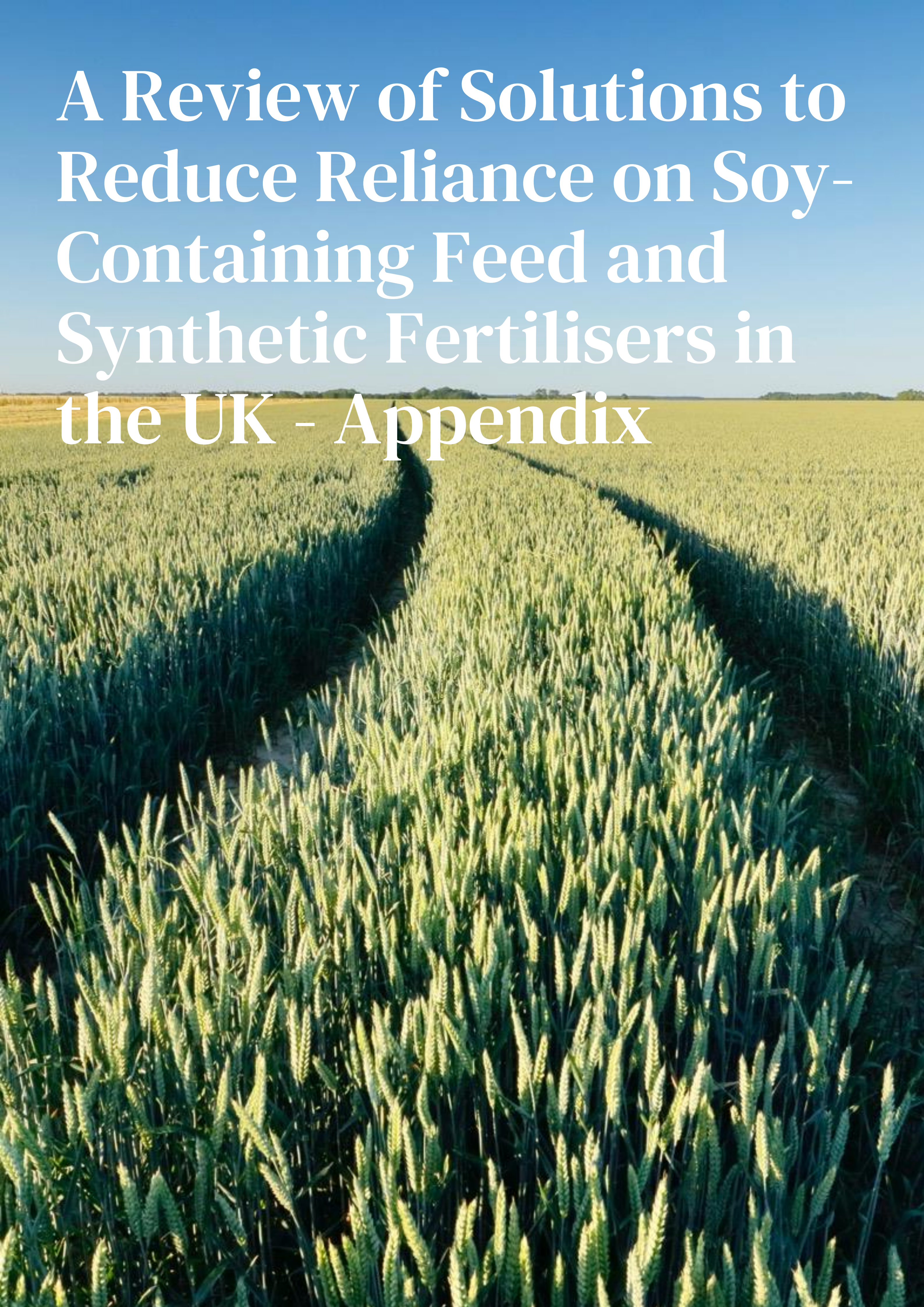
A Review of Solutions to Reduce Reliance on Soy-Containing Feed and Synthetic Fertilisers in the UK - Appendix



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A 1.1 Transformation Potential

Table 1 Transformation Potential of Soy-containing Solutions

Solution	Extent of reduction per unit area/per animal?	Justification	Scalability	Justification
Insect protein	● (green)	By 2050, insect protein produced in the UK could replace 239,000 tonnes of soy protein per year (sparing 66,000 ha land per year). By 2050, 540,000 tonnes of soy is projected to be demanded by the UK pig, poultry and salmon sectors. It is not possible to displace all soy because there is insufficient food waste projected to be available to feed the required number of insects, and because conversion losses from food waste to insect protein means that the process of conversion is not 100% efficient.[1] Note that even with this projected figure for insect protein availability, there is also some uncertainty about whether, in the years leading up to 2050, sufficient food waste will be produced to achieve this scale of insect protein production. If the insects are fed on 'industrial side streams' (which may include food waste) then the mean CO_2/kg of protein for chickens fed on insects is 17.38, compared to soybean meal at 18.55. However, if the insects are fed on 'composite feed', emissions are slightly higher at 18.63.[2] Note that these calculations are subject to a high degree of uncertainty.	● (amber)	It is only applicable as a feed for poultry, pigs, and aquaculture - it is not suitable for other livestock. Production limitations surrounding the availability of food waste as feedstock may eventually limit scalability. Insects can be fed on alternatives to food waste, but insects fed by composite feed results in higher GHG emissions than soymeal feed.[2]

Solution	Extent of reduction per unit area/per animal?	Justification	Scalability	Justification
Microbial protein	●	Microbial protein production has a quasi-zero land footprint. Microbial protein provides more protein per land area compared to soybean production; it contains more than 70% crude protein, whereas soy-containing animal feed contains 40-50% crude protein and fish meal contains 60-65% crude protein.[3] It could therefore theoretically replace a substantial amount of soy-containing animal feed. However, more research is needed to ascertain whether it could completely replace soymeal, or whether certain other nutrients contained in soy would need to be added to microbial protein feed as a supplement.	●	Microbial protein is widely applicable to different livestock including ruminants, pigs and chickens, as well as in aquaculture.[Error! Bookmark not defined.] Microbial protein production is independent of climate and weather conditions.[4] Scalability is limited by the availability of feedstock, particularly a source of carbon. There are two key categories of feedstock: 1. Gas feedstocks: this includes natural gas and direct air capture (DAC) of CO_2. However, in a future decarbonised economy, this feedstock is likely to be less available. 2. Biomass feedstocks (e.g. food waste and woody materials): these are generally limited by the availability of land. Food waste as a feedstock does not contribute any additional agricultural land footprint, but food waste availability is likely to be limited in a more circular economy.
Growing alternative grain legumes	●	In theory, 100% of imported soy could be replaced by growing alternative grain legumes in the UK. However, the UK's soy land footprint is up 1.7 million a, which is roughly the size of Wales, so this could drive further land conversion.[5] It is more likely that homegrown alternative would replace a small share of imported soy as part of a wider effort to diversify cropping.	●	Grain legumes can be widely grown on any land suited for arable crops (e.g., grades 1-3a in the UK), but would require a large area of land to replace imported soy. They are also well suited as break/cover crops as part of arable rotations.

Solution	Extent of reduction per unit area/per animal?	Justification	Scalability	Justification
Pre-consumer food and organic waste	●	Food surplus/waste captured from food processing could be increased by 200,000 tonnes per year,[6] but the protein content varies depending on the source, and it is uncertain what amount of soy this could replace. Distillers grains, a by-product from brewers and increasingly from biofuel production, are an example of pre-consumer organic waste that is already used widely as animal feed.[7]	●	Whilst there is the opportunity to increase current usage, the availability of by-products is limited by the size of the food production system. WRAP (2021) suggests there is significant potential to increase the amount of post-production line waste used in the UK (by 21%), whilst relaxing legislation on post-consumer food could provide 2.5 million tonnes of food waste for pigs each year.[8]

A 1.2 Wider Environmental Impact

Table 2 Wider Environmental Benefits and Potential Unintended Consequences of Soy-containing Solutions

Solution	Wider Environmental Benefits	Potential Unintended Consequences
Insect protein	**Reduced demand for agricultural land:** Through land sparing, preventing habitat destruction and biodiversity loss. If maximised in the UK, WWF estimates that insect protein could release 150,000 hectares of land globally from soy production.[9] **High-value use for waste:** Using food/organic waste in the generation of animal feed is better than landfill/incineration and potentially better than anaerobic digestion. **Fertiliser production:** Insect frass (excrement) produced as a result of insect production has a value as a fertiliser in crop production systems, and can be used to displace inorganic fertiliser use. **Disease/pests** (within insect farm): As insect production scales up, there could be heightened risk of pests and diseases entering into the production system.	**Food waste:** Creates a market for food waste, thereby disincentivising attempts to reduce the production of food waste. **Carbon emissions:** If insects are reared in sub-optimal conditions, production generates higher emissions compared to soybean or fishmeal.[10] **Waste management**: Whilst insect frass (excrement) can be a highly valuable material, at certain quantities/storage conditions this material may be considered hazardous waste. **Virgin material extraction:** There is a risk that, should purpose-grown substrate be shown to produce a more consistent quality of insect protein more efficiently than food waste, without effective regulation it will replace food waste as the primary substrate.
Microbial protein	**Reduced demand for agricultural land:** Through land sparing, habitat destruction and biodiversity loss are prevented. **No nutrient loss:** Micro-organisms are able to synthesise proteins without loss of nitrogen or phosphorus (unlike crops, insects and food waste).[11] **Reduction of water footprint:** The production of microbial protein uses about 20-140 times less water than fishmeal and soybean meal, respectively.[11] **Mitigation of CO_2 emissions**: Where carbon is captured using renewable energy, and is used as a feedstock for protein production, the recycling of CO_2 enables a carbon-negative protein production process.	**On-farm soil health:** If using crop residues as carbon source, removal of too much crop residue from the field would mean that insufficient carbon (and other nutrients) is returned to the soil. **Increased reliance on fossil fuels**: By scaling up the production of microbial protein using natural gas.[11] **Carbon emissions:** Feedkind, an animal feed microbial protein produced from natural gas, has a 10 times higher carbon footprint compared to soy protein concentrate.[12]

Growing alternative grain legumes	**Increased diversification of cropping:** Incorporating a variety of grain legumes into the UK cropping system could reduce pests and disease and increase resilience.[13] **Increased biodiversity**. Grain legumes provide additional forage for pollinators. **Decreases fertiliser demand**: Legumes fix atmospheric nitrogen, in turn decreasing embodied and on-farm GHGs, and reducing water pollution from nutrient leaching. However, this could lead to a displacement of agriculture oversees where fertilisers may still be applied, simply transferring these impacts to an oversees farm. This indirect land-use change is complicated, and more information can be found from Legume Hub.[14]	**Indirect land-use change:** Growing alternatives to soy in the UK on a large scale would lead to a complex series of knock-on effects. To put into perspective the scale of transformation that would be required to do this, WWF's Riskier Business report found that the size of farmland required to grow all of UK's soy feed for 2016-2018 was an average of 1.7 million ha/year (an area the size of Wales).[15] Firstly, it should be noted that soy is a highly land efficient crop (from a protein/feed perspective), and it is unlikely that the UK could grow any alternatives in a more land-efficient way, meaning that the overall land footprint of UK consumption may in fact increase by switching to homegrown grain legumes. What's more, to grow these crops in the UK, it would likely displace cereal production to other countries, resulting in UK farmers sacrificing high-yielding crops such as wheat. The decision to switch from importing soy to growing grain legumes in the UK in any major way would have to factor in these complex interactions between UK farming and the global food system.
Pre-consumer food and organic waste	**Reduced demand for agricultural land:** Through land sparing, this solution can prevent habitat destruction and biodiversity loss.	**Food waste:** Creating an outlet for food waste can disincentivise attempts to reduce the production of food waste. **Disease spread**: Spreading of livestock disease if by-products aren't stored or treated properly. Consumption of by-products may also increase toxin and pathogen presence in animal tissues and products (stated in Landworker's Alliance application).

A 1.3 Development Stage and Barriers to Uptake

Table 3 Development Stage and Key Barriers of Soy-containing Solutions

Solution	Development stage	Key barriers to uptake
Insect protein	**TLR9** Technology is market-ready and insect protein feed is currently permitted for pets and for aquaculture feed.	**Regulation:** Current UK legislation prevents insect protein from dead insects being fed to any farmed livestock intended for human consumption. Note that in 2021 the European Union (EU) amended the Feed Ban Regulations to allow for poultry and pigs to consume insect protein, though it is uncertain whether the UK will follow suit.[16] Live insects are however not considered an ABP and can used as animal feed. **Market acceptance:** Although research by PROteINSECT showed an over 70% consumer acceptance rate, the feed industry is unlikely to use protein sources that might compromise the demand for their customers' (livestock producers) products.
Microbial protein	**TRL 4** Not yet market-ready, still in R&D and trialling phase of development (though some solutions, e.g., Uniprotein and SYLFEED, examples of fish feed, are almost market-ready).[17] [18] Deep Branch (a UK and Netherlands-based company) is developing a single-cell protein for the animal feed industry using CO_2 and hydrogen, as well as renewable energy sources.[19] A commercial facility is expected to launch in the Netherlands in 2025, with an anticipated 600,000 tonnes per annum global capacity by 2030, utilising over one million tonnes of CO_2 every year.	**Regulation:** Gaining legal recognition of some microbial protein products as an animal feed.[20] **Feedstock supply:** As the economy is decarbonised, feedstock of carbon will be less readily available. **Technological readiness:** Direct air capture of carbon requires substantial space, energy and equipment and therefore is currently too expensive to produce commercial quantities of protein.
Growing alternative grain legumes	**TRL9** Legumes are widely grown in the UK already, although not many are used in animal feed. There is an increasing trend for greater use of homegrown feed (for food security and a belief that it will reduce oversees deforestation).	**More expensive:** Soy is highly land efficient (cheaper land costs) and imported soy comes with cheaper labour costs.

Solution	Development stage	Key barriers to uptake
Pre-consumer food and organic waste	**TRL 9** Poultry oil/meal commonly used (with capacity to increase), and currently 660,000 tonnes of food surplus from food production are used (with capacity to increase).	**Regulation: Regulation:** Post-consumer food wate and some animal by-products as feed are banned in the UK, and there are legislative barriers for the use of waste streams in animal feed.[21] [22] The foot-and-mouth outbreak of 2001 that resulted from feeding post-consumer food waste to pigs,[23] and the BSE crisis of the 1990s that resulted from the feeding of ruminant processing products to ruminants, are emblematic of why this regulation was introduced. [24] **Perishability:** Many by-products (especially those generated in livestock and fish processing) are highly perishable so require infrastructure and knowledge for stabilisation. This is a capital investment cost.

A 1.4 Strength of Evidence

Table 4 Strength of Evidence associated with Soy-containing Solutions

Solution	Strength of Evidence	Explanation	Evidence Gaps
Insect protein		A lot of research and evidence on the transformation potential of the solution, including in the UK specifically. However, there are still some key evidence gaps surrounding scalability.	The future of food waste supply uncertain. There is little discussion around overcoming consumer aversion to livestock fed by insects The potential carbon savings are subject to considerable uncertainty
Microbial protein		There is a lot of research on the potential to use microbial proteins, but this generally focusses on its use as a substitute for human food, rather than animal feed.	There is a lack of evidence of its ability to replace soymeal in the field. There is a lack of evidence of unintended consequences on the production and use of microbial proteins.

Growing alternative grain legumes		There is a significant amount of research in this field, particularly in the UK and Europe, and many farms already grow grain legumes.	There remains a knowledge gap on which cropping strategies are most effective for protein diversification, with consideration to yield, land use, and other environmental impacts.[25]

Solution	Strength of Evidence	Explanation	Evidence Gaps
Pre-consumer food and organic waste		There is limited research on the use of food system by products. There is research on the use of post-consumer food waste as feed, as well as opportunities for increasing pre-consumer food waste direction to animal feed.[26]	Uncertainty over the quantities and nutritional content of various feedstocks and therefore their potential to replace soy.

A 1.5 Applicability to the UK Context

Table 5 Applicability of Soy-containing Solutions to the UK Context

Solution	Applicable to UK?	Is it being implemented / trialled in UK?	Level of UK Government Support	UK based organisations that are developing/ promoting/implementing this
Insect protein	Y	N Regulation does not permit it, so not currently operating, though there are investors and researchers actively exploring at this research stage.	The UK Government has restrictions in place that limit the use of this solution. There is currently no indication that regulatory changes are being considered.[27] However, live insects are acceptable as animal feed.	**NGOs:** • WWF **Tech start-ups:** • Entocycle **Partnership organisations:** • Agrigrub **Research institutions:** • Queen's University Belfast

Microbial protein	**Y**	**Y** Not yet technologically ready, but is in trial stage, such as the pilot project with Deep Branch at the Drax power plant in Yorkshire.	**Deep Branch funding:** • Pilot project at the Drax power plant in Yorkshire secured £3m in Government funding.[28] • Additional $4.8m in BEIS funding secured in 2022 for Deep Blue Carbon project (integrating carbon capture and low-carbon hydrogen). **Other UK government funding** for research into "sustainable protein": • In 2022, UKRI pledged £20m towards sustainable protein research & development. • Novel Low Emission Food Production systems competition.	**NGOs:** • WWF **Agri- Tech start-ups:** • Deep Branch **Research organisations:** • King's College London • University of Nottingham
Solution	**Applicable to UK?**	**Is it being implemented / trialled in UK?**	**Level of UK Government Support**	**UK based organisations that are developing/ promoting/implementing this**
Growing alternative grain legumes	**Y**	**Y** Legumes have been grown in the UK for centuries. As of 2019, faba/fava beans were the most widely grown grain legume in the UK, then field peas, then fresh peas, then fresh beans.[29] Other grain legumes that can be grown in the UK are soy, navy beans, and lupins.	Pre-ELMS and within ELMS, there are payments for establishing and maintaining legumes within grasslands, however there are no direct payments for growing and harvesting grain legumes as part of permanent or rotational arable land.[30] The Welsh Sustainable Farming Scheme does include support for growing and harvesting grain legumes ('protein crops') as part of arable rotations.[31]	**Research Institutions:** • Processors and Growers Research Association (research group interested in agronomic impacts of new technologies/practices) **NGOs** • Size of Wales (climate NGO with the aim of reducing tropical deforestation)

Pre-consumer food and organic waste	Y	Y Globally, some by-products are used extensively in feed already.[32] Is part of the land use model piloted by Landworker's Alliance.	**Food system by products** • No reference to Government support for food system by-products. • Defra and Animal and Plant Health Agency have guidance on the use of animal by-products as animal feed.[33] **Pre-consumer food waste** • Making animal feed from former food is third (out of eight) on Defra's food waste hierarchy.	**Food system by products** • Landworker's Alliance **Pre-consumer food waste** • WRAP • Defra

A 2.0 Synthetic Fertiliser Solutions

A 2.1 Transformation Potential

Table 6 Transformation Potential of Fertiliser Solutions

Solution	Extent of reduction per unit area/per animal?	Justification	Scalability	Justification
Precision fertiliser technology		2015 UK data shows reduction of 10kg nitrogen/ha across tillage and land and grasslands, which was 7.6% of the 2015 average application rate of 132kg nitrogen/ha. Overall, authors estimate 10% reduction of applied synthetic nitrogen.[34]		Precision fertiliser measures are applicable wherever fertiliser is used, including cropland, grassland, forestry, and horticulture.

Controlled release fertilisers (CRF)		**Quantities**: A recent field study using CRF in rice farming showed a reduction in fertiliser application quantities of 20%.[35] A study by Masuda et al (2003) showed that nitrogen application could be reduced by 40%.[36] **Rates:** Various studies in Japan on crops including maize, sugarcane, potatoes, tea and numerous vegetables, have shown that nitrogen application rates could be reduced by 20-60%.[37]		Applicable to where fertiliser is used, including cropland, grassland, forestry, and horticulture. No barriers to scalability in theory.

Solution	Extent of reduction per unit area/per animal?	Justification	Scalability	Justification
GM nitrogen fixing arable crops		Difficult to quantify the extent of reduction, as it will depend on the crop in question, the environment, and the specific GM trait - which are still in the laboratory phase. If the nitrogen producing capabilities of legumes can be replicated, then the need for fertiliser on arable crops may be negated entirely, as legumes in good soil conditions do not need fertiliser, and can return nitrogen to the soil.[38] Engineering the production of biofilms by cereals may produce a result where the introduced bacteria cannot provide all the nitrogen a plant needs,[39] so it would result in a reduction, as opposed to elimination of fertiliser entirely. Note, that this has not been quantified.		Relevant to all arable farms growing cereal crops. No clear barriers to being scaled to all arable farms, but genetic modification will need to happen for each individual crop.

Cover crops: legumes in crop rotations		Leguminous cover crops reduce the nitrogen fertiliser requirements for subsequent cash crops by 32-115kg nitrogen/ha.[40] There is less research on the reduction of fertiliser for subsequent cash crops if the leguminous cover crops are harvested as grain legumes. However, less than 25% of respondents to a 2017 UK survey of cover crop farmers reported a reduction in the use of chemical fertilisers.[41] This can partly be explained by the fact that these were not all leguminous cover crops.		Widely applicable to cropland and already implemented globally, with greater uptake in the US and France than the UK. It seems like most cover crops to-date are non-leguminous.
Solution	**Extent of reduction per unit area/per animal?**	**Justification**	**Scalability**	**Justification**
Solid compost		Depends significantly on the composition of the compost, which can vary substantially. Over a 4-year average, a 2003 study found that silage maize required 23 kg/ha less of nitrogen from synthetic fertiliser when vegetable, fruit and garden waste compost was applied (16% reduction).[42] However, when combined with the optimum slurry amount, the study identified there was 105kg less nitrogen than when synthetic fertiliser was used alone (71% reduction). Compost acts as a slow-release fertiliser, particularly for N where only 5-10% of total N in compost becomes available within the first year.[43]		Relevant for all farmland; pasture and arable, as well as orchards. Lack of green waste and food waste due to competition from bioenergy sector. However, this competition will reduce as bioenergy subsidies are phased out.

Liquid compost/ compost tea		A 2018 study, in which compost tea was applied to strawberries, showed that compost tea provided similar macro- and micro-nutrients as standard compost from municipal waste, ruminant compost, and fertiliser treatments.[44] Other studies from 2015[45] and 2017[46] have shown increased yields after applications of compost tea in certain crops - in the latter case, by 35-50%. However, a study in 2021 found no effect on the plant grown and yield following compost tea application to soybeans, and no effect on bacterial diversity in the soil.[47]		Theoretically applicable to both arable and pasture land, but field trials appear to have only been done on arable crops. Due to the need to remain oxidised throughout production and storage, it is difficult to store and transport without being constantly aerated. This generally limits its feasible production except for in relatively small batches on small farms.
Solution	**Extent of reduction per unit area/per animal?**	**Justification**	**Scalability**	**Justification**
Manure		A 2022 study showed that yields in a citrus orchard can be maintained while applying 30% less chemical fertiliser when the fertiliser was combined with optimum amounts of organic manure.[48] Over 4 years, a 2003 study found that silage maize required 92 kg/hectare less of nitrogen from synthetic fertiliser when manure was applied (62% reduction).[49] When combined with the optimum compost amount, this was 105 kg of nitrogen less than synthetic fertiliser alone 71% reduction). Opinions are mixed, but manure is often not considered suitable as a direct replacement for synthetic fertiliser as its nutrient content is harder to predict and tailor.[50]		Applicable to all farm types. There is little scope for manure application to be scaled up. This is due to significant use already, and regulation. 80% of farms already use manure to at least some extent.[51]

Seaweed		There is some evidence that seaweed-based fertilisers can reduce the need for solid inorganic fertilisers. A 2016 study assumed that bioavailability of nitrogen and phosphorus in seaweed fertilisers was similar to manure, and therefore that 1kg of phosphorus biofertiliser substitutes 0.95 kg of mineral phosphorus fertiliser, and 1kg of nitrogen biofertiliser substitutes 0.69kg of mineral nitrogen fertiliser.[52] A 2010 study in India demonstrated a 50% reduction in chemical fertiliser required per row of marigolds (with c. 40% increase in flower weight) after application of seaweed liquid fertiliser.[53] Farghali et al (2023) estimated that the application of 50 gigatonnes of dry weight seaweed (at 5 tonnes per hectare) would spare 1 million square kilometres of land.[54]		This is widely applicable - pre-war seaweed was widely used by farmers as a natural fertiliser. Scalability may be limited by availability of product: aquaculture production of seaweed is currently not price effective. There is also a risk of harming marine environments through large scale production. Land-based production in tanks is currently too expensive.
Solution	**Extent of reduction per unit area/per animal?**	**Justification**	**Scalability**	**Justification**
Shellfish by-product for wastewater nutrient recovery		Direct data is unavailable. The scope of use is seen as a "general soil improver" for use at local farm level, with up to a 7% phosphate content. [55] This is within the nitrogen/phosphorus/potassium range of many typical agricultural fertilisers. It would not be able to replace fertiliser in field entirely, as additional nutrients are required.		Applicable to all field types. 10-200 tonnes of phosphate can be extracted *per year per wastewater treatment plant*.[56] A limiting factor is the amount of crab carapace. Further information is required on the dry weight of crab carapace potentially harvestable from the UK. However, according to Scottish Association for Marine Science (SAMS) the availability of material is "enormous" and enough for produce "high quantities of alternative fertiliser product".

Fish waste (fishery and aquaculture by products)		**Commercial fish fertiliser product:** According to Dora Agri, use of their fish emulsion fertiliser product can increase the utilisation rate of plants to chemical fertiliser by 10-30%. The study also identified the potential for an equivalent reduction in synthetic fertiliser use.[57] There are no scientific studies on replacement potential, just yield changes in comparison to synthetic fertiliser. Outcomes are dependent on crop type and fertiliser concentrations. **Fish silage/emulsion:** Fish silage at concentrations of 5% produced comparable yield and quality of pak-choy as with commercial nitrogen/phosphorus/potassium fertiliser.[58] This would imply a 1:1 replacement potential. **Fish compost:** A fish-based compost also increased potato production by 30% compared to mineral fertiliser.[59]		For farm use, all references are for use on crops, although theoretically applicable to pasture. Based on the availability of fish waste, the UK would be enough to replace approximately 9% of synthetic fertiliser for phosphorus requirements (based on Eunomia calculations using Ahuja et al, 2020;[59] Smithers, 2019;[60] Statista, 2023).[61] Note that figures do not include waste from aquaculture excreta. A challenge to scalability includes the alternative competing uses for fish waste. In Norway for example, these products are used as feed for fur animals.
Rotational grazing		Very difficult to quantify, as practices vary widely, notably the length of grazing period.[62] A study found a 50% reduction in fertiliser application over 3 years for sheep farm in Wales (progressive decrease year on year).[63] Rotational grazing also allows for approximately 20% more grass to be grown.[64]		Relevant for all farms with grassland pasture for livestock but some additional fertiliser likely still required. Is mainly used in dairy farming currently. Potential to scale more in beef. The potential to increase overall stocking rates whilst improving soil fertility would be attractive to farmers.

Solution	Extent of reduction per unit area/per animal?	Justification	Scalability	Justification
Anaerobic digestate		The composition of digestate (and therefore the ability to replace synthetic fertiliser) varies depending on the biomass inputs, and the form of output. Typical nutrient values on the NNFCC website are:[65] • Nitrogen: 2.3 - 4.2 kg/tonne • Phosphorous: 0.2 - 1.5 kg/tonne • Potassium: 1.3 - 5.2 kg/tonne In theory, if farmers applied enough digestate, it could completely replace synthetic fertiliser.		Digestate could in theory be used wherever conventional fertilisers are used, however there is significant variation in the nutrient content of digestate so the degree to which it can replace synthetic fertilisers is variable.
Human urine as fertiliser		A 2008 study found that almost identical yields (94%) can be achieved with a 50% replacement of synthetic fertiliser with human urine.[66] Global warming potential (GWP): Results show a 29-47% reduction in GWP compared to synthetic fertiliser. Note this is due to both synthetic fertiliser offsetting as well as reduced wastewater plant energy consumption.[67]		Although this requires specialist toilets, the solution is highly scalable. In Germany, the replacement potential of synthetic fertilisers for diverted urine and faeces is 25%, and preplacement potentials for the UK will be comparable. Whilst this solution in question only looks at diverted urine, the urine contributes Nitrogen and Potassium, and therefore a significant proportion of this 25% value will be constituted by the urine component.[68]
Adding biochar to soils		Nutrient use efficiency (NUE) of conventional fertilisers used in crop production is 30-40%; biochar-based fertilisers have an NUE of 50-60% because of biochar's slow-release mechanism.[69] This means farmers would only have to apply 50-80% of the quantity of fertiliser if using biochar-based fertiliser (Eunomia calculation).		Biochar-based fertilisers could in theory be used wherever conventional fertilisers are used. However, there are evidence gaps and market barriers to uptake.

Nitrification inhibitors		A 2015 study performed a meta-analysis on nitrogen inhibitors studies and reported that overall, their application decreased total nitrogen loss by 16.5%.[70] Synthetic nitrogen inhibitors such as Dicyandiamide can reduce nitrification by up to 60%,[71] and biological nitrogen inhibitors such as specific varieties of wheat can reduce nitrification by up to 79%.[72]		Nitrogen inhibitors appear to be applicable wherever conventional nitrogen fertilisers are applied (i.e., arable land, grassland, horticulture and forestry), although they are more effective at low soil temperatures. Less is known about the scalability of biological nitrogen inhibitors, although in theory, they are widely applicable.

Solution	Extent of reduction per unit area/per animal?	Justification	Scalability	Justification
Perennial crops		This will vary crop-to-crop. Taking intermediate wheatgrass (IWG) as an example (which has been bred to produce a grain that can be used in a similar way to wheat)[73], its optimum nitrogen fertiliser rate when grown as a monoculture is between 61-94kg nitrogen/ha,[74] compared to annual wheat crops of 130-220kg nitrogen/ha.[75] This is because of IWG's more extensive root system. Using these numbers, this works out to be a 28-72% reduction in nitrogen fertiliser demand (Eunomia calculation). However, IWG yields are currently significantly less than annual wheat, so fertiliser per yield may not currently show an actual reduction. The fertiliser reduction could be enhanced if perennial grains are intercropped with legumes.		This will vary crop-to-crop. IWG's global distribution is Europe, Western Asia, and North America, whereas PR23 (perennial rice) is grown in China, SE Asia, and Africa.[76]
Multi-species swards		This will depend upon the seed mixture used, but those with legumes (e.g., clovers) will reduce nitrogen fertiliser demand more significantly. Taking Teagasc's 2022 study[77] and the SmartGrass Project[78] as reference points, multi-species swards with integrated legumes achieve reductions in nitrogen fertiliser demand of 45-100% when compared to conventional perennial ryegrass systems, with no impact on forage yield.		Applicable to all permanent grasslands in the UK as well as leys used in rotations, although the species that can be used will vary according to site-specific factors (e.g., soil pH, temperature, rainfall).

A 2.2 Wider Environmental Impact

Table 7 Wider Environmental Benefits and Potential Unintended Consequences of Fertiliser Solutions

Solution	Wider Environmental Benefits	Potential Unintended Consequences
Precision fertiliser technology	Limited from the research undertaken.	**Embodied GHGs:** The sourcing and manufacture of high-tech equipment may have a high carbon footprint.
Controlled release fertilisers (CRF)	Limited from the research undertaken.	**Soil acidity:** Some coatings can increase soil acidity in large quantities, such as CRFs coated in sulphur. **Degradation/plastic pollution**: Synthetic polymer coated CRFs may be difficult to degrade. **Delayed release** (tailing effect): Because they release nutrients gradually, this may continue to happen after harvesting, resulting in unnecessary potential leaching and ammonia production. This typically happens after 85% of the nutrients have been released and absorbed.
GM Nitrogen fixing arable crops	Limited from the research undertaken.	**Cross breeding:** Genes from these crops could spread to wild relatives, leading to the creation of hybrid plants with unintended consequences for the natural ecosystem.[79]
Cover crops: legumes in crop rotations	**Improves soil health:** By reducing soil erosion and runoff, and by smothering weeds. **Improves biodiversity**: By attracting pollinators and other insects to farms. **Increases carbon sequestration:** The additional vegetation sequesters CO2, with the sequestration rate for general cover crops estimated at 0.32 Mg of carbon per ha per year.[80] **Animal feed by-product**: Grain legumes can be harvested and used as animal feed, decreasing demand for other forms of feed, thereby reducing the environmental impact of their growth. However, this would reduce the nitrogen content left in the soil for the subsequent crop.	**Increase pesticides**: Some evidence points to higher slug populations, which damage crops and requires an increase in slug pellets.[81] **May increase crop disease:** Some evidence points to cover crops increasing the likelihood of disease in subsequent cash crops. This would require more land to grow the same quantity of crop.[82]

Solid compost	**Soil benefits:** Increases to soil microbial biomass, lower pH levels, more organic matter, reduced topsoil bulk densities (theoretically improved infiltration rates), improves soil stability, pathogen suppression and increased earthworm populations.[83, 84, 85]	**Nutrient leaching and air pollution during production**: Without oversight, unregulated composting sites can result in air and water pollution. Ammonia, nitrous oxide, and methane represent the main gases that need to be controlled.[86]
Solution	**Wider Environmental Benefits**	**Potential Unintended Consequences**
Liquid compost/ compost tea	**Improves soil microbiology** (fungal, bacterial, yeast): Theoretically, the brewing process should amplify the microorganisms in the compost, though evidence on this is inconclusive. **Disease prevention:** Significant reduction of seed-borne pathogens, as they are replaced by the compost microorganisms.[87]	**Water use:** Amounts of water used to clean the sprayer, and make and dilute the brew, may be unsustainable, depending on the size of the farm, frequency of use and availability of water sources locally.[88]
Manure	**Soil benefits:** Increases to soil microbial biomass, lower pH levels, more organic matter, reduced topsoil bulk densities (theoretically improved infiltration rates), improves soil stability, and increased earthworm populations.[84]	**Nutrient leaching**: Over applying manure can lead to leaching of nutrients. The fact that over 40% of farmers applying it do not use a calibrator when applying (Defra, 2021) means this could be a serious issue.[89] Lory et al (2015) also state that aspects of manure application mean that over application of manure is more common than over application of fertilisers.[90] **Air pollution:** Defra's (2023) survey found that 75% of livestock farmers store manure in fields or in heaps on solid bases.[89] In addition, 14% of farmers store slurry in lagoons without strainers. These examples of storage are aa significant issue for the release of ammonia to the atmosphere.[91]
Seaweed[92, 93, 94]	**Reduces pesticide inputs**: By containing anti-fungal and anti-nematodal compounds. **Bioremediation of polluted soils:** By removing pollutants such as DDT and heavy metals from contaminated land. **Improves soil health:** By improving soil structure and amending soil pH. **Increases carbon sequestration (seaweed biochar):** By transforming seaweed biomass into stable carbon that is then mixed into and stored within the soil. **Osmoprotection:** By producing osmoprotective compounds that reduce abiotic stress (e.g., salination and drought), which may increase resilience to climate change.	**Soil acidification:** Sulphur compounds in some seaweeds can lead to microbial oxidation of sulphur to sulphates, leading to soil acidification. **Soil salination:** Through long-term or excessive application, particularly where seaweed is directly applied to soil.[92] **Heavy metal contamination:** Can occur if the seaweed has accumulated heavy metals during cultivation. Contamination levels should be checked prior to application.[95] **Unknown consequences of seaweed cultivation:** There is a high level of uncertainty about possible environmental impacts (e.g., algal disease, entanglement of mega-fauna, alteration of hydrodynamic regimes) of large-scale cultivation of macroalgae, though current small-scale cultivation in Europe is seen as "low risk".[96]

Solution	Wider Environmental Benefits	Potential Unintended Consequences
Shellfish by-product for wastewater nutrient recovery	**Improves soil health**: Contains important alkaline and transition metals essential for soil health. Also, chitin shell increases organic matter content, buffers against soil acidification, and provides antibacterial properties. **Waste reduction:** Makes use of an otherwise waste material otherwise destined for landfill or incineration. **Reduced energy costs and emissions at wastewater plant:** May reduce wastewater treatment costs and energy expenditure, as traditional filtration systems will have less nutrients/contaminants to remove.[97]	**Potential for accumulation of co-absorbed contaminants:** It needs to be ensured that these are not present in sufficiently high quantities for use as fertiliser.
Fish waste (fishery and aquaculture by products)	**Improved soil health:** Microorganisms feed off fish protein and organic matter. Also benefits for soil pH, improving soil compaction, as well as earthworm populations.[98]	**Reduction fishing**: Whilst some fish waste is produced from parts not used for human consumption, 'reduction fishing' also occurs, where inedible fish species like Atlantic Menhaden are fished for their use in fertiliser production. In 30 years, populations of Menhaden have dropped by 90%.[99]
Rotational grazing	**Improved soil health**: Improved organic material quantity due to trampling and as well as soil stability due to larger roots. Both also increase water holding capacity and drainage (reduced leaching). Larger roots also provide more sugars for microorganisms.[100] **Biodiversity:** Allows for more mature and diverse pastures, providing improved habitat for pollinators, birds and voles.[100] **Livestock pollution control:** Increased fencing allows for improved control over livestock movement and thus their manure entering water bodies.[101] **Parasite management:** Grazing tall grass reduces the risk of ingesting larvae, and the rest periods help to break the parasite cycle.[101]	**Increased stocking potential**: The potential to stock more livestock on the same size of land could feasibly increase enteric fermentation and associated GHG emissions overall.

Solution	Wider Environmental Benefits	Potential Unintended Consequences
Anaerobic digestate (AD)	**Renewable energy by-product**: AD plants produce biogas along with digestate. Biogas is a renewable energy source that can displace fossil fuels by being injected into the gas grid or, more commonly, generating electricity. The UK Government is supportive of this as a form of low-carbon energy in its pursuit of Net Zero.	**Does not reduce on-farm GHGs:** As loose nitrogen in the soil is emitted as nitrous oxide. **Does not reduce nutrient leaching**: As there can still be nutrient excess that leaks into groundwater and surface waters. **Does not reduce air pollution**: As there is still volatilisation to ammonia. **Microplastics pollution:** Depending on the feedstock, there can be high concentrations of microplastics in digestate fertiliser. When this is applied to land, it can bioaccumulate in crops, animals, and then humans, or can leach and contaminate surface waters and groundwater. This is an area of increasing research and public scrutiny. **Increases demand for biomass/land:** Biomass/land already has competing demands. If energy crops are used in AD plants, an increased demand for digestate fertiliser would further increase the demand on this finite resource, potentially driving land conversion and global negative impact on climate and nature. **Does not incentivise food waste prevention**: If food waste is used in AD plants, an increased demand for digestate fertiliser provides an outlet for food waste and therefore does not incentive food waste prevention/reduction which should be a priority.

Human urine as fertiliser	**GHG reduction in wastewater treatment:** Reduces GHG emissions at wastewater treatment plants.	**May increase air pollution on-farm**: On-farm emissions of ammonia were higher for urine spreading than synthetic fertiliser, and on-farm GHG emissions were slightly higher.[102] **Salts and acidity:** Overuse could potentially result in an increase in soil acidity due to the presence of urea.
Adding biochar to soils	**Increases carbon sequestration:** Biochar has been widely tipped as a solution to climate change as it stores carbon in the soil. **Improves soil health:** By improving nutrient retention, reducing compaction, and increasing fungi, microbial and bacterial soil activity. **Decreases soil/crop contamination:** Biochar has been found to immobilise heavy metals in soils, preventing uptake into plants and leaching into groundwater, reducing contamination.[103]	**Increases demand for biomass/land:** Biomass/land already has competing demands. Increased demand for biochar would further increase the demand on this finite resource, potentially driving land conversion and global negative impact on climate and nature. **May increase pollution:** If poorly managed, biochar production can produce polycyclic aromatic hydrocarbon (PAH) pollutants which pollute soils, water, and air and is harmful to human health. However, in the EU there are limits put on PAH concentrations in fertilisers so if adhered to, this should not be a problem.[104]

Solution	Wider Environmental Benefits	Potential Unintended Consequences
Nitrification inhibitors	Limited evidence (beyond those from reducing nutrient leaching) from the research undertaken.	**Increases air pollution:** By increasing volatilisation to ammonia, particularly for synthetic nitrogen inhibitors. What's more, ammonia can go through deposition and oxidation to produce indirect nitrogen oxide emissions, increasing GHGs.[105] **Food safety concerns**: Nitrogen inhibitor residues have been found in crops and livestock, raising concerns over food safety, both for animals and humans. **Off-farm environment:** Nitrogen inhibitors have been found to transport off-farm and the environmental impact on ecosystems is not well-known. **Soil health concerns:** Nitrogen inhibitors prevent natural biological processes from occurring, and farmers may be concerned about an impact on soil biota.

Perennial crops	**Increases carbon sequestration:** No-till systems allow carbon to stay stored in the soil. **Improves soil health:** By reducing soil erosion, improving nutrient retention, and increasing fungi, microbial and bacterial soil activity. **Increased farm resilience:** To drought and flood events (climate change adaptation).	**May cause indirect land-use change:** Currently, yields of perennial grain tend to be lower than annual varieties (with the exception of PR23 rice), meaning more land will be required to yield the same harvest. **May increase crop disease**: By giving pathogens access to living tissue year-round.[106] **May increase on-farm GHGs:** Depending on site-specific factors, perennial grains may increase nitrous oxide emissions.[107] However, compared to the likely reduction in nitrogen fertiliser application, overall, on-farm GHGs would likely still decrease.
Multi-species swards	**Improves soil health:** By increasing water/nutrient retention, deepening root systems, and enhancing soil biodiversity. **Increased farm resilience**: To drought and flood events (climate change adaptation). **Improved animal health:** Animals benefit from a more nutritionally diverse diet.	**Winter grazing concerns**: Many species, particularly herbs, are not tolerant of grazing in wet conditions as growing points/crowns can become damaged. As such winter grazing is currently not recommended by Farm Advisory Service in Scotland.[108] This means grazing opportunity is lost over winter. **Livestock health:** First-hand experience suggests it will take time for farmers to work out optimum mixes for persistence and animal health.[109]

A 2.3 Development Stage and Barriers to Uptake

Table 8 Development Stage and Key Barriers of Fertiliser Solutions

Solution	Development stage	Key barriers to uptake
Precision fertiliser technology	**TRL9**	**High capital cost:** High-tech precision fertiliser equipment is too expensive for many farmers. **Complex technology:** Precision fertiliser relies on technology, such as harnessing data from computers, remote sensors, and satellite guidance and positioning systems. This can be complex, and many farmers may not be technology-literate or supportive. **Farmer training and support:** To interpret and utilise precision fertiliser technology. **Difficulty of monitoring:** Farmers would need to monitor soil data long-term to optimise fertiliser application. This costs time and money.
Controlled release fertilisers (CRF)	**TRL 9/7** While established, improvements continue, and new coating technology including nanoparticles is assessed as TRL 7	**Cost:** Cost for farmers of CRF is higher than conventional fertilisers.[110] However, a cost benefit analysis by Lyu et al (2021) amongst Chinese rice farmers found that overall, due to improved performance of the crop, there was an economic benefit of switching to CRF of 5.21-11.44%.[111]
GM Nitrogen fixing arable crops	**TRL4**	Not market ready.[112] **Research barriers:** For reciprocating bacterial relationships - the challenge of plants dealing with non-cooperative mutant bacteria; the intense energy requirements for plants if they had genes to fixate themselves; how to ensure nitrogen fixing bacteria don't shut down with additional nitrogen. **Future barriers:** Once market ready, a foreseeable barrier is that in the first years of use in a field, yields of nitrogen fixing cereals may be lower than for non GM cereals utilising fertiliser. Even if functional, each crop would require new legislation authorising its use following risk assessment and public consultation.

Solution	Development stage	Key barriers to uptake
Cover crops: legumes in crop rotations	**TRL9**	**Farmer training and support**: Farmers will need guidance and support to change existing practices. **Increases labour costs**: To plant, treat, and monitor cover crops. **Seed costs:** Cover crops cost upfront money and the payback is over many years. The exception is leguminous cover crops which can be harvested and sold as feed. **Increases pests**: Meaning farmers may have to pay more for pesticides (e.g., slug pellets). **May increase crop disease**: Although most research does not support this, there are examples of disease in subsequent cash crops (particularly the presence *of Aphanomyces euteiches* in soils), and farmers are likely to be worried about this.
Solid compost	**TRL 9**	**Variable nutrient availability:** Organic matter in the soil must be mineralised. This depends on a variety of environmental factors including temperature, moisture, soil chemistry and microbial communities. This can make the timing and quantity of application difficult, and a barrier to farmers.[113] **Availability and expense of input material:** Current market prices of green compost are approximately 50% higher for phosphate than synthetic fertiliser, and 4 times higher for potassium. Even more significant for green/food waste compost, but nitrogen is cheaper.[114] Availability is dependent on competing demands for other uses of such waste (i.e., energy production). **Regulatory barriers to production on-farm:** In order to compost volumes of waste to spread on soil, a T23 waste exemption is required. There are limits on the amount that can be stored on-farm. If farmers want to incorporate animal waste into their compost, they must get the site approved by an Animal and Plant Health Agency (APHA) inspector. **Resource barriers to production on-farm**: Infrastructure and technology required (e.g., pile cover, shredding machine) is expensive. It also requires a lot of time to produce the compost. All these issues are cited by Viane et al (2016) as barriers to farmers composting on site.[115]

Solution	Development stage	Key barriers to uptake
Liquid compost/ compost tea	**TRL 8**	**Inconsistency of effects:** Benefits are reliant upon the quality of the compost used to make the tea. The effectiveness of this solution is therefore very unpredictable because no two batches are exactly the same, even if farmers use compost from the same pile. **Supply chain challenges:** Once it is brewed, the compost tea must be used immediately. Compost teas cannot be stored for later use because when the available oxygen is used up, the tea becomes anaerobic and the microorganisms it contains die. **Water use:** Further research is required into the sustainability of water use; in a future environment of increased drought stress, this may be a significant challenge for farms lacking their own water sources. **Upfront capital investment:** The cost of investing in equipment e.g., new sprayers. **Ongoing costs**: A demonstrable increase in yield is necessary to justify the additional cost per hectare.

Manure	**TRL 9**	Market-ready and widely used. **Regulation**: There are rules for water quality that limit application, and manure is not allowed in proposed protected landscapes. From 2025, low emission slurry spreading (LESS) equipment will be compulsory for farms stocked with above 100 kg organic nitrogen/ha (currently at 150kg nitrogen/ha). A total ban on manure spreading is proposed as part of Natural England's Protected Landscapes. **Cost:** Manure management is only going to be profitable compared to other fertiliser forms on farms with a manure source with a relatively high nutrient concentration, and where it can be applied relatively near to the operation.[116] In Johnson's (2022) survey, the cost of transportation was the most commonly cited barrier to uptake amongst US farmers.[117] Additional concerns from a US farmer survey included: odour, timeliness of nutrient availability and field readiness, and access to labour for application.
Seaweed	**TRL 9**	**Economic barriers to cultivation of seaweed**: large start-up investment costs, lack of access to finance, uncertainty regarding markets for the species that can currently be cultivated, and the mechanisation of harvesting needed to scale up cultivation so that it is economically viable. **Supply chain challenges:** Ensuring that seaweed biomass does not ferment and degrade in storage/transport (except in the case of seaweed compost). **Environmental barriers to cultivation of seaweed**: Unknown environmental impacts associated with the cultivation of seaweed at scale. **Production of extract**: Extraction and refinement of seaweed-based biostimulant without loss of its biostimulant potential is complex and therefore not yet optimised.

Solution	Development stage	Key barriers to uptake
Shellfish by-product for wastewater nutrient recovery	**TRL 7**	**Regulatory acceptance:** According to EU Fertilising Product Regulations, crab carapace can qualify, but further testing would be required for it to be allowed due to possible toxic contamination.[118] **Seasonality of use:** Seasonality of agricultural use may not coincide with the production cycle of the crab carapace matter. However, if the crab carapace matter is mixed with other organic fertilisers, it can be stored and this will not be an issue.[118]

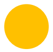
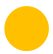
Fish waste (fishery and aquaculture by products)	**TRL 7/9** **TRL 7: Fish effluence from fish farms** **TRL 9: Fish fertilisers from fish waste**	The market appears to be mainly for horticulture, with limited references for crop application. **Cost:** High cost for farmers currently.[119]
Rotational grazing	**TRL 9**	**Cost:** Requires additional fencing (preferably portable electric), water systems, and mobile shelters. May also require additional labour depending on size of farm and type of rotational grazing practiced. **Specialist knowledge:** Requires careful planning and management to ensure movement of livestock at right times, as well as good understanding of pasture ecology and animal behaviour. **Stock qualities:** Modern breeds are not as well suited as traditional breeds for mob grazing.[120]
Anaerobic digestate	**TRL 9**	**Regulation:** In the UK, any AD plants not fed by farm waste must meet PAS110 standard to no longer be considered waste and be sold as 'bio-fertiliser'. **Decreasing financial support:** UK Government incentives (Renewable Heat Incentive and Feed-In Tariffs) are being pulled back and installation of AD plants is reducing.[121] **High capital costs:** For machinery and infrastructure/logistics. **Technical expertise** To operate AD plants. **Uncertainty:** Over fertiliser quality: as nutrient content of digestate varies widely.
Human urine as fertiliser	**TRL 7**	**Public willingness:** To consume urine-fertilised food. In one survey, only 59% of people stated a willingness to eat urine-fertilised food.[122] **Public willingness:** To use toilet infrastructure. The NoMix (urine diverting) toilet was discontinued commercially in 2020 when people complained about using them (e.g., required regular cleaning).[123] [124] There can also be odour problems if stored before transport.[125] **Challenges with infrastructure**: If piped, acetic acid required to prevent corrosion. It would also require extensive new piping. Urine recycling technologies are not yet mature and aren't commercially available.[125] **Legal framework:** Whilst not prohibited for use on crops, there is a need to update regulations that accepts the use human waste derived fertiliser.[126]
Solution	**Development stage**	**Key barriers to uptake**
Adding biochar to soils	**TRL 5**	**High capital cost:** Biochar is currently very expensive and not commercially competitive. **May decrease yields in the short-term**: Potential for lower yields than purely synthetic fertiliser in the short-term.[127] **Uncertainty of efficacy:** There are few long-term trials which have tested long-term efficacy of biochar-based fertilisers.

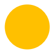
Nitrification inhibitors	**TRL 9** *(synthetic)* **TRL 6** *(biological)*	**Already adopted quite widely**: Particularly in the US, where 24% of nitrogen fertiliser sold in 2017 had been pre-treated to improve efficacy (which includes nitrogen inhibitors). **Marginal economic gains:** In most cases, nitrogen inhibitors economic gains are marginal, particularly when compared to the typical fluctuations of fertiliser prices.[128] **Lack of understanding within industry:** Over the roles and practical application of nitrogen inhibitors due to a lack of guidance and outreach.[128] **Lack of research**: For biological nitrogen inhibitors, this is a novel research area and there is a lack of knowledge/understanding of their role, and which plants are optimal.
Perennial crops	**TRL 4**	**Low yields**: Currently, no perennial grain variety is commercially viable for UK production. However, if technological progress continues at the current rate, there will be likely be perennial grains with commercially viable yields in ~20 years, and the reduction in labour and input costs for growers could be huge.
Multi-species swards	**TRL 9**	**Radical change to standard farming practices**: The current method of perennial ryegrass with intense nitrogen fertiliser application has been used for 60 years and is well-established in the UK and beyond as the de-facto method of pasture farming. It produces high yields of good quality feed, is persistent, allows winter grazing, and recovers quickly following grazing.[129] **Multi-year solution:** First-hand experience shows that it takes time for farmers to work out the optimum species mix for their farm. There will likely be issues with persistence and livestock health in the first few years.[130] **Seed costs:** TOMS research found that on average multi-species mixes were from 9-12% more expensive than comparable binary grass/clover mixes.[131] **Difficulty of monitoring**: It will likely take farmers a few years of monitoring to work out the optimum species mix for their farm.[131]

A 2.4 Strength of Evidence

Table 9 Strength of Evidence associated with Fertiliser Solutions

Solution	Strength of evidence for whether the solution works/has unintended consequences	Explanation	Evidence Gaps
Precision fertiliser technology		Lots of research, both in the UK and overseas.	This will vary measure-to-measure and in general, there are few evidence gaps. One notable exception is that after 30 years since GPS-aided machines were introduced, there is actually very little evidence from properly controlled experiments that the mechanised management of in-field spatial variation can really improve nitrogen use efficiency.
Controlled release fertilisers (CRF)		Considerable body of research, particularly from Asia.	Lack of correlation between data obtained from lab studies and the actual nutrient release rate in practical applications.[132] A developing field as capsule technology is changing. Comparison data with standard fertiliser application could be unfair - it is not always compared with best fertiliser management practices when reporting their advantages.[132]
GM nitrogen fixing arable crops		Lots of research conducted globally over the last 40 years.	Various evidence gaps related to technicalities of research, and results will differ on the type of GM fixing that is being aimed at (e.g., how to minimise/overcome high energy costs for the plant).
Cover crops: legumes in crop rotations		Lots of research, both in the UK and overseas.	More research is needed on the potential of enhanced disease pressure on subsequent cash crops. For example, there's an indication that vetch may lead to higher levels of Aphanomyces euteiches in soils.[82] There is a lack of consensus on the effect on follow-on cash crop yields,[133] so more research on the factors affecting this is needed.

Solution	Amount of evidence for whether the solution works/has unintended consequences	Explanation	Evidence Gaps
Solid compost		Good empirical data on yield returns and wider soil and microbial benefits.[134, 135] Relatively scarce but good data on potential fertiliser reduction, although it depends on the type and quality of compost used.	Variation in empirical data accounted for by variation in compost quality. Data on availability of green and food waste in the UK context is required.
Liquid compost/ compost tea		Limited empirical evidence. A few academic papers report variation in effectiveness, with one example of long term farm trials in the UK showing a slight but not statistically significant increase in yield.	Lack of statistically significant evidence showing yield increase. Lack of evidence on the impact of crop type and quality of compost on yields/other benefits.
Manure		Extensive amount of evidence on benefits to yield and long term soil and microbial benefits, as well as evidence for potential fertiliser reduction.	Reported significant variation in potential fertiliser reduction. Manure quality is an important reason for variation.
Seaweed		A lot of evidence that the solution works, particularly as a biostimulant, but still some significant research gaps.	Lack of field trials of seaweed fertiliser in the UK. Lack of evidence on: • Extent to which seaweed-derived biofertilisers can entirely replace synthetic fertiliser for different crops in different seasons and locations.[136] • Possible impacts of long-term application to the soil on soil salinity and microbial communities. • Precise mode of action of seaweed extracts. • Cultivation of seaweed - the environmental impacts of cultivation of seaweed at a large scale.

Solution	Amount of evidence for whether the solution works/has unintended consequences	Explanation	Evidence Gaps
Shellfish by-product for wastewater nutrient recovery		Evidence is fairly limited, with one directly relevant academic paper found.	Lack of evidence on: • The amount of phosphate that can be recovered per wastewater plant (large ranges given in Pap et al (2023).[137] • The amount of crab carapace that will be procurable.
Fish waste (fishery and aquaculture by products)		Studies for application effects on cereals, ley and potatoes are scarce. Research is much more common for horticultural and ornamental plants.[138]	Lack of evidence on: • Precise quantification of scalability for UK context. Lack of data for fertiliser reduction, although some data on yield comparisons between fertiliser and fish sileage for crop plants.[139]
Rotational grazing		Extensive amount of research both within the UK and abroad into environmental benefits, but there is a lack of empirical data on specific fertiliser reduction potential.	Two papers report increased nitrogen soil levels for rotational vs continuous, and two report no difference.[140] No conclusive evidence over soil carbon, forage biomass and plant species composition. Effects on root system, biodiversity and grazing season length is anecdotal, not empirical.[140]
Anaerobic digestate		There has been lots of research since the 1970s.	Lots of evidence that digestate works as a bio-fertiliser, e.g., Defra/WRAP's 2010-2015 'Digestate and compost in agriculture (DC-Agri)' project which collated field experiments across the UK to provide a robust evidence base to support the confident use of digestate and composts as renewable fertilisers by farmers and growers.[141] There is significant academic literature supporting digestate's use as a fertiliser.

Solution	Amount of evidence for whether the solution works/has unintended consequences	Explanation	Evidence Gaps
Human urine as fertiliser	●	A significant amount of relevant literature, with one particularly robust lifecycle analysis,[142] as well as a paper concerning consumer acceptance.[143]	More research is required into how long and how costly to put in place the infrastructure, as well as the optimal scale of decentralisation.
Adding biochar to soils	●	Lots of academic research over the last 15 years on biochar application to soils, primarily focused on carbon storage but increasingly on soil fertility and nutrient efficiency.	Evidence gaps on the long-term impacts of biochar on crop yields.
Nitrification inhibitors	●	Synthetic nitrogen inhibitors (amber): Established market for nitrogen inhibitors and lots of research in the UK and overseas. Biological nitrogen inhibitors (red): Novel research area with many uncertainties and evidence gaps.	For both synthetic and biological nitrogen inhibitors, more research is needed on their effectiveness under different farming practices and environmental conditions, such as the crop being grown, type of fertiliser being applied, timing and rate of fertiliser application, soil type, soil temperature, soil pH, soil organic matter and clay content, and rainfall. For synthetic nitrogen inhibitors, more research is needed on the wider environmental impacts of synthetic nitrogen inhibitors, i.e., if they pollutants in and of themselves, and if they bio-accumulate. For biological nitrogen inhibitors more research is needed to realise their potential. In particular, questions such as 'which plants are most effective?', and 'is this mediated by soil type?' remain unanswered.[144]
Perennial crops	●	There is significant academic interest in perennial grains, and there have been many trials for IWG/Kernza, and there is ongoing plant breeding. However, there need to be higher yielding varieties for this to be a viable solution.	More research is needed on the impact of intercropping perennial grains with legumes, as some researchers are touting this as a way to improve yields and co-benefits (like reducing fertiliser demand). More research is needed on perennial grains' impact on nitrogen oxide emissions and crop disease.
Multi-species swards	●	A series of trials have been conducted in the UK over the past five years,[145, 146] providing on-farm practical evidence of feed yields and the challenges farmers face in implementing MSS.	Optimum species mixes will be different for each farm and animal. More research is required on which species are effective and persistent (although there is already some research and tools/support for farmers on this).

A 2.5 Applicability to the UK Context

Table 10 Applicability of Fertiliser Solutions to the UK Context

Solution	Applicable to the UK?	Is it being implemented / trialled in UK?	Level of UK Government Support	UK based organisations that are developing/ promoting/implementing this
Precision fertiliser technology	Yes	Yes Precision fertiliser measures are currently used on 22% and 6% of cropland and grassland in the UK, respectively.[147]	● ELMS states that the UK Government is "exploring how [it] can pay for using precision-farming approaches" for grassland, arable land, and permanent crops.[30] Payments are not confirmed yet, as they are currently being explored, but they are estimated to be £10 to £50 per ha, coming by Summer 2023. There is also a landing page on the Defra Farming Blog devoted to precision fertiliser.[148]	**Agri-tech companies** • John Deere (Agri-tech company that sells precision fertiliser equipment, e.g., their Harvest Lab range) • Amazone (agri-tech company that sells precision fertiliser equipment) • Yara (fertiliser company with precision fertiliser tools and services e.g. At farm app for farmers to monitor nitrogen across farms) • Nitrobar (agri-tech company that sells precision fertiliser equipment) • Kuhn (agri-tech company that sells fertiliser spreaders) **Research groups** • The Organic Research Centre (developed the Public Goods Tool with Defra) **Multi-stakeholder partnerships** • International Fertiliser Society (trade association for fertiliser industry)

Solution	Applicable to the UK?	Is it being implemented / trialled in UK?	Level of UK Government Support	UK based organisations that are developing/ promoting/implementing this
Controlled release fertilisers (CRF)	Yes	Yes Multiple UK based suppliers of CRF. It is also actively discussed and promoted on online farmer networks.	● No evidence of support found.	**Agri-tech companies** • Beanstalk CRF (Agritech company) • Yara UK (Agritech company) • ICL (Agritech company) • Green-tech (landscaping supplier) **NGOs** • Progressive Farming Trust (Shortlisted org) **Advisory Groups** • AHDB (Farming Advisory Service and advocacy group) • Farmer's Weekly (Farming news and advisory service)
GM Nitrogen fixing arable crops	Yes	No No evidence found but there may be research institutes or UK-based Universities conducting research. Other GM research is ongoing. For example, researchers at Cambridge are looking at GM of barley to improve symbiotic relations with fungi to allow for improved nutrient availability).	● The Government has voiced support for GM crops generally, stating in the wake of the departure from the EU that there would be increased "opportunities" for this.[149] Currently, regulations around the use of GM crops remain under debate.	**Research organisations** • Council for Science and Technology (not nitrogen fixing specific) • Gene Watch UK (not nitrogen fixing specific)

Solution	Applicable to the UK?	Is it being implemented / trialled in UK?	Level of UK Government Support	UK based organisations that are developing/ promoting/implementing this
Cover crops: legumes in crop rotations	Yes	Yes Cover crops (some with legumes) are used in arable rotations and organic farms.	Pre-ELMS, there was already support for establishing and maintaining legume and herb-rich swards (GS4) and establishing two-year sown legume fallow (AB15) on arable lands. ELMS includes incentives on arable land for: [30] • Establishing winter cover crops (SW6)': £129 per ha. • Establishing two-year sown legume fallow: £593 per ha. • Establishing and maintaining legume and herb-rich swards: £102 per ha. SFI arable and horticulture soils standard includes payments for: • Having green cover on at least 70% of the land in the standard over winter (with the 70% including 20% multi-species cover crops at the intermediate level)': £22-40 per ha.	**Organic and regenerative farmers** • Hodemedod's (online retailer that "works with British farmers to provide pulses and grains from fair and sustainable UK production, organic where possible.") **Research groups** • (Shortlisted org) Processors and Growers Research Association (research group interested in agronomic impacts of new technologies/practices) **NGOs** • (Shortlisted org) Size of Wales (climate NGO with the aim of reducing tropical deforestation)

Solution	Applicable to the UK?	Is it being implemented / trialled in UK?	Level of UK Government Support	UK based organisations that are developing/ promoting/implementing this
Solid compost	Yes	Yes Application of compost is a common farming practice in the UK, particularly on crops.	The Environment Agency in conjunction with WRAP produced the BSI PAS 100 certification for quality compost. Defra has partnered with knowledge platform Agricology, supporting composting.	**NGOs/multi-stakeholder partnerships** • WRAP • Agricology (Partners with orgs including Defra, WRAP, ZWS funded) **Government departments** • Environment Agency **Energy producers** • OLUS Energy (Green Waste procurers and recyclers) • Renewable Energy Association (merged former orgs promoting composting)
Liquid compost/ compost tea	Yes	Yes UK-based Innovative Farmers group have conducted multi-year trials on UK farms.		**NGOs** • Kent Wildlife Trust **Farmer-led research consortiums** • England Compost Teas Group (Innovative Farmers)

Manure	Yes	Yes 79% of farms apply manure at least in part.[150] (Defra, 2021)	2018 farming rules for water, place limits on application on certain areas of land with specific nutrient loads. From 2025, low emission slurry spreading (LESS) equipment will be compulsory for farms stocked above 100 kg nitrogen/ha (currently at 150 kg nitrogen/ha). Natural England's protected landscaped plans outlaw manure application. ELMs grants are available in the context of improved storage to limit pollution e.g. Slurry Infrastructure Grants under Countryside Stewardship.	**NGOs** • Soil Association • The Sustainable Food Trust • WRAP **Associations** • NFU **Equipment suppliers,** • FGS Agri (Spreading technology)

Solution	Applicable to the UK?	Is it being implemented / trialled in UK?	Level of UK Government Support	UK based organisations that are developing/ promoting/implementing this
Seaweed	Yes	Yes Use at a small-artisanal scale, to gain a reduction rather than a complete replacement of agrochemical inputs.	Government funding for SeaGrown, a project that aims to develop innovative mechanised systems for seaweed cultivation (though this is with the aim of using it to produce energy). Cefas (the Government's marine and freshwater science experts) have been carrying out a number of projects on wild and farmed macroalgae since 2003.[151] Seaweed is not explicitly mentioned in ELMS guidance, but the Sustainable Farming Incentive (SFI) nutrient management standard does reference "opportunities to maximise the use of natural sources of crop nutrients on land".	**NGOs, agri-tech companies, research organisations, small businesses** • WWF (seaweed to replace fertiliser on arable) **Research organisations:** • Scottish Association for Marine Science (seaweed cultivation) **Biotech firms** • Ficosterra (biostimulant extracts) • Farms: e.g., Claydon Estate (on-farm trials) **Small artisanal businesses** • Atlantic Mariculture (kelp biofertiliser) **Agri-tech companies** • For the Love of the Sea (on-farm trials and scaling production of seaweed-based biostimulant concentrate)
Shellfish by-product for wastewater nutrient recovery	Yes	Yes Scottish Association for Marine Science demonstrated efficacy at Scottish Water Wastewater Development Centre.	Partnering Scottish Association for Marine Science [SAMS] scheme is Scottish Water, which is a public company accountable to Scottish Parliament, as opposed to England and Wales where water companies are privately owned.	**Research organisations and partnerships** • Scottish Association for Marine Science [SAMS] • SAMS have a "consortium" of partners, incl. – Environmental Research Institute (ERI) – Scotland's Rural College (SRUC) – Scottish Agricultural College (SAC) – Scottish Water

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Fish waste (fishery and aquaculture by products)	Yes	Yes For example, Scottish Sea Farms Fish are trialling new technologies for the harvesting of fish excreta from aquaculture, for use on-farms	No evidence of support found	**Fish farm associations, Agritech (limited)** • Scottish Sea Farms (Company) **A variety of horticultural organisations and institutions, but not for agriculture** • One example of Agritech company found (based in Asia)
Rotational grazing	Yes	Yes Rotational grazing is practiced widely, particularly since the widespread availability of electric portable fencing. Mob grazing is becoming gradually more popular (widely practiced in US).	Included as part of the Sustainable Farming Incentive under ELMS.[30]	**Agricultural advisory boards/NGOs** • ADHB (Advisory board) • Farm Advisory Service (Advisory board) • Climate Change Focus Farm (NGO - advisory service) • Zero Carbon-farm

Anaerobic digestate	Yes	Yes NNFCC website has a 'biogas map' which contains all operational AD plants in the UK.[152] As of April 2021, there were 642 distributed fairly evenly across the UK.	The UK Government used to provide financial support for AD plant installations (Renewable Heat Incentive and Feed-In Tariffs), but they are pulling these back. Previous Government support for digestate is highlighted by the Defra- and WRAP-funded 2010-2015 project 'Digestate and compost in agriculture (DC-Agri)' project.[153] ELMS does not allow digestate to be used in its measures that focus on low nutrient input.[30] Digestate application is controlled in Nitrate Vulnerable Zones Biogas is strongly supported by the UK Government as an alternative to fossil fuels e.g., in its 2021 Net Zero Strategy.[154] Digestate itself is also mentioned in the Net Zero Strategy.	Implementation of AD plants and digestate is widespread across the UK (642 in operation as of April 2021). Originally, these were academic and Government-funded trials and tests, but now many private growers and producers use them. Examples of farms using AD plants (taken from RASE 2011) for digestate are[155]: • Hill Farm (Wales/Shropshire dairy farm) • Copys Green Farm (Norfolk dairy farm) • Caerfai Farm (Wales potato farm) • Lodge Farm (Wales mixed dairy/arable farm) • Liquor Farm (Scotland cattle farm)

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Human urine as fertiliser	Yes	Yes Vandenbergh UK are progressing with lab trials currently, as well as using site specific urine gathering with a view to upscale.	No evidence of support found.	**Research organisations and partnerships** • Vandenbergh • Permaculture Research Institute
Adding biochar to soils	Yes	Yes There are a few trials of biochar and biochar-based fertilisers. For example, a trial on 6 ha of farmland in Lancashire started in October 2022.[156]	No mention of biochar in ELMS, the Agricultural Transition Plan 2021 to 2024, or on Defra's farming blog. Government funding has been awarded through alternative streams to biochar research and trials, e.g., DESNZ's Direct Air Capture and Greenhouse Gas Removal Programme from 2020-present awarded >£10m funding to 4 different biochar projects across the country.[157]	**Carbon removal start-ups** • CapChar Ltd (carbon removal start-up) • Black Bull Biochar Ltd (a consortium that includes Arla Foods, CEH, BSW Timber, and R&S Biomass Equipment that has received DESNZ funding for 'The Biochar Network' project) • Ricardo UK Ltd (global engineering and environmental consultancy that has received DESNZ funding to test a new pyrolysis system) • AgriCaptureCO2 (EU Horizon 2020 project focused on regenerative agriculture - funding the Lancashire Council biochar trial) **Bioenergy companies** • Seven Wye Energy Agency (consortium led by Seven Wye and Pure Leapfrog that has received DESNZ funding for the 'Mersey Biochar' project) **Research groups** • Organic Research Centre (agri-food research group) • Biorenewables Development Centre (research group interested in biomass applications) **Local Authorities** • Lancashire County Council (local authority delivering biochar trial on 6 ha farmland)

Solution	Applicable to the UK?	Is it being implemented / trialled in UK?	Level of UK Government Support	UK based organisations that are developing/ promoting/implementing this
Nitrification inhibitors	Yes	Yes Nitrogen inhibitors are available in the UK (particularly DCD) and are used commercially, although not widely.	● Most Government support and interest is in urease inhibitors rather than nitrification inhibitors, but this shows a willingness to consider inhibitors as a method to reduce on-farm nitrogen emissions from fertilisers.	**Fertiliser retailers and farmers who purchase them** • ADM Agriculture (agri company that sells 'enhanced' nitrogen fertilisers which have nitrogen inhibitors, e.g., Alzon neo-nitrogen) • OMEX (agri company that sells nitrogen inhibitors additives that can be added to fertilisers to reduce nitrification, e.g., Didin). • Corteva and Agrovista (two agri companies that sell nitrogen inhibitor additives, e.g., N-Lock Max). • There are farmers purchasing and applying these products across the UK.
Perennial crops	Yes	Yes At a very small scale and potentially just one farm in Herefordshire.[158]	● Although perennial grains are not directly mentioned, they tick many of the boxes included in ELMS and organic certification (e.g. no soil disturbance, a permanent living root in the soil, and 100% ground cover).[30] It is worth noting that the US National Institute of Health has published research that supports perennial grains as a sustainable agriculture solution.[159]	Very few examples in the UK, seemingly only small-scale self-funded trials by regenerative farmers, such as Ben Taylor-Davies (regenerative farmer at Townsend Farm in Herefordshire who is doing a Kernza trial).[158]

Multi-species swards	Yes	Yes There are a series of multi-stakeholder trials in the UK and Ireland. [160, 161, 131]	Pre-ELMS, there was already support for establishing and maintaining legume and herb-rich swards (GS4).[30] ELMS includes incentives on grasslands for: - Establishing and managing a multi-species herbal ley (OP4): £115 per ha. - Establishing and maintaining legume and herb-rich swards (GS4): £382 per ha. - Establishing and maintaining legumes in an existing grass sward': £102 per ha.	• Farm Carbon Zero ('ARCZero') (7 farmers across Northern Ireland) Public sector organisations • Farm Advisory Service in Scotland (public sector organisation that provides support, tools and evidence for farmers) Research groups • AgriSearch (research institute in Northern Ireland), AFBI (research institute), ADAS (consultancy), James Drummond (farmer at Lemmington Hill Head farm in Northumberland), and Dale Orr (County Down Organic farmer in Northern Ireland) are all partners on the SUPER-G (2021) project. • Duchy College Rural Business School, Agritech Cornwall, and Rothamsted Research are all partners on TOMS project in Cornwall Seed retailers • Germinal (R&D and retailer of multi-species seed mixes that comply with ELMS)

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