and food waste and may have waste produced on farm added, such as crop resiudes or animal manure. Through microbial decomposition, these materials transform into nutrient-rich compost. Compost gradually releases nutrients and organic matter into the soil, and is applied consecutively over several years. Compost is more stable and resistant to decomposition than manure alone.
Liquid compost/ compost tea	Replace	Liquid compost is made by mixing solid compost with non-chlorinated water in an aerated vat to allow micro-organisms to multiply. This is then sprayed onto crops. Liquid compost may contain high concentrations of soluble nutrients that are more accessible to plants than solid compost, and so a small amount of solid compost can be applied to a wider area when converted to liquid compost to produce the same yield.
Manure	Replace	Manure is excrement from livestock and is a well-established means for fertilising crops and pastureland. Slurry is liquified manure, and can be more easily applied to fields. Slurry contains nitrogen, phosphorus, potash, potassium, as well as carbon. Manure can be applied directly, as slurry, or can be added to compost or used in digestate production.
Seaweed	Replace	Seaweed can provide plant-available nitrogen and phosphate, much like compost and manure. Seaweed can be applied: • Fresh or dried; • As a compost; • As a solid hydrochar; and • Sprayed as a liquid extract.

Shellfish by-product for wastewater nutrient recovery	Replace	Waste crab shells or 'carapace' can be ground up and added to a reactor in a wastewater treatment plant. Nitrogen and phosphate from human wastewater adsorbs into the ground shell, which can then be applied to crops as a fertiliser.
Fish waste (fishery and aquaculture by-products)	Replace	Fish waste, including the raw material not suitable for human eating such as intestines and spine, can be processed into fertiliser. Fish waste is rich in nitrogen, phosphate, potassium and calcium and can therefore support plant growth. It can be made into dry fertiliser as fish meal or fish powder, or into liquid fertiliser as a fish emulsion, and can be applied directly to crops or fields. Dry fertilisers can also be made into fish composts with the use of bulking agents. In addition, the faeces and uneaten feed from aquaculture can be harvested into a sludge similar to fertiliser. This is also referred to as fish waste.
Rotational grazing	Replace	This involves moving livestock regularly between fields, so that the grass is given time to recover. During rest periods, the grass grows and thus increases organic matter in the soil, which releases plant-available nitrogen. During grazed periods, cattle add manure to soil which also provides plant-available nitrogen.
Anaerobic digestate	Replace	Anaerobic digestate is one of the outputs of anaerobic digestion (AD) plants. AD plants convert biomass, such as food waste, energy crops, sewage, or agricultural wastes into biogas, with digestate as a by-product. The digestate - which is either dry, liquor, or slurry - can be applied as an alternative fertiliser to synthetic fertilisers. It can also be used in intensive greenhouse cultivation.
Human urine as fertiliser	Replace	Human urine contains high levels of nitrogen, phosphorus and potassium, and in a diluted form (approximately 1:10 urine to water), can be used as fertiliser. The urine is diverted using specialist toilets, then transported to a fertiliser production centre either via a pressurised pipe system, or via trucks. If transported via the pipe system, the addition of acetic acid is required to prevent corrosion.

Adding biochar to soils	Reduce	Biochar refers to charcoal used for soil amendment rather than for fuel. It is produced by heating biomass at relatively low temperatures (between 300-800°C) in low oxygen conditions, representing a process of pyrolysis. Biochar can improve fertiliser use efficiency in two ways: 1. By increasing soil water retention (and thus reducing leaching) due to porous physical structure; and 2. By increasing nutrient retention of cations due to a negatively charged surface. However, these characteristics are highly variable and are dependent on factors such as what the biochar is made from, how it is made, and the type of soil it is added to.
Nitrification Inhibitors (NIs)	Reduce	Nitrification Inhibitors (NIs) delay the nitrification of ammonium, which reduces leaching, therefore increasing the nitrogen use efficiency of fertilisers. They are an example of a controlled release fertsilier. NIs can be either biological or synthetic. Biological NIs occur naturally in certain plant species, such as some wheat and rice, and are secreted from roots, whereas synthetic NIs are added to fertiliser.
Perennial crops	Reduce	Unlike annual crops, perennial crops do not need to be replanted each year. There are many crops that are naturally perennial and have been used in farming systems for millennia, such as fruits and nuts. Since the 1980s, researchers have been trying to breed perennial grain crops. This includes for example, intermediate wheatgrass (IWG), which produces wheat grains sold as Kernza, and PR23 - a perennial rice developed and grown in China. Some perennial grains like IWG can also be grazed. Perennial grain crops maintain long-term soil health better than annual varieties, thereby reducing the need for fertiliser. They can also be intercropped with legumes to further reduce the need for fertiliser.

Multi-species swards	Reduce	Multi-species swards (MSS) are grasslands used for pasture that consist of a variety of plants from different families including clovers, grasses, brassicas, herbs, chicory, and plantain. By improving soil health and integrating legumes into the mix to fix atmospheric nitrogen, MSS decrease the quantity of fertiliser needed when compared to a typical pasture system of perennial ryegrass

11 accompanied by a brief explanation of how the solution intends to reduce reliance on synthetic fertiliser.

There are two different types of solutions to reduce reliance on synthetic fertiliser:

1. Those that reduce absolute quantity of fertiliser required (whether that be synthetic or organic), these are labelled as ‘reduce’ in
2. Table 11 Summary of Fertiliser Solutions

Solution	Reduce or Replace?	How it works
Precision fertiliser technology	Reduce	This is an umbrella term for measures which enable farmers to add only the precise amount and/or type of fertiliser required by a specific crop in a particular location at a given time, thus reducing excess use. The term is applied to the management of in-field sppatial variation in particular. Technology such as artificial intelligence and drones can provide data on the spatial and temporal variation in fertiliser needs, as well as the variation in the nutrient content of organic fertilisers. It is important to note that good knowledge of a farm/farming practices can increase fertiliser application "precision" but this study has focused on higher tech solutions.
Controlled release fertilisers (CRF)	Reduce	These are granulated fertilisers encapsulated in coatings which break down slowly when added to soil, and therefore release nutrients at a rate appropriate to the needs of the plant.
GM nitrogen fixing arable crops	Reduce	Research is ongoing into how crops could fix (or capture) their own nitrogen. Legumes already do this by developing a symbiotic relationship with bacteria in root nodules which convert atmospheric nitrogen into ammonia. This is then exchanged with the plant for carbon. Various approaches are being trialled, which include: transferring nitrogen fixing genes into bacteria which typically associate with cereals; adding nitrogen fixing genes to new crops; and genetically engineering the plant to produce biofilms extruding into the soil to house existing nitrogen fixing bacteria.

Cover crops: legumes in crop rotations	Reduce	Cover crops ('green manure') are crops or vegetation that cover soil to protect it within an arable rotation. When used as cover crops, legumes have the added benefit of fixing nitrogen from the atmosphere, making it available for plants. They do this through a symbiotic relationship with bacteria that live in their root nodules, whereby the plant supplies the bacteria with carbon, which the bacteria uses as energy to fix atmospheric nitrogen which it then supplies the plant.
Solid compost	Replace	Compost is made using aerobic digestion of organic materials in a composting system. It is typically made from green waste and food waste and may have waste produced on farm added, such as crop resiudes or animal manure. Through microbial decomposition, these materials transform into nutrient-rich compost. Compost gradually releases nutrients and organic matter into the soil, and is applied consecutively over several years. Compost is more stable and resistant to decomposition than manure alone.
Liquid compost/ compost tea	Replace	Liquid compost is made by mixing solid compost with non-chlorinated water in an aerated vat to allow micro-organisms to multiply. This is then sprayed onto crops. Liquid compost may contain high concentrations of soluble nutrients that are more accessible to plants than solid compost, and so a small amount of solid compost can be applied to a wider area when converted to liquid compost to produce the same yield.
Manure	Replace	Manure is excrement from livestock and is a well-established means for fertilising crops and pastureland. Slurry is liquified manure, and can be more easily applied to fields. Slurry contains nitrogen, phosphorus, potash, potassium, as well as carbon. Manure can be applied directly, as slurry, or can be added to compost or used in digestate production.
Seaweed	Replace	Seaweed can provide plant-available nitrogen and phosphate, much like compost and manure. Seaweed can be applied: • Fresh or dried; • As a compost; • As a solid hydrochar; and • Sprayed as a liquid extract.

Shellfish by-product for wastewater nutrient recovery	Replace	Waste crab shells or 'carapace' can be ground up and added to a reactor in a wastewater treatment plant. Nitrogen and phosphate from human wastewater adsorbs into the ground shell, which can then be applied to crops as a fertiliser.
Fish waste (fishery and aquaculture by-products)	Replace	Fish waste, including the raw material not suitable for human eating such as intestines and spine, can be processed into fertiliser. Fish waste is rich in nitrogen, phosphate, potassium and calcium and can therefore support plant growth. It can be made into dry fertiliser as fish meal or fish powder, or into liquid fertiliser as a fish emulsion, and can be applied directly to crops or fields. Dry fertilisers can also be made into fish composts with the use of bulking agents. In addition, the faeces and uneaten feed from aquaculture can be harvested into a sludge similar to fertiliser. This is also referred to as fish waste.
Rotational grazing	Replace	This involves moving livestock regularly between fields, so that the grass is given time to recover. During rest periods, the grass grows and thus increases organic matter in the soil, which releases plant-available nitrogen. During grazed periods, cattle add manure to soil which also provides plant-available nitrogen.
Anaerobic digestate	Replace	Anaerobic digestate is one of the outputs of anaerobic digestion (AD) plants. AD plants convert biomass, such as food waste, energy crops, sewage, or agricultural wastes into biogas, with digestate as a by-product. The digestate - which is either dry, liquor, or slurry - can be applied as an alternative fertiliser to synthetic fertilisers. It can also be used in intensive greenhouse cultivation.
Human urine as fertiliser	Replace	Human urine contains high levels of nitrogen, phosphorus and potassium, and in a diluted form (approximately 1:10 urine to water), can be used as fertiliser. The urine is diverted using specialist toilets, then transported to a fertiliser production centre either via a pressurised pipe system, or via trucks. If transported via the pipe system, the addition of acetic acid is required to prevent corrosion.

Adding biochar to soils	Reduce	Biochar refers to charcoal used for soil amendment rather than for fuel. It is produced by heating biomass at relatively low temperatures (between 300-800°C) in low oxygen conditions, representing a process of pyrolysis. Biochar can improve fertiliser use efficiency in two ways: 3. By increasing soil water retention (and thus reducing leaching) due to porous physical structure; and 4. By increasing nutrient retention of cations due to a negatively charged surface. However, these characteristics are highly variable and are dependent on factors such as what the biochar is made from, how it is made, and the type of soil it is added to.
Nitrification Inhibitors (NIs)	Reduce	Nitrification Inhibitors (NIs) delay the nitrification of ammonium, which reduces leaching, therefore increasing the nitrogen use efficiency of fertilisers. They are an example of a controlled release fertsilier. NIs can be either biological or synthetic. Biological NIs occur naturally in certain plant species, such as some wheat and rice, and are secreted from roots, whereas synthetic NIs are added to fertiliser.
Perennial crops	Reduce	Unlike annual crops, perennial crops do not need to be replanted each year. There are many crops that are naturally perennial and have been used in farming systems for millennia, such as fruits and nuts. Since the 1980s, researchers have been trying to breed perennial grain crops. This includes for example, intermediate wheatgrass (IWG), which produces wheat grains sold as Kernza, and PR23 - a perennial rice developed and grown in China. Some perennial grains like IWG can also be grazed. Perennial grain crops maintain long-term soil health better than annual varieties, thereby reducing the need for fertiliser. They can also be intercropped with legumes to further reduce the need for fertiliser.

Multi-species swards	Reduce	Multi-species swards (MSS) are grasslands used for pasture that consist of a variety of plants from different families including clovers, grasses, brassicas, herbs, chicory, and plantain. By improving soil health and integrating legumes into the mix to fix atmospheric nitrogen, MSS decrease the quantity of fertiliser needed when compared to a typical pasture system of perennial ryegrass

3. 11, and
4. Those that replace synthetic with other nutrient sources, which are labelled as ‘replace’ in the Table.

Table 11 Summary of Fertiliser Solutions

Solution	Reduce or Replace?	How it works
Precision fertiliser technology	Reduce	This is an umbrella term for measures which enable farmers to add only the precise amount and/or type of fertiliser required by a specific crop in a particular location at a given time, thus reducing excess use. The term is applied to the management of in-field sppatial variation in particular. Technology such as artificial intelligence and drones can provide data on the spatial and temporal variation in fertiliser needs, as well as the variation in the nutrient content of organic fertilisers. It is important to note that good knowledge of a farm/farming practices can increase fertiliser application "precision" but this study has focused on higher tech solutions.
Controlled release fertilisers (CRF)	Reduce	These are granulated fertilisers encapsulated in coatings which break down slowly when added to soil, and therefore release nutrients at a rate appropriate to the needs of the plant.
GM nitrogen fixing arable crops	Reduce	Research is ongoing into how crops could fix (or capture) their own nitrogen. Legumes already do this by developing a symbiotic relationship with bacteria in root nodules which convert atmospheric nitrogen into ammonia. This is then exchanged with the plant for carbon. Various approaches are being trialled, which include: transferring nitrogen fixing genes into bacteria which typically associate with cereals; adding nitrogen fixing genes to new crops; and genetically engineering the plant to produce biofilms extruding into the soil to house existing nitrogen fixing bacteria.

Cover crops: legumes in crop rotations	Reduce	Cover crops ('green manure') are crops or vegetation that cover soil to protect it within an arable rotation. When used as cover crops, legumes have the added benefit of fixing nitrogen from the atmosphere, making it available for plants. They do this through a symbiotic relationship with bacteria that live in their root nodules, whereby the plant supplies the bacteria with carbon, which the bacteria uses as energy to fix atmospheric nitrogen which it then supplies the plant.
Solid compost	Replace	Compost is made using aerobic digestion of organic materials in a composting system. It is typically made from green waste and food waste and may have waste produced on farm added, such as crop resiudes or animal manure. Through microbial decomposition, these materials transform into nutrient-rich compost. Compost gradually releases nutrients and organic matter into the soil, and is applied consecutively over several years. Compost is more stable and resistant to decomposition than manure alone.
Liquid compost/ compost tea	Replace	Liquid compost is made by mixing solid compost with non-chlorinated water in an aerated vat to allow micro-organisms to multiply. This is then sprayed onto crops. Liquid compost may contain high concentrations of soluble nutrients that are more accessible to plants than solid compost, and so a small amount of solid compost can be applied to a wider area when converted to liquid compost to produce the same yield.
Manure	Replace	Manure is excrement from livestock and is a well-established means for fertilising crops and pastureland. Slurry is liquified manure, and can be more easily applied to fields. Slurry contains nitrogen, phosphorus, potash, potassium, as well as carbon. Manure can be applied directly, as slurry, or can be added to compost or used in digestate production.
Seaweed	Replace	Seaweed can provide plant-available nitrogen and phosphate, much like compost and manure. Seaweed can be applied: • Fresh or dried; • As a compost; • As a solid hydrochar; and • Sprayed as a liquid extract.

Shellfish by-product for wastewater nutrient recovery	Replace	Waste crab shells or 'carapace' can be ground up and added to a reactor in a wastewater treatment plant. Nitrogen and phosphate from human wastewater adsorbs into the ground shell, which can then be applied to crops as a fertiliser.
Fish waste (fishery and aquaculture by-products)	Replace	Fish waste, including the raw material not suitable for human eating such as intestines and spine, can be processed into fertiliser. Fish waste is rich in nitrogen, phosphate, potassium and calcium and can therefore support plant growth. It can be made into dry fertiliser as fish meal or fish powder, or into liquid fertiliser as a fish emulsion, and can be applied directly to crops or fields. Dry fertilisers can also be made into fish composts with the use of bulking agents. In addition, the faeces and uneaten feed from aquaculture can be harvested into a sludge similar to fertiliser. This is also referred to as fish waste.
Rotational grazing	Replace	This involves moving livestock regularly between fields, so that the grass is given time to recover. During rest periods, the grass grows and thus increases organic matter in the soil, which releases plant-available nitrogen. During grazed periods, cattle add manure to soil which also provides plant-available nitrogen.
Anaerobic digestate	Replace	Anaerobic digestate is one of the outputs of anaerobic digestion (AD) plants. AD plants convert biomass, such as food waste, energy crops, sewage, or agricultural wastes into biogas, with digestate as a by-product. The digestate - which is either dry, liquor, or slurry - can be applied as an alternative fertiliser to synthetic fertilisers. It can also be used in intensive greenhouse cultivation.
Human urine as fertiliser	Replace	Human urine contains high levels of nitrogen, phosphorus and potassium, and in a diluted form (approximately 1:10 urine to water), can be used as fertiliser. The urine is diverted using specialist toilets, then transported to a fertiliser production centre either via a pressurised pipe system, or via trucks. If transported via the pipe system, the addition of acetic acid is required to prevent corrosion.

Adding biochar to soils	Reduce	Biochar refers to charcoal used for soil amendment rather than for fuel. It is produced by heating biomass at relatively low temperatures (between 300-800°C) in low oxygen conditions, representing a process of pyrolysis. Biochar can improve fertiliser use efficiency in two ways: 5. By increasing soil water retention (and thus reducing leaching) due to porous physical structure; and 6. By increasing nutrient retention of cations due to a negatively charged surface. However, these characteristics are highly variable and are dependent on factors such as what the biochar is made from, how it is made, and the type of soil it is added to.
Nitrification Inhibitors (NIs)	Reduce	Nitrification Inhibitors (NIs) delay the nitrification of ammonium, which reduces leaching, therefore increasing the nitrogen use efficiency of fertilisers. They are an example of a controlled release fertsilier. NIs can be either biological or synthetic. Biological NIs occur naturally in certain plant species, such as some wheat and rice, and are secreted from roots, whereas synthetic NIs are added to fertiliser.
Perennial crops	Reduce	Unlike annual crops, perennial crops do not need to be replanted each year. There are many crops that are naturally perennial and have been used in farming systems for millennia, such as fruits and nuts. Since the 1980s, researchers have been trying to breed perennial grain crops. This includes for example, intermediate wheatgrass (IWG), which produces wheat grains sold as Kernza, and PR23 - a perennial rice developed and grown in China. Some perennial grains like IWG can also be grazed. Perennial grain crops maintain long-term soil health better than annual varieties, thereby reducing the need for fertiliser. They can also be intercropped with legumes to further reduce the need for fertiliser.

Multi-species swards	Reduce	Multi-species swards (MSS) are grasslands used for pasture that consist of a variety of plants from different families including clovers, grasses, brassicas, herbs, chicory, and plantain. By improving soil health and integrating legumes into the mix to fix atmospheric nitrogen, MSS decrease the quantity of fertiliser needed when compared to a typical pasture system of perennial ryegrass

3.2 Transformation Potential

This section aims to distinguish which solutions have the potential to radically reduce synthetic fertiliser inputs, compared to those which are likely to have a marginal difference – though these latter cases may still have many useful applications in a diversified food system. To assess this, Table 12**Error! Reference source not found.** presents two red amber green (RAG) ratings for:

1. **Extent of reduction per unit area**: this refers to the extent to which a solution could replace or improve synthetic fertiliser.
2. **Scalability**: this refers to the extent to which a solution could replace or improve synthetic fertiliser. Note that this only considers the biophysical limits to scalability (e.g., feedstock availability and applicability to different location/production systems), rather than manmade limits such as legislation and cost which are considered under *Barriers to Uptake* in Section 3.4.

Scoring criteria for extent of reduction per unit area

- **Red:** estimated to reduce demand for synthetic fertilisers by less than 20%.
- **Amber:** estimated to reduce demand for synthetic fertilisers by 20-50%.
- **Green:** estimated to reduce demand for synthetic fertilisers by more than 50%.

Scoring criteria for scalability

- **Red:** some notable biophysical limits on production and application (e.g., feedstock availability), meaning could only reduce a small amount of synthetic fertiliser globally.
- **Amber:** some biophysical limits on production and application but could still reduce a significant quantity of synthetic fertiliser globally.
- **Green:** could either improve or replace the majority of synthetic fertiliser for the relevant farm type globally.

Table 12 Transformation Potential of Fertiliser Solutions

Solution	Extent of reduction per unit area	Scalability
Precision fertiliser technology	🔴	🟢
Controlled release fertilisers (CRF)	🟠	🟢
GM nitrogen fixing arable crops	🟢	🟠
Cover crops: legumes in crop rotations	🟢	🟠
Solid compost	🟠	🔴
Liquid compost/ compost tea	🟠	🟠
Manure	🟢	🟢
Seaweed	🟢	🔴

Shellfish by-product for wastewater nutrient recovery	🟠	🟡
Fish waste (fishery and aquaculture by products)	🟠	🔴
Rotational grazing	🟠	🟠
Anaerobic digestate	🟢	🟠
Human urine as fertiliser	🟢	🟠
Adding biochar to soils	🟠	🔴
Nitrification Inhibitors (NIs)	🟠	🟢
Perennial crops	🟢	🟠
Multi-species swards	🟢	🟢

Extent of reduction per hectare

There are two different types of solutions to reduce reliance on synthetic fertiliser: (1) those that reduce absolute quantity of fertiliser required; and (2) those that replace synthetic with organic fertiliser.

For measures that aim to replace synthetic fertilisers with alternatives, this research question looks at the extent to which synthetics could be replaced. The most promising of these are manure, digestate, seaweed, and human urine, with the former two already used commercially in the UK. In theory, these all have the potential to significantly replace synthetic fertilisers in terms of nutrient content. However, the nutrient content varies depending on the source of the feedstock, with seaweed, shellfish by-products, and fish waste remaining relatively unknown.

For measures that aim to reduce overall fertiliser demand, those which are changes to farming practice using existing low-tech practices were found to be by-and-large the more effective. For pasture, multi-species swards that contain a large clover content are particularly promising, with trials in the UK that used little-to-no fertiliser resulting in yields similar to conventional fertiliser-intense pasture farming [41] [42] (although it should be noted that Scotland's Farm Advisory Service does not currently recommend winter grazing as many species are not tolerant of grazing in wet conditions).[43] For arable, integrating legumes as cover crops in arable rotations can significantly reduce nitrogen fertiliser requirements for subsequent cash crops.[44] However, it is unclear how much residual nitrogen is left in the soil if the grain legumes are harvested for human and animal feed, given that most of the fixed nitrogen is contained within the harvested grain legumes. If, however, the residual nitrogen left in the soil was significant, this solution would provide the benefit of both decreasing synthetic fertiliser demand and reducing reliance on imported soy.

Although research indicates that the extent of reduction from new technologies that aim to reduce overall fertiliser demand is less, measures such as precision technology, CRFs, and NIs can still play a significant role in reducing national and global synthetic fertiliser demand.[45] [46] [47] Finally, there are two measures (perennial crops and GM nitrogen-fixing crops) that – although varieties suited to UK farms do not yet achieve commercially competitive yields – have potential to significantly reduce overall fertiliser demand in the medium- to long-term.[48] [49]

Scalability

Of the fertiliser measures, the most scalable ones fall into two categories: 1) new synthetic fertiliser technologies, and 2) existing low-tech practices. The former includes precision technology, CRFs, and NIs, which aim to improve existing synthetic fertiliser technologies, meaning they could, in theory be implemented wherever synthetic fertilisers are used. The latter includes multi-species swards, rotational grazing, and cover cropping, which could, in theory, be implemented on all pasture and arable land. The scalability of these six measures is highly significant.

Of the less scalable measures, there are a variety of barriers that present themselves. The first is a limited availability of the necessary materials which is an issue for compost, fish waste, and seaweed (although the latter could be alleviated if seaweed cultivation expands rapidly)[50], and the amount of shellfish by product procurable uncertain. A similar issue presents itself for the biochar and digestate measures. Biochar requires land to grow the original feedstock, and while digestate is a by-product of the AD process, the AD process itself should ideally be using only waste organic material, and not creating demand for biomass directly. In both cases, in a world with competing demands for land and biomass, this likely restricts scalability. However, despite limits to scalability, there could well be scope for these approaches to provide valuable solutions within a food system where fertiliser solutions are more diverse.

An obstacle for both the human urine measures is a lack of the infrastructure necessary to collect, transport, process, and store the materials. Finally, regarding the two measures that are currently unviable (perennial crops and GM nitrogen-fixing crops), these will require bespoke modifications to specific crops for these to be scalable both in the UK and overseas. However, the example of the rice-variety PR23 - which is already widely grown in China - highlights the transformative potential of these lab-born solutions. [51]

3.3 Environmental Impact

While some solutions may represent high transformation potential and scalability, some are new and relatively untested, and several run the risk of having unintended environmental consequences. Table 13Table 7 provides a summary of how the solutions can contribute to the environment beyond reducing GHG emissions, nutrient leaching, and ammonia emissions, while also noting the potential unintended consequences associated with each solution. As presented in the Table, these solutions are grouped into those that reduce absolute quantity of fertiliser required (labelled as ‘reduce’), and those that replace synthetic with organic fertiliser (labelled as ‘replace’). Generally, those that reduce the quantity of fertiliser used contribute to a reduction in total GHG emissions (both on-farm and in their production), whereas those that replace synthetic fertiliser as organic substitutes only reduce GHG emissions from production (if their production processes are indeed less carbon-intensive than synthetic fertiliser) and not on-farm, unless combined with other measures.

Table 13 Wider Environmental Benefits and Potential Unintended Consequences of Fertiliser Solutions

Solution	Reduce or Replace?	Environmental Benefits	Unintended Consequences
Precision fertiliser technology	Reduce	• Limited (beyond those from reducing GHG emissions, nutrient leaching, and ammonia emissions).	• Equipment may have an embodied carbon footprint through materials and manufacture, although equipment is generally small additions to existing machinery.

Controlled release fertilisers (CRF)	Reduce	• Limited (beyond those from reducing GHG emissions, nutrient leaching, and ammonia emissions).	• Coatings high in sulphur could increase soil acidity. • Synthetic polymer coatings may be difficult to degrade, potentially leading to soil contamination.
GM nitrogen fixing arable crops	Reduce	• Limited (beyond those from reducing GHG emissions, nutrient leaching, and ammonia emissions).	• Crossbreeding with wild relatives could lead to the creation of hybrid plants with possible unintended consequences for the natural ecosystem.[52]
Cover crops: legumes in crop rotations	Reduce	• Improves soil health. • Sequestration of soil carbon.[53] • Benefits to pollinators and insects. • Potential to provide an animal feed grain legume while reducing fertiliser requirement for subsequent cash crop.	• Some research indicates the risk of increased disease in subsequent cash crops.[54] • Some research indicates higher levels of slugs, although cover crops can provide a habitat for natural slug predators.[55]
Solid compost	Replace	• Improves soil health.[56]	• Does not reduce on-farm GHGs, nutrient leaching.[57]
Liquid compost/ compost tea	Replace	• Improves soil health.	• Increased water use.[58]
Manure	Replace	• Improves soil health.[59]	• Still can result in on-farm GHGs, nutrient leaching, or air pollution.[60]
Seaweed	Replace	• Contains compounds that can kill pests so can also reduce pesticide use. • Increases carbon sequestration.	• There is uncertainty over soil salinisation, and heavy metal contamination.[61] • The marine impacts of large-scale seaweed harvesting are unclear.[62]
Shellfish by-product for wastewater nutrient recovery	Replace	• Increases soil carbon sequestration. • Prevents soil acidification. • Has antibacterial properties. • Helps manage a waste stream arising elsewhere.	• Still can result in on-farm GHGs, nutrient leaching, or air pollution. • Potential for contaminants to absorb onto the crab shell which would be toxic for soils.
Fish waste (fishery and aquaculture by products)	Replace	• Improves soil health.[63] • Helps to manage a waste stream arising elsewhere.	• Still can result in on-farm GHGs, nutrient leaching, or air pollution. • Could lead to over-fishing whereby inedible fish species like Atlantic Menhaden are over-fished for their use in fertiliser production.[64]
Rotational grazing	Reduce	• Improves soil health.[65] • Increases soil carbon sequestration. • Rest periods can help break parasite cycles. • More control over cattle movements can help control manure leaching into waterways.	• Some research suggests rotational grazing increases land use per animal, although other papers suggest the opposite is true.
Anaerobic digestate	Replace	• AD plants primarily produce biogas (with digestate being a by-product of the process) which is a renewable energy source.	• Still can result in on farm GHGs, nutrient leaching, or air pollution. • Microplastic contamination of soil.[66] • Disincentivises food waste prevention.

Human urine as fertiliser	Replace	• Reduces GHG emissions at wastewater treatment facilities.	• Still can result in on-farm GHGs, nutrient leaching, or air pollution.[67]
Adding biochar to soils	Reduce	• Increases soil carbon sequestration. • Improves soil health. • Reduces soil and water heavy metal contamination.[68]	• Increases demand for biomass and land. • If poorly managed, biochar production can produce polyaromatic hydrocarbon (PAH) pollutants.[69] • GHG emissions from energy-intensive production process.
Nitrification Inhibitors (NIs)	Reduce	• Limited (beyond those from reducing GHG emissions, nutrient leaching, and ammonia emissions).	• May increase air pollution by increasing volatilisation of ammonia, particularly for synthetic NIs. [70] • Synthetic NI residues have been found in crops and livestock, raising concerns over food safety. • Wider environmental impacts of synthetic NIs on ecosystems, such as bioaccumulation, are still relatively unknown.
Perennial crops	Reduce	• Improves soil health. • Increases soil carbon. • Increases resilience to climate change through deeper, stronger root networks.	• May cause indirect land-use change. • May increase crop disease by giving pathogens access to living tissue over a long period.[71]
Multi-species swards	Reduce	• Improves animal health due to varied diet). • Clove can have higher protein content so reduces requirement for feed. • Attracts pollinators and insects. • Improves soil health. • Increases resilience to climate change through greater variety of species.	• Many species, especially herbs, are intolerant to grazing in wet conditions, so some authorities currently do not recommend winter grazing.[43] • Potential for reduced livestock health if species mix isn't appropriate.[72]

Wider environmental benefits

Synthetic fertilisers cause greenhouse gases emissions both in their production and in their on-farm application via the elevation of the nutrient status of soils, where mobile nitrate in the soil is converted to nitrous oxide, which is a potent greenhouse gas. Synthetic fertilisers can also decrease water quality as excess nutrients leach into local water bodies, which has knock-on harmful effects for fresh-water and marine ecosystems. Synthetic fertilisers also lead to ammonia emissions when applied on-farm, which is one of the key air pollutants highlighted in the UK Government's Clean Air Strategy.[73] It is important to note that solutions which replace synthetic fertilisers and provide nutrients to the soil can also result in these on farm impacts (seen in the 'Potential unintended consequences' column in Table 13) as well, and therefore only some of the solutions reduce these specific. on-farm impacts

However, many of the measures deliver other significant co-benefits. These quite often include improving soil health, increasing biodiversity, and enhancing carbon sequestration, but there are more niche benefits to some measures, for rotational grazing improving manure management and human urine reducing GHG emissions from wastewater treatment plants.

Improving soil health will increase farming resilience to extreme weather events such as droughts and floods that are increasing in prevalence and intensity due to climate change. Perennial crops and multi-species swards measures are likely to have the greatest potential to achieve this due to the deep and complex root networks they develop within the soil.

The measures with the most environmental benefits are those that change existing farming practice using low-tech practices such as rotational grazing, multi-species swards, and leguminous cover crops. The latter is especially promising as they provide a harvestable grain legume that can be used as animal feed, thus reducing the land required globally to grow animal feed whilst providing farmers with an additional income source.

The measures that improve synthetic fertiliser technology such as precision technology, CRFs, and NIs, have limited further benefits.

Potential unintended consequences

Reducing our use of synthetic fertilisers through the measures outlined in Table 13 will represent a significant shift in the way land is farmed, and so any potential unintended consequences should be considered carefully.

Notably, the measures that replace synthetic fertilisers with a like-for-like organic alternative (i.e., manure and digestate) do not in fact reduce on-farm GHG emissions, nutrient leaching (water pollution), or ammonia emissions (air pollution) as they function in a similar way to synthetic fertilisers when applied to land.[2] However, they do still reduce GHG emissions from the production of synthetic fertiliser. It is important to note that measures such as using manure and digestate are already used for this purpose and any further replacement of synthetics would depend on increased production of these alternatives, which is possible within a more circular economy. One additional potential solution – not researched within this report – would be to recover phosphorus from wastewater treatment systems. Wastewater treatment plants are significant sources of phosphorus pollution into waterbodies and they represent a missed opportunity within the phosphorus cycle. The UK's water industry is not optimal for this as its wastewater treatment network is also used for rain water drainage, which dilutes the phosphorus within the system and releases waste water directly to water bodies in storm events; however, it will be essential to increase recovery of phosphorus to protect finite phosphorus reserves (particularly within the context of 'peak phosphorus').[74]

All the measures that utilise waste (e.g., fish waste, compost, and digestate) should be approached with caution as their widespread uptake will disincentivise waste prevention which ought to be the priority. Particularly problematic would be if, rather than using waste, these technologies come to rely on purpose grown or harvested feedstocks. For example, using fish waste may be considered beneficial, but it may lead to additional fishing in order to provide the feedstock required for fertiliser.[64]

A frequent unintended consequence mentioned in the literature is the potential for increased prevalence of pests and diseases. This is particularly the case for cover crops[54] and perennial grain crops[71], and is an issue that farmers are naturally concerned about, even though there is little evidence to-date to support this. One notable exception to this lack of evidence is the increased slug populations reported by farmers in the UK as a result of cover cropping,[55] although natural predators (or pesticides) could be used to manage this.

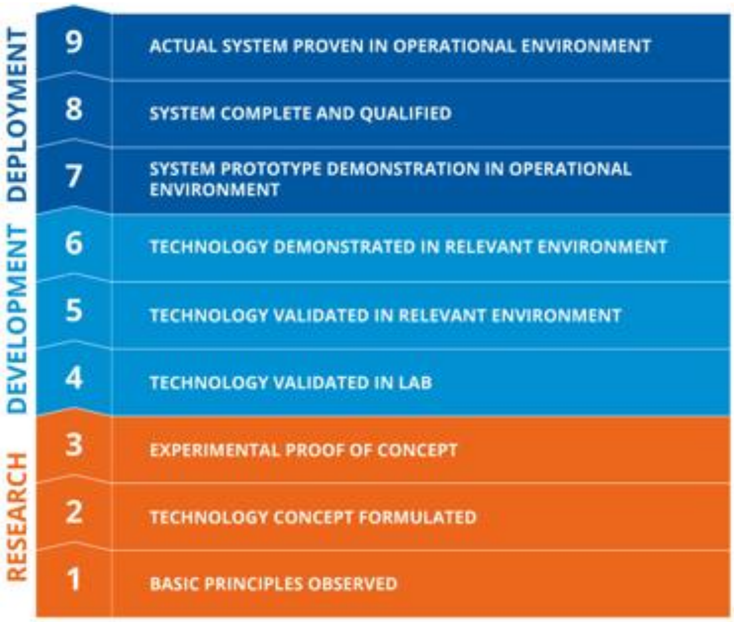
There are also bespoke issues to consider for some of the measures, including the potential for microplastic pollution from digestate[66] and soil acidification from seaweed and CRFs [61] Furthermore, unintended consequences for some of the measures are likely to be unknown as they are novel technologies that have not been widely tested as of yet. This is particularly the case for GM nitrogen-fixing crops, seaweed, and synthetic NIs.

[2] The exception to this is compost which has slow-release properties, meaning less nutrients are lost to the environment in the form of GHGs, water pollution, and air pollution.

3.4 Development Stage and Barriers to Uptake

This section assesses the development stage of each solution against the Technology Readiness Level (TRL) scale (Figure 2), and accordingly, references the key barriers to uptake in relation to the UK context. These are presented in Table 14Table 8. Please refer to Section 2.4 for an explanation of the TRL.

Figure 2 Technology Readiness Level Scale



Source: TWI

Table 14 Development Stage and Key Barriers of Fertiliser Solutions

Solution	Development stage	Key barriers to uptake
Precision fertiliser technology	• TRL9	• **Cost:** High upfront capital cost. Monitoring requirements also costly. • **Skills**: Requires specialist training to use the technology and monitor effects long term.
Controlled release fertilisers (CRF)	• TRL 9/7 *While established, improvements continue and new coating technology including nanoparticles is assessed as TRL 7*	• **Cost**: Too expensive for most farmers.[75]
GM Nitrogen fixing arable crops	• TRL4	• **Research challenges:** Many challenges to be overcome before functional (see appendix).[76] • **Legislation:** As a GM crop, each species would require new legislation. Takes time to process and approve. • **Public and political acceptability:** There could be resistance from public and political audiences about the suitability and ethics.

Cover crops: legumes in crop rotations	• TRL9	• **Costs:** Increased labour, pesticide and seed costs, often with longer payback times. • **Skills:** Farmers may require training to learn the practices.
Solid compost	• TRL 9	• **Cost**: Infrastructure to make the compost on farm is expensive .[77] It can also be expensive to buy and transport. . Field experiments show that money is rarely saved in the first few years of use. [78] • **Regulation:** There are limitations to the amount of compost storable on farm and licenses are required to compost waste. • **Skills:** Application is difficult because of variable timings for nutrients to become available.[79]
Liquid compost/ compost tea	• TRL 8	• **Consistency:** Hard to ensure product consistency. • **Storage:** Can only be stored up to a week without continued aeration. • **Water use:** Requires more water. • **Cost:** Cost of equipment is high. • **Farmer attitudes:** Farmers are hesitant to use it due to uncertainty over efficacy.
Manure	• TRL 9	• **Regulation:** Limits on the amount of manure which can be applied (although this does not impede the replacement effect against synthetic fertilisers), and specialist technology required for application above specific nitrogen loads.
Seaweed	• TRL 9	• **Cost:** The production processes can be expensive • **Storage:** Seaweed can ferment and degrade in storage/transport (apart for seaweed compost). • **Optimisation:** The extraction and refinement of seaweed not yet optimised.
Shellfish by-product for wastewater nutrient recovery	• TRL 7	• **Regulation:** Further testing is required before it is approved.[80]
Fish waste (fishery and aquaculture by products)	• TRL 7/9 • TRL 7: *Fish effluence from fish farms* • TRL 9: *Fish fertilisers from fish waste*	• **Cost:** Fish fertiliser currently has a high cost for farmers. [81] Market is predominantly oriented towards horticulture.
Rotational grazing	• TRL 9	• **Cost:** Requires additional infrastructure such as fencing, water systems, and shelter, which also requires labour costs. [82] • **Skills:** Requires good knowledge of pasture ecology to enable planning. • **Stock:** Some breeds which are less deep bodied than others are less suitable for high intensity rotational grazing because they are less able to utilize the tall forage.[83]

Anaerobic digestate	• TRL 9	• **Regulation:** Specific standards must be met for digestate to be used as fertiliser. • **Costs:** High capital costs for infrastructure, coupled with decreasing financial support.[84] • **Required skills:** Technical expertise required to produce AD on farm. • **Consistency:** Variability in digestate nitrate content.
Human urine as fertiliser	• TRL 7	• **Regulation:** There is a need to update legislation to make it usable (although it is not explicitly prohibited).[85] • **Market acceptance:** Attitudes to using urine diverting toilets are likely to be negative. Additionally, high proportions of people could be unwilling to eat food fertilised by human urine, which could create market barriers. 41% of participants in one survey reported an unwillingness to eat urine fertilised food.[86] . • **Infrastructure:** If piped to production centres, extensive new piping would be required.
Adding biochar to soils	• TRL 5	• **Cost:** Expensive and not commercially competitive for farmers yet. • **Farmer attitudes:** Biochar properties are highly variable depending on the feedstock and production conditions, and its efficacy is dependent on the soil to which it is added. Therefore, it is hard to predict effect, and farmers are hesitant to use it.[87]
Nitrification Inhibitors (NIs)	• TRL 9 *(synthetic)* • TRL 6 (*biological)*	• **Cost:** NI economic gains are marginal.[88] • **Skills:** Most farmers lack an understanding of how to use the technology[Error! Bookmark not defined.]
Perennial grain crops	• TRL 4	• **Profit:** Low yields with lack of commercially viable products.
Multispecies swards	• TRL 9	• **Skills:** Takes farmers time to develop knowledge of optimum yields.[89] • **Costs:** Higher seed costs for multi-species sward mixes than binary grass/clover.[90] • **Pests:** requires more weed control.

Development stage

The majority of solutions are market ready, and proven to work in operational environments (TRL 9). Compost tea is almost at this stage of development but is not yet conclusively proven in an operational environment. For three solutions (controlled release fertilisers, fish waste, and NIs) some variants of the solution are at the highest stage of development, but there are also variants which are less developed. For example, controlled release fertilisers have been in commercial development since 1960, but there is also ongoing research into new material coatings which are in various stages of research, particularly in the field of nanoparticle technology.

The solutions at the earliest stage of development are GM nitrogen-fixing arable crops, and perennial grain crops. Different means for achieving nitrogen fixation are at different stage of development, with the production of extruding biofilms showing the most immediate potential. Despite this, no solution is beyond the R&D stage and has conclusive results from long term field trials.[91] Perennial wheat is still in the laboratory / plant breeding phase and will need to produce higher, consistent yields to be commercially competitive. Yields that will be on par with conventional wheat are predicted to be met in about 20 years.[92] Meanwhile, yields of the perennial rice crop PR23 already match those of annual varieties, and as a result it has been gaining a strong foothold in rice-growing regions of China and is now expanding into Southeast Asia and Africa.[93]

Research indicates that the solutions of shellfish by product for wastewater nutrient recovery and human urine as fertiliser, share the similarities of making available the nutrients contained in waste water available to plants; they just collect the nutrients by different means. The research also signals that both solutions are at similar stages of development, having been proven in operational environments but are not at the stage of market readiness for wide scale adoption in the UK (notably a Swedish company did commercially produce a urine diverting toilet for the purposes of nutrient extraction, but this was discontinued following low consumer acceptance in 2014).[94]

Barriers to uptake

The barriers preventing adoption of the solutions are varied, but **cost** is the most significant, being identified across thirteen of the solutions. Nevertheless, it is acknowledged that costs and prices are dynamic, and the trade-offs between different solutions may change over time. For some of the solutions, the cost barrier is largely one of upfront capital investment. The efficient production of on farm compost is an example of this, due to cost requirements associated with equipment like in-vessel composters. For other solutions, ongoing costs make them less profitable than synthetic fertilisers. For some solutions, like leguminous cover crops, the payback times may be delayed over many years. The benefits to soil health and microbial activity (with knock on benefits for plant health and productivity) from organic solutions, may also not be realised until after many years following repeated applications or repetitive seasonal use. Furthermore, costs may vary depending on the specific nutrient contained within the fertiliser. These examples highlight the complexity for farmers when making decisions around cost on whether to use alternatives to synthetic fertilisers.

Related to cost are barriers around concerns with **consistency** of the alternative fertiliser product and therefore its efficacy, which the literature shows is a particular issue for compost, compost tea, and anaerobic digestate. This is despite the introduction of the PAS100 and PAS110 certifications standards for quality compost and anaerobic digestate respectively.

Regulation and legislation are also a barrier for several of the solutions (compost, manure, anaerobic digestate, human urine, shellfish by product for nutrient recovery, and GM nitrogen crops). The barriers for manure and anaerobic digestate relate to controls on the amount that can be applied to farmland, as well as the technology use to apply it in the case of manure. For compost, regulatory permits are required to produce it and store it above certain quantities on farm. For human urine, shellfish by product for nutrient recovery, and GM nitrogen crops, legislative change or approval is required before they can be used for agricultural purposes in the UK.

Even where solutions are well developed, farmers may not always have the required **skills, time, or financing** to apply or implement the solution. High-capacity requirements in this regard were identified for the solutions of precision fertiliser technology, leguminous crops, rotational grazing, and multispecies swards. Depending on the solution, farmers may require specialist knowledge and skillsets related to optimum species mixes for yield (multispecies swards), pasture ecology (rotational grazing), the use of complex technologies (precision fertilisers) and knowledge of crop rotation practices and specie attributes (leguminous cover crops).

There may also be **operational difficulties** associated with some solutions, such as difficulties in having the time to move livestock between fields in rotational grazing, whilst the length of time the product can be stored before it degrades is particularly an issue for compost tea and seaweed. At the systems level, the solution of using human urine as fertiliser at scale would require significant changes to public infrastructure, with the introduction and common use of urine diverting toilets as well as the installation of a specialist pipe network or the implementation of extensive localised storage facilities and transportation networks.[95] Societal attitudes and common sanitary practices would also require change.[96]

3.5 Strength of Evidence

This Section aims to distinguish the strength of evidence associated with each solution, including whether the solution works, and/or has unintended consequences. To assess this, Table 15 provides a Red Amber Green (RAG) rating for each solution which has been scored against the criteria presented below. In addition, the table lists evidence gaps where applicable.

<u>Scoring criteria</u>

- **Red:** This solution is at an early stage of research with limited evidence to date.
- Amber: This solution has a growing body of evidence with some outstanding research areas.
- **Green:** This solution has been thoroughly researched and has few evidence gaps.

Table 15 Strength of Evidence for Fertiliser Solutions

Solution	Strength of Evidence	Evidence Gaps
Precision fertiliser technology	🟡	• Varies technology-to-technology, but some have uncertainties, e.g., there is little evidence from properly controlled experiments that GPS-aided machines and the mechanised management of in-field spatial variation can really improve nitrogen use efficiency.
Controlled release fertilisers (CRF)	🟡	• Uncertainty over release rates as these differ between in the lab versus in the field.[97] • Generally, this is a developing field as new capsule technologies have developed, with effects to be further assessed.
GM Nitrogen fixing arable crops	🟡	• There are several uncertainties in the research, such as how to minimise and overcome high metabolic energy costs to the plant. • More field trials required for promising avenues of the research
Cover crops: legumes in crop rotations	🟡	• Further research is required into the potential for increased disease associated with subsequent crops[54] • Further research is required on the effects on subsequent crops.[98]
Solid compost	🟡	• Data is required on the availability of green and food waste in the UK. • Further information is also needed to understand where the feedstock is and how easy it would be to aggregate.
Liquid compost/ compost tea	🔴	• More evidence is required on the potential yield increases and environmental benefits, such as improved soil health.
Manure	🟢	• None identified.

Seaweed		• More field trials are required to demonstrate the efficacy and replacement potential. • More research into soil impacts is required, including into increased salinity. • There is uncertainty over the impacts of seaweed cultivation at scale.
Shellfish by-product for wastewater nutrient recovery		• There is uncertainty over the amount of crab carapace that will be procurable and the amount of phosphate that can be recovered per wastewater plant.[99]
Fish waste (fishery and aquaculture by products)		• Further research is required on the replacement potential. • There is a lack of data on fish meal availability in the UK.
Rotational grazing		• Soil carbon found to generally increase with a rotational grazing system (although some studies have found no difference). Different studies report both increases and no differences for soil nitrogen when rotational grazing is implemented. Inconsistent findings on forage biomass. There is no empirical evidence for the effect on root system strength or grazing season length, but anecdotal for the latter. [100]
Anaerobic digestate		• None identified.
Human urine as fertiliser		• There is uncertainty over the cost and length of time required to install infrastructure, as well as optimal production plant location placements.
Adding biochar to soils		• There is uncertainty over the long-term effect on yields.
Nitrification Inhibitors (NIs)		• Further research is required into the synthetic and biological effectiveness under different conditions. • Further research is required on the wider environmental impacts of synthetic NIs. • Further research is required on the overall efficacy of biological NIs.[101]
Perennial grain crops		• More research is required on the impact of intercropping with legumes to increase yields. • More research is required into nitrogen oxide emissions and crop disease.
Multispecies swards		• Ongoing research and testing is required to work out the optimal species mix for each farm.

Summary

The solutions with the strongest body of evidence are precision fertiliser technology, manure, rotational grazing, anaerobic digestate, and multispecies swards. For rotational grazing and multispecies swards, there are gaps in knowledge which would benefit from further research to clear up inconsistencies in effectiveness and refine knowledge around application, but there is nonetheless a considerable amount of research which has been conducted to demonstrate their effectiveness.

It is difficult to provide a detailed assessment of the strength of evidence for the 17 solutions within the budget of this project, but most solutions researched have a growing body of evidence, whereas two – shellfish by-product for wastewater nutrient recovery and compost tea – stand out as being at an early stage with relatively limited research to date. The evidence gaps can be broadly grouped into categories. There is an uncertainty regarding effects on yield and plant growth (perennial grain crops, NIs, biochar, fish waste, seaweed), and relatedly, there is a need for some solutions to demonstrate efficacy in field trials, and not just under laboratory conditions. This is particularly the case for GM nitrogen fixing crops and some controlled release fertilisers. Three of the solutions (seaweed, NIs, and perennial grain crops) would especially benefit from further research globally into their potential for unintended environmental consequences. For some solutions facing both scalability and uptake barriers further research would help elicit the scale of the problem. This is the case for compost, fish waste, human urine diverted from toilets, as well as shellfish by-product for wastewater nutrient recovery.

3.6 Applicability to the UK Context

With some solutions emerging from contexts outside of the UK, this Section aims to distinguish the applicability of solutions to the UK context. To assess this, Table 16 outlines whether the solution is: being implemented or trialled in the UK; provides a Red Amber Green (RAG) rating for the level of Government support; and lists stakeholder types that are currently developing, promoting, or implementing the solution within the UK. Please note that all solutions have been identified to be applicable to the UK farming context.

Scoring criteria

- **Red:** The UK Government has restrictions in place that limit the use of the solution.
- **Amber:** The UK Government has shown interest in this solution but does not provide financial support.
- **Green:** The UK Government provides financial support for this solution.
- Grey: The UK Government has no position or involvement in this solution.

Table 16 Applicability of Fertiliser Solutions to the UK Context

Solution	Is it being implemented / trialled in UK?	Level of UK Government support	UK-based Organisations Involved in this Solution
Precision fertiliser technology	Y	● (Green)	• Yara, Nitrobar and John Deere (agri-tech companies). • The Organic Research Centre. • The International Fertiliser Society.
Controlled release fertilisers (CRF)	Y	● (Grey)	• Yara UK and ICL (agri-tech companies). • AHDB and Farmer's Weekly.
GM Nitrogen fixing arable crops	N	● (Grey)	• (For GM more generally) Gene Watch UK and the Council for Science and Technology.
Cover crops: legumes in crop rotations	Y	● (Green)	• Small agricultural NGOs. • Research Associations.
Solid compost	Y	● (Green)	• Environment Agency. • OLUS Energy (green waste procurer). • Agricology.
Liquid compost/ compost tea	Y	● (Grey)	• Wildlife Trusts. • Innovative Farmers.
Manure	Y	● (Red)	• Agricultural certification associations. • FGS Agri (equipment supplier).

Seaweed	Y		• Ficosterra. • Research Associations.
Shellfish by-product for wastewater nutrient recovery	Y		• Research associations including the Environmental Research Institute. • Scottish Water.
Fish waste (fishery and aquaculture by products)	Y		• Scottish Sea Farms. • In the UK, retailer market for fish fertilisers is mostly for horticulture.
Rotational grazing	Y		• Defra. • AHDB. • Farm Advisory Service. • Zero Carbon Farm (small NGO).
Anaerobic digestate	Y		• The Permaculture Research Institute.
Human urine as fertiliser	Y		• The Organic Research Centre. • Biorenewables Development Centre. • Ricardo UK Ltd (environmental consultancy). • Small start-ups. • Black Bull Biochar Ltd (consortia of private companies).
Adding biochar to soils	Y		• ADM Agriculture, Agravista and OMEX (fertiliser retailers).
Nitrification Inhibitors (NIs)	Y		• The Permaculture Research Institute.
Perennial grain crops	Y		• Self-funded trials by individual farmers.[102]
Multi-species swards	Y		• Research partnerships. • AgriSearch and AFBI (research groups). • Germinal (retailer of multi-seed species).

Usage and applicability to the UK

All but one of the solutions is currently being implemented or trialled in the UK. The exception is GM nitrogen fixing crops, for which no examples of studies based in the UK were found (the US appears to be a pioneering region, with researchers at the University of California, for example, leading the way in GM biofilm production for nitrogen fixation[103]), although there is a considerable body of research in the UK into GM crops more widely.

Level of UK Government support

Seven of the solutions have, or have had, financial provision for them from Government. Four of them (precision fertiliser technology, leguminous cover crops, rotational grazing and multi-species swards) are, or are likely to be provided for under the ELM scheme in England or farm subsidy in Scotland, Wales and Northern Ireland.[39] For the solution of biochar, UK Government has provided funding for research via the Department for Energy Security and Net Zero[104], whilst for seaweed, Cefas – the UK Government marine research body – has provided funding for research into its potential uses[105]. In the case of compost in England, Defra has funded a research project led by WRAP to demonstrate the business case for compost use, and are partners with compost advocates Agricology[106]. The same research project also looked at the benefits of digestate applied on farms, but due to Government restrictions on application, this solution has been RAG rated red (see below). The solution of crab shell by product for nutrient recovery, is technically supported by Scottish Government but this is more indirect. Scottish Water (a public body) is a partner of the Scottish Association for Marine Science – the group pioneering research into the solution in the UK. Two solutions (manure and anaerobic digestate) are encumbered as potential solutions by Government regulation which places limits on their on-farm application, with regulation becoming increasingly restrictive for manure in particular. For the remainder of the solutions, Governments at the national or devolved level have no position or involvement with them.

UK-based organisations involved in these solutions

The types of UK based organisations that support or promote the solutions are relatively well distributed across solutions. Nonetheless, agri-tech firms are involved mostly in precision fertiliser technologies, controlled release fertilisers, NIs, and bio stimulants made from seaweed. Research consortiums are associated with the majority of solutions. Those that are farmer-led appear most frequently for organic practices which have been known about for some time, such as rotational grazing, multispecies swards and leguminous cover cropping, but they have also been pioneering, as in the case of the Innovative Farmers group with compost tea.[107]

4.0 Conclusion

It is hard to reach overall conclusions across the disparate solutions reviewed, but this section highlights key themes and conclusions in common. As in the overall report soy and fertiliser solutions are treated separately.

Soy

The key reason for reducing reliance on soy in animal feed is to reduce the associated land footprint *globally*. To avert deforestation, we need to halt the expansion of global agricultural land and facilitate natural regeneration. The agricultural land footprint needs to be considered at a global level because the food system is so interconnected. Without a global reduction in demand, it is likely demand and environmental impacts will simply be transferred between locations, not reduced or eliminated. In this report, four potential solutions for reducing reliance on soy were covered.

Soy is an excellent crop: it is high in protein, extremely land use efficient ,and fixes its own nitrogen. Simply replacing soy with locally grown grain legumes (that are often less land use efficient) will not reduce the global agricultural land footprint and may simply displace other crops overseas that may ultimately lead to deforestation. Therefore, the most transformative solutions are those that substantially *reduce* land use associated with animal feed. Nevertheless, legumes are valuable, nitrogen fixing crops that should be promoted to facilitate lower input and diverse systems in their own right. Land use efficiency could potentially be increased by replacing non-grain legumes used as cover crops with grain legumes, but further research is needed to understand how much nitrogen carries over to the subsequent crop. This may provide both nitrogen fixation benefits and additional animal feed without displacing other production.

Using food waste as animal feed is a good alternative to soy but has some limitations. If food waste is fed directly to livestock there are a range of health and safety issues, meaning this is highly regulated, reducing the availability of feedstock from post-consumer food waste in particular. Additionally, the nutritional content of a food waste stream can be extremely variable causing unpredictability and making it hard to manage. Feeding food waste to insects via insect farming, and then feeding insects to livestock can help overcome both these issues, but there are some conversion losses. Furthermore, food waste is not ideal as a feedstock, as food waste prevention is a global priority, with greater environmental benefits than simply utilising food waste efficiently as feed when it arises. Additionally, although a third of all food globally is wasted, not all of this is captured in ways that can be used as animal feed. The scalability of this option is therefore constrained. Further research into the potential of alternative feedstocks (e.g., sewage) fed to insects could be useful here.

Microbial protein is a more novel but potentially more scalable alternative. Unlike insects, micro-organisms can synthesize new protein, via fermentation, if provided with a suitable source of carbon, hydrogen, oxygen, and nitrogen. Carbon is the most challenging element to provide. Carbon could come from fossil fuel effluent or direct air capture, but the former is soon to be phased out and the latter is hard to scale. Inedible crop residues (or cacti grown in semi-arid regions) provide a more promising feedstock option. Although the technology is still in its infancy, the potential to displace soy is very large. This is a key area that needs further research.

In summary, to reduce the reliance on soy-containing animal feeds a mix of solutions is likely needed. Grain legumes (of which soy is one) are a great crop but do not reduce global land use. Food waste fed either directly to animals or via insects is a great option in the medium term but ultimately food waste needs to be reduced (and associated land released from agriculture). Microbial protein using inedible crop residues is still in its development phase but its potential to radically reduce global agricultural land use is huge.

Synthetic Fertiliser Inputs

The benefits of reducing synthetic fertiliser inputs are more varied than the benefits of reduced reliance on soy for animal feed. These benefits include reducing greenhouse gas (GHG) emissions (both on-farm and in-production); reducing water pollution (from nutrient leaching); and reducing air pollution (by decreasing ammonia emissions). In contrast to soy, they are many more potential solutions for reducing reliance on fertiliser and seventeen were shortlisted covered in this report. These fall into two main categories: those that reduce the *need* for fertilisers (whether these are synthetic or organic) and organic *alternatives* to synthetic nitrogen. *Reducing* the need for fertilisers contributes to reductions in all the impacts listed above. However, *alternatives* may only reduce the manufacturing GHG emissions, except for those that improve soil structure and therefore reduce leaching.

A direct like-for-like swap of synthetic for organic fertiliser (e.g., manure or compost), does not achieve all desired environmental benefits, primarily due to the fact nutrient loss issues remain. Therefore, the aim should primarily be to reduce the overall demand for fertilisers whilst substituting the remaining demand from synthetic to organic (as far as possible). Demand reduction is a win-win for both farmers and the environment as it lowers input costs whilst reducing emissions and pollution.

Many of the solutions covered in this report are based on reinstating existing techniques that were used historically but have become less widespread since the rise of industrial farming and the “Green Revolution” (e.g., compost, seaweed, and integrating legumes into crop rotations.. The main barriers to uptake of these are often lack of knowledge or skills amongst modern farmers, increased time or costs (though these may also relate to the fact these technologies do not currently benefit from economies of scale), and potentially scalability issues (e.g., the consequences of large scale seaweed farming or harvesting are unclear). These more natural techniques often have the greatest overall environmental benefit, particularly in terms of improving soil health which is a fundamental component of all sustainable food systems. The barriers to change in these cases are not simply or even primarily technical. To overcome knowledge barriers, farmers need robust, impartial, consistent and tailored advice. To overcome cost barriers, farmers need financial support. Financial support might not simply be direct payments for investment or running costs, but could also involve solutions that reduce risk.

Some solutions assessed are new technologies that are market ready but not yet in widespread use, although there is perhaps potential for further innovation to improve them (e.g., precision fertilizer technology, controlled release fertilisers, and nitrification inhibitors). The main barriers to uptake for these again include cost, and potentially a lack of knowledge and skills. Additionally, concerns over unintended environmental consequences, real or imagined, may be a factor. As above, advice and financial support are needed to make these solutions more widespread, but once they become more widespread, costs may well reduce. Further research and development could optimise these solutions further and would also provide clarity on potential wider consequences.

Finally, some solutions assessed are developing technologies that are not yet market ready (e.g., perennial grain crops and GM nitrogen fixing crops) but have significant transformative potential in the medium to long term. These need targeted research and development, considering both solution development and research on risks and any unintended consequences. Research efforts should be accelerated to make a material difference within relevant timescales.

To conclude, there is no single solution to reducing reliance on synthetic fertilizer that will solve all our problems. The food system is too diverse for a one-size-fits all approach. A mixture of solutions will be required, including both those that reduce overall fertilizer use and those that replace synthetics with organic alternatives, and also a mix of both low- and high-tech solutions. Even in a fully optimised future food system, it is also worth acknowledging that synthetic fertilisers may still have a necessary place in some contexts, for example where localised nutrient shortages occur. This is especially likely for phosphorus and potassium, which have few natural processes that add them to land.

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