High Value Biorenewables

UK GROWN:
HOW BIOTECHNOLOGY CAN UNLOCK HIGHER VALUE PRODUCTS FROM UK CROPS

A report by:

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Contents

Executive Summary

The High Value Biorenewables (HVB) Network commissioned this review in order to identify target crops, which in combination with industrial biotechnology, have the potential to deliver UK grown resources for higher value biorenewable markets. This review includes innovation from within and beyond the HVB Network, to provide inspiration for further innovation, development and collaboration in the UK to realise the full value of these crops.

The overall aim was to identify and review exemplar plants and fungi that are suited to UK climate conditions and present an opportunity, in combination with industrial biotechnology, to deliver higher value biorenewable products.

Data was gathered from scientific, industry, news, government, patent and market research sources to identify opportunities and challenges across supply chains for potentially high value crops. Twenty-six interviews were conducted with experts from the research, industry, and consultancy community, as well as related networks.

The review explores how industrial biotechnology (IB) can be applied across biorenewables supply chains to create value from UK grown crops in a number of ways.

- Breeding: The review provides examples where breeding efforts have, or could, lead to higher value products. In particular, the UK has strong expertise and supply chain infrastructure around specialist oilseed crops, and this is seen as a target area for further innovation and development. Examples are also provided for work on colourants and plant derived anticancer and antioxidant compounds.
- Crop, seed and soil treatments: The rapidly emerging 'biostimulants' market is still being defined and regulations are likely to be introduced within the next few years. The use of micro-organisms to support crop health and regenerate soils will become more established and widespread as the scientific evidence and understanding develops. This opens a multitude of opportunities related to biotechnology innovation.
- Extraction: Enzymes have been used to enhance extraction of target compounds, such as in fruit pressings, and antioxidant, and aroma compounds. Examples are provided for rosmarinic acid from sage, betalain from beetroots and carotenes from carrot residues. It does not seem that this area has gathered much attention in the UK to date and could warrant further investigation.
- Biotransformation: Biotechnology can be used to enhance the value of compounds extracted from crops. The review highlights work conducted on colourants, antioxidants and flavours, conjugated fatty acids and glucosinolates.

There is an opportunity for the UK to further develop high value markets for the residues and offcuts from existing crops, such as beetroots, carrots, potatoes, soft fruits, apples, brassicas and forestry.

As industry commits to net zero targets, along with reduced biodiversity and environmental impacts, they are looking towards research and innovation to develop new solutions that are naturally derived, biodegradable, but deliver high quality and performance. In addition, recent supply issues have highlighted the importance of localised sourcing.

Experts highlighted that the issue of land use should be considered when proposing UK grown biorenewable products. They also drew attention to how non-food crops can bring significant benefits to rotational farming by increasing diversity and supporting soil health, beneficial species such as pollinators and pest-predators, and helping manage pest and disease cycles and suppress weeds by providing a break between food crops. This review identifies a number of emerging and underutilised crops that could be expanded in the UK to this end. In addition, various crops have multiple uses and can be used for foods as well as extracted higher value products.

Experts also highlighted how fermentation and vertical farming provide alternative production methods to conventional growing of crops for higher value products, and that these different methods need to be assessed when selecting the best production approach. The full impacts, resource inputs and related supply chain land use must be accounted for when comparing the efficiencies of the different approaches. Field scale or basic greenhouse growing, as covered in this review, can be a more cost-effective and resource efficient approach, even where a bioreactor route has been developed, but may be of lower purity or consistency due to greater variation in the plant material. Currently there are several examples of markets, such as stevia compounds and squalene/squalane, where different specifications of products are produced using multiple methods, each serving different markets.

High value markets are seeing substantial growth in several areas where UK crops can deliver. The global crop biostimulants market is emerging and growing exceptionally fast, valued at $2.85 billion in 2021 and growing to $6.69 billion by 2029 with a CAGR over 11%. The natural dyes market is also seeing similar growth rates of over 10%. The plant derived health fatty acid markets, antioxidants, natural colourants, fragrances, and flavours all show continued strong growth, with global trends driving these markets.

Whilst recognising the strong biotechnology capability in the UK, some experts interviewed for this review felt that more investment and technical expertise in extraction and processing for high value products was needed to transform innovation into commercially viable enterprises. As with many sectors the transition from innovation to commercialisation is challenging, with a lack of connectivity between investors and start-ups. Furthermore, the co-ordination required between farmers supplying materials, the processors and the end users adds another layer of complexity to scaling up. The UK appears to be behind European and North American markets in terms of cross-supply chain collaboration and public-private investment to enable the full value realisation of UK crops. The exception is the strong model set by the supply chain of the oilseeds sector within the UK. This review highlights the examples of collaborative ventures that have been observed overseas. This is a critical time for biorenewables, with synergies between the agricultural transition and industry's recognition of its imperative role in greenhouse gas reduction.

Commercialisation of higher value products from UK crops is a vital piece of the puzzle to unlock development of multiple markets that can drive the broader biorenewables market. These products offer an opportunity to support the transition to Net Zero and towards regenerative, high diversity farming, thus supporting multiple governments objectives, so long as commercialisation is executed with sustainable systems principles: fair share, with social and ecological benefits derived from the economic returns.

1. Background

The High Value Biorenewables (HVB) Network commissioned this review in order to identify target crops, including plants and fungi, which in combination with industrial biotechnology (IB), have the potential to deliver UK-grown resources for higher value biorenewable markets. This includes:

- Functional food and feed ingredients
- Medicinal or Pharmaceutical and healthcare products related to bioactives or drug delivery
- High performance chemicals or materials

This mission to both source and transform raw materials within the UK is an opportunity to deliver against various UK government objectives, such as the Net Zero Strategy, Build Back Better, the Agricultural Transition Plan (ATP), UK biodiversity targets and public health priorities, as well as developing the UK Science Superpower through research and innovation.

This review includes innovation from within the HVB Network, but also covers examples of research and commercial activities that go beyond the current network in the UK, and includes international endeavours which apply to UK crops. The intention is to provide inspiration for further innovation, development and collaboration in the UK to realise the full value of these plants and fungi.

1.1 Aim and Scope

The overall aim was to identify and review exemplar plants and fungi that are suited to UK climate conditions and present an opportunity, in combination with industrial biotechnology, to deliver higher value biorenewable products.

The scope for this review is outdoor land-based and aquatic (marine or freshwater) plants and fungi. The focus covers species that can grow under UK conditions, ideally with low inputs and environmental impact, and with potential resilience to climate change in the UK. This includes already readily available crops where components or compounds of higher value can be extracted or derived, perhaps prior to broad biomass processing, for example as part of a biorefinery. The focus is on opportunities where there is potential to add value to these crops through the application of industrial biotechnology (IB). This may take the form of breeding, crop treatments, extraction or separation technologies, or conversion of compounds to higher value products.

As this project is focused on production that is suited to the UK environment, the scope excludes systems with highly controlled environments such as intensive indoor or vertical farming, and bioreactors. Algae and microbes are also excluded in this study as they are covered within other Networks in Industrial Biotechnology and Bioenergy (NIBBs). Animals and highly processed by-products or wastes are also not covered in this study, although any parts of the plant or fungi that can be recovered directly from the field or growing location (i.e., crop residues, or raw off-cuts or rejects) are in scope.

In summary, the opportunities explored needed to meet the following criteria:

- Land and aquatic plants and fungi that can grow without highly controlled conditions, (polytunnel or basic greenhouses were in scope). This includes field or on-farm crop residues that could be recovered or 'raw' offcuts, pressings and rejects from primary processing

AND

- Confers a specific property or component with the potential to be used to manufacture higher value products (over $10/kg), beyond use as a generic feedstock for fermentation

AND

- There is a role for industrial biotechnology (IB) to add to, or help extract, this value

The scope excluded the following:

- Algae or microbial species as the source of material
- Vertical farming or other highly controlled environment growing approaches
- Processed by-products or waste other than 'raw' offcuts, pressings and rejects

1.2 Approach

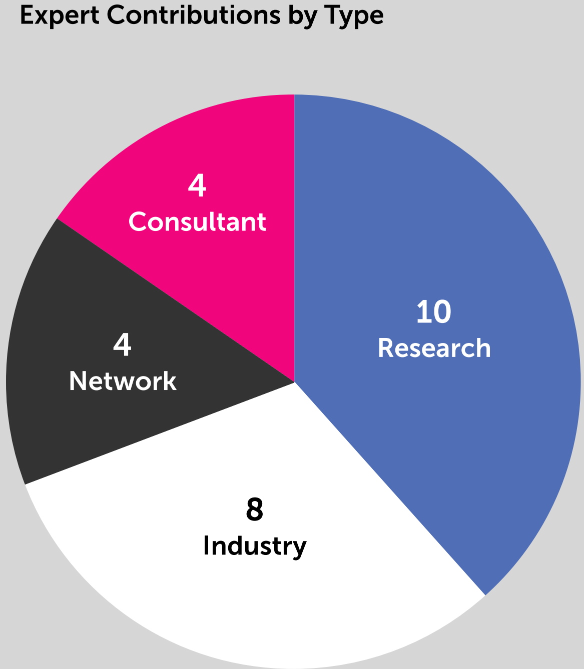
Secondary searches of publications were conducted, covering agricultural, food, medical, industrial, and research-orientated information sources.

Broad secondary searches included:

- Alternative Crops Technology Interaction Network (ACTIN) project findings
- Scientific publications
- Food and health industry news and publications
- Government reviews and strategy/policy reports
- Funded project reports (e.g. from Defra, Innovate UK, Cordis)
- Targeted patent searches
- Company websites
- Market research publications

Discussions were also held with twenty-six experts from seed companies, growers, and technology end-users, along with key bioeconomy, agriculture and biotechnology consultants and research institutes (Figure 1.1).

Figure 1.1. Expert contributions by type



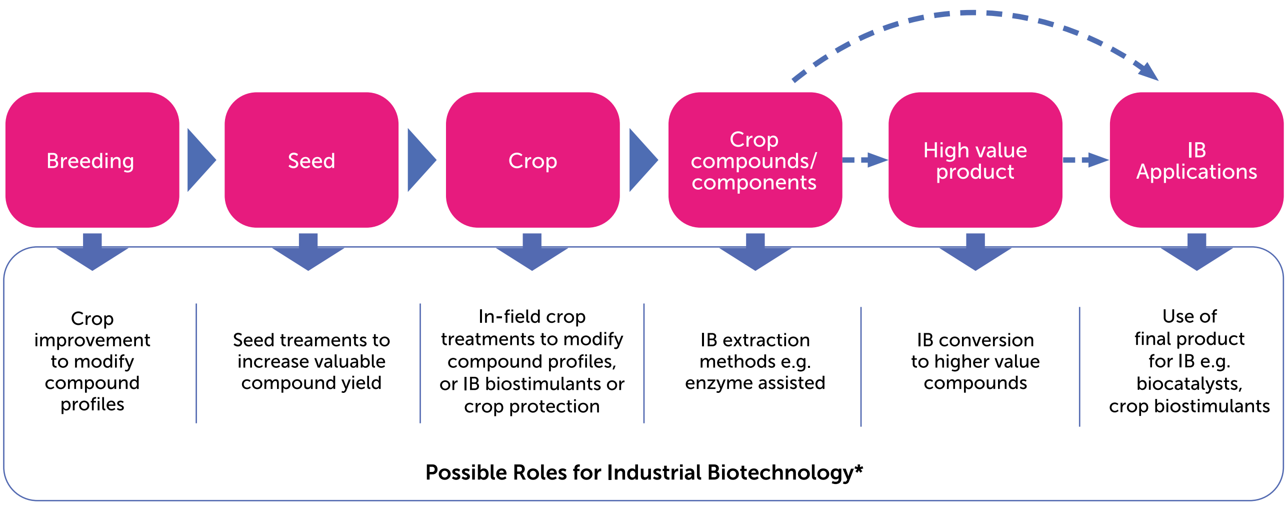
2. Key themes and considerations

This section outlines key themes that were highlighted by interviewees as relevant to growing crops in the UK for higher value biorenewables.

2.1 The role of industrial biotechnology in adding value

Industrial biotechnology (IB) can be applied across the supply chain to create value from UK-grown crops in a number of ways. Figure 2.1 outlines the key points where IB can contribute to improve the crop itself or processing stages. In addition, the final crop product could be an enzyme extract to be used for bioconversion.

Any crop trials and research projects must comply with relevant genetics, seed trade and other sector and research regulations, including the Access and Benefit Sharing Regulations relating to biological resources. Defra has published guidance in 2022 (DEFRA, 2022).



* As defined within scope of this study

Additional steps not always required

2.2 Commercial viability of conventional crop production of higher value products

Experts highlighted issues raised by growing UK crops versus direct microbial and enzymatic biosynthesis routes for production. Fermentation can be a highly efficient method to derive higher value target compounds that exist in nature in low concentrations, or where a highly consistent and pure extract is required. Microbial and enzymatic approaches can also be used to biotransform compounds from crops into higher value products, as seen in stevia sweeteners in Box 2.1 below. These approaches, when used for appropriate products, can require less land than growing crops. However, when assessing the true efficiency of fermentation, it is important to consider the resource implications of the whole system, for instance:

- Inherent carbon and resources embedded in the physical infrastructure.
- The energy, water and cleaning chemical requirements required to maintain a closed, indoor, disease-free system.
- Inputs such as nutrients, minerals, co-factors, and additives to support the system, and antibiotics to control microbial populations (Eurofins, 2011), including transportation of these inputs.
- The full land-use implications of all these inputs required from external sources, and avoidance of 'offshoring' the true footprint.
- Costs and resources for extraction and purification of target compounds.
- Ongoing maintenance and end-of-life footprint of buildings and equipment.
- The ability to scale up effectively and efficiently, where a larger volume of product is required.

In addition, there are still many plant compounds for which the biosynthetic pathways have not been elucidated, so these cannot yet be replicated via synthetic biology.

As shown in Box 2.1, there are several examples where target compounds are being produced via both methods – fermentation and crop production – to serve different markets. The fermented versions are often of a higher purity and specification to meet healthcare or pharmaceutical grade requirements. Whereas, the crop-derived products may be of a lower concentration or purity and can be produced more efficiently to serve markets such as food, household or nutraceutical ingredients.

Box 2.1. Examples of parallel fermentation and crop-derived production

Sweegen

HB Natural Ingredients

The global market for sweetener, stevia, reached a value of USD $590 million in 2020, with CAGR growth of over 8% during 2021-2026.

The stevia plant has been bred and cultivation practicies developed to enhance target compounds to maximise the natural extract yield. Steviol glycosides from stevia plants are extracted and can be further valorised through industrial biotechnology:

1. Through bioconversion using enzymes from GM-organisms to target steviol glycosides, such as rebaudioside D and rebaudioside M t achieve a desired profile for specific uses. This process is mimicking the natural maturation processes that would occur in the stevia plant
2. Through glucosylation by the addition of glucose units using enzymatic process.

These two routes, using naturally extracted steviolglycosides, sit alongside fermentation production from sugar feedstock, by the likes of Tate and Lyle, DSM, Cargill and Evolva.

Currently there is sufficient demand and market differentiation for ll these approaches to co-exist.

Sources: (Imarc Group, 2021), (HB Natural Ingredients, 2022)

Neossance® Squalane
Amyris

The global squalene market was estimated at USD $153.93 million in 2021 and is expected to reach USD $166.97 million in 2022, with projected growth at CAGR 9% to reach USD $253.24 millio by 2027.

Squalene is a triterpene traditionally extracted from sharks' livers and used as an emollient and moisturiser. 300 sharks ar required for 1 tonne of squalene, and in2021 2.7 million sharks were caught for this market.

Squalane, a hydrogenated version of squalene, is created from olives and other crops, including amaranthus. Refined olive oil is now the primary botanical source of squalane. In 2008, L'oreal and Unilever announced that they would remove shark squalene from their cosmetic brands in favour of renewable plant-based sources.

In 2014, Amyris started producing squalene from sugar using engineered microbes.

Nevertheless, it seems that yields achieved are not sufficient for global demand for industrial or food supplement purposes, and as of 2022 there remains simoe challenges.

There is another example where cop-produced and fermentation products currently sit alongside each other.

Sources: (MarketResearch, 2021), (Green Peace, 2019)

Vertical farming is another alternative option to field or basic greenhouse production and can enable the production of targeted compounds through a controlled environment and permit the successful growth of sensitive crops that might suffer from normal UK conditions, pests and diseases. Similar input costs and resource requirements to bioreactors should be considered when assessing the full impact of controlled farming approaches. To date, growing under highly controlled conditions is costly, requiring a high level of inputs, and is only viable for premium crops, for instance salads and herbs, or pharmaceutical products.

2.3 Growing for food and biorenewables: land-use efficiency

Industry and research experts highlighted the increasing pressure on UK land, and the balance required in future to improve both UK food security and biodiversity. This is a key argument for fermentation and vertical farming, although, as discussed above, the full land-use impact must be considered for all the inputs and resources required. There is considerable pressure on UK land, especially premium farmland, and there is ongoing debate over the balance of use for food, feed, and non-food crops. Land is already used in the UK for non-food crops, with 96,000 hectares of bioenergy crops, representing just over 1.6% of arable land, in 2019 (DEFRA, 2019).

As discussed in previous sections, there is significant opportunity to derive value from residues from food crops, both from in-field residues and from off-cuts and quality-based rejects from initial sorting or cutting processes. Both Zero Waste Scotland (Zero Waste Scotland, 2022) and WRAP (WRAP, 2022) have collated data on these kinds of materials.

In addition, there are certain crops that can be grown for dual use, such as hemp, whose oilseed can be used for food and stalk can be used for fibres.

Furthermore, non-food biorenewable crops can play an important role in the agricultural transition, with multiple benefits to enhance the farming system. The current lack of diversity of crops on many UK farms is leaving the industry exposed to risk of harvest failures and reduced biodiversity, as well as increased pest and disease incidence and persistent weeds such as blackgrass. Introducing greater variety of crops into a rotation, along with intercropping options, which can include non-food crops, can help reduce these risks, improve soil health, reduce the need for agrochemical inputs and, by enabling farmers to access diverse markets, boost their economic resilience. The relatively niche markets for some higher value products mean that sufficient volumes can be derived from relatively small acreage of land with little impact on food production, and diverse rotations can result in higher subsequent yields, such as wheat after hemp. In addition, intercropping may be an option for some higher value crops to be grown as beneficial crops alongside more traditional crops, or as catch and cover crops grown between main crops to protect and improve soil.

Lastly, some non-food crops, particularly certain natives species, are suited to growing on marginal land. It should be noted that marginal land may consist of valuable scrub and priority habitats such as wet woodland, and so should not be automatically dismissed as insignificant. However, growing some of these niche crops on the corners and poorer, less productive areas of arable land can be an excellent way for farmers to diversify, restore soil health, and support flood mitigation and other ecosystem services.

Overall, the balance for growing of non-food crops as part of a beneficially diverse system should be considered within the context of each farm and its regional priorities.

2.4 Materials from crops where the UK has established large-scale production

In contrast to growing non-food crops for biorenewables, as discussed in the previous section, there is an immediate source of materials from field residues, rejects or off-cuts for some UK food crops where there already exists large-scale cultivation, markets and processing activities.

Examples of this in the UK include fresh produce that does not meet buyer specifications is diverted into added-value streams to reduce waste. Box 2.2 highlights two examples of this activity underway in the UK.

These examples demonstrate the potential for extracting value from British crop rejects, as well as providing future sources for higher value extracts, such as colourants, aromas and bioactives.

Examples of UK crops where there are significant residues and 'raw' by-products or rejects with potential higher value properties are shown in Table 2.1. Some of these examples are explored further in later sections of this report.

B-hive

UK company with valorisation process to use low-grade potato and peelings to extract clean label high-quality protein.

In May 2021, it was announced that Branston Ltd would invest £6 million to build a commercial-scale factory based on B-hive's process.

HUNTAPAC

Leading British carrot packing company, Huntapac has installed a drying line to produce carrot powder from intake that does not meet the full specifications for fresh produce. The colour, thickening and flavour delivered by this powder opens a range of new markets, and extends the use of this valuable UK crop.

Table 2.1. Examples of significant residues with value from large-scale UK crops

Crop	Part	HIgh Value Relevance
Wheat	Bran	Vanillin
Potato	Leaves Fresh tuber offcuts/rejects	Solanesol Enzymes, glycoalkaloids
Apple	Pressed Pulp	Antioxidants, aroma
Carrots	Fresh produce rejects	Antioxidants, colourants
Brassica	Stalks, leaves	Glucosinolates
Sugar beet	Pulp	Arabinose, galacturonic acid
Onion	Outer skin	Quercetin antioxidant
Soft fruits	Fresh Produce Rejects Pulp	Antioxidants, colourants, flavours
Legumes	Pods	Dietary fibre
Pine trees	Forestry brash and offcuts	Vanillin
Forestry	Bark	Tannins

2.5 Opportunities where current supply is limited or becoming less acceptable

Continuing problems with restrictions on certain substances, such as forever chemicals, neonicotinoids and cosmetic ingredients, along with resistance to antibiotic and plant protection agrochemicals are all factors driving innovation for novel, naturally-derived solutions which are effective and comply with regulations and testing requirements, but are less harmful to people and the environment. Replacement of animal-derived compounds with plant-based sources is another trend. The examples of plant-derived squalane replacing shark's liver extract, meadowfoam oil replacing sperm whale fat, the growth in plant protein products and the emergence of vegan labelled products beyond the food sector are all demonstrations of this.

The rapidly changing landscape has reminded industry of the importance of ensuring security and quality of supply. In addition, changes in weather patterns and resource supplies, demands for improved biodiversity and net zero targets are driving industries to consider shorter, more local and more reliable supply chains, and move away from petrochemical-derived ingredients and long transportation chains, thus increasing the interest in locally sourced biorenewables. For instance, Unilever has effectively committed to sourcing over 100 ingredients from biorenewable biological sources by 2030 (Unilever, 2022).

2.6 Competing on a global market: focus where quality is key

Many higher value plant extracts are supplied from China and India. To compete in this area, UK farmers and processors will need to target customers who are demanding greater supply assurance, quality and traceability and/or a smaller environmental footprint who are willing to pay for the higher cost of UK production. To this end, this review has identified several markets where there is demand for these qualities:

- Colourants, flavours and fragrances.
- Antimicrobials, antioxidants, specialist fatty acids and other bioactives for health benefits.
- Dyes for textiles.

2.7 Success through co-operative models and public–private investment in processing

Industries in France, Denmark, the Netherlands and North America have obtained significant government support through investment to help develop value-added products from their crops.

Three factors seem to play an important part in the success of these:

- Farmer and/or industry-wide co-operatives.
- Significant, often public–private investment.
- Financial and policy support by government.

Table 2.2. Examples of co-operative models and investment globally

		Company	Model	Comment
	**Potato**	Avebe, the Netherlands	Co-operative with over 2,000 members	Starch manufacturer that has Invested €66 million in its innovation and sustainability programme in 2021, creating functional proteins, and other potato derived high value products.
	**Sugar beet**	Cosun Beet, the Netherlands	Co-operative	€3 million grant from the province of Groningen to build a new sustainable biorefinery. They process all parts of the sugar beet into natural ingredients for food, energy, biobased and related industries.
	**Curds and whey**	Arla, Denmark	Co-operative	The Arla Foods Ingredients division has invested €40 million to expand their whey protein capacity in 2013; in 2016 they invested €40 million in a whey protein hydrolysate plant; and have also opened a €120 million lactose processing manufacturing plant.
	**Hemp**	La Chanvriere, France	Co-operative	A hemp co-operative, which founded the FRD (Fibre Research Development) in 2007, an interface between the farmers and process industries. The group have made investments in innovation around production and packaging equipment.
	**Canadian peas**	Protein Industries Canada	Not for profit	Innovation SuperCluster with co-investment projects. Seeking capital investment for constructing processing facilities. It is expected that $2.4 million will be invested between Protein Industries Canada and the partners to support execution of this project. The majority, $1.8 million, will come from Protein Industries Canada, with the remainder coming from consortium partners.
	**Mostly sugar beet and wheat**	Bazancourt Biorefinery, France	Industrial symbiosis ecosystem	One of the largest biorefineries in the world, with over $1 billion investment, processing 4m tonnes of biomass each yearinto numerous products including active ingredients for cosmetics, fine and speciality chemicals and technical applications. More than 1,200 employees, and €800 million in annual turnover.

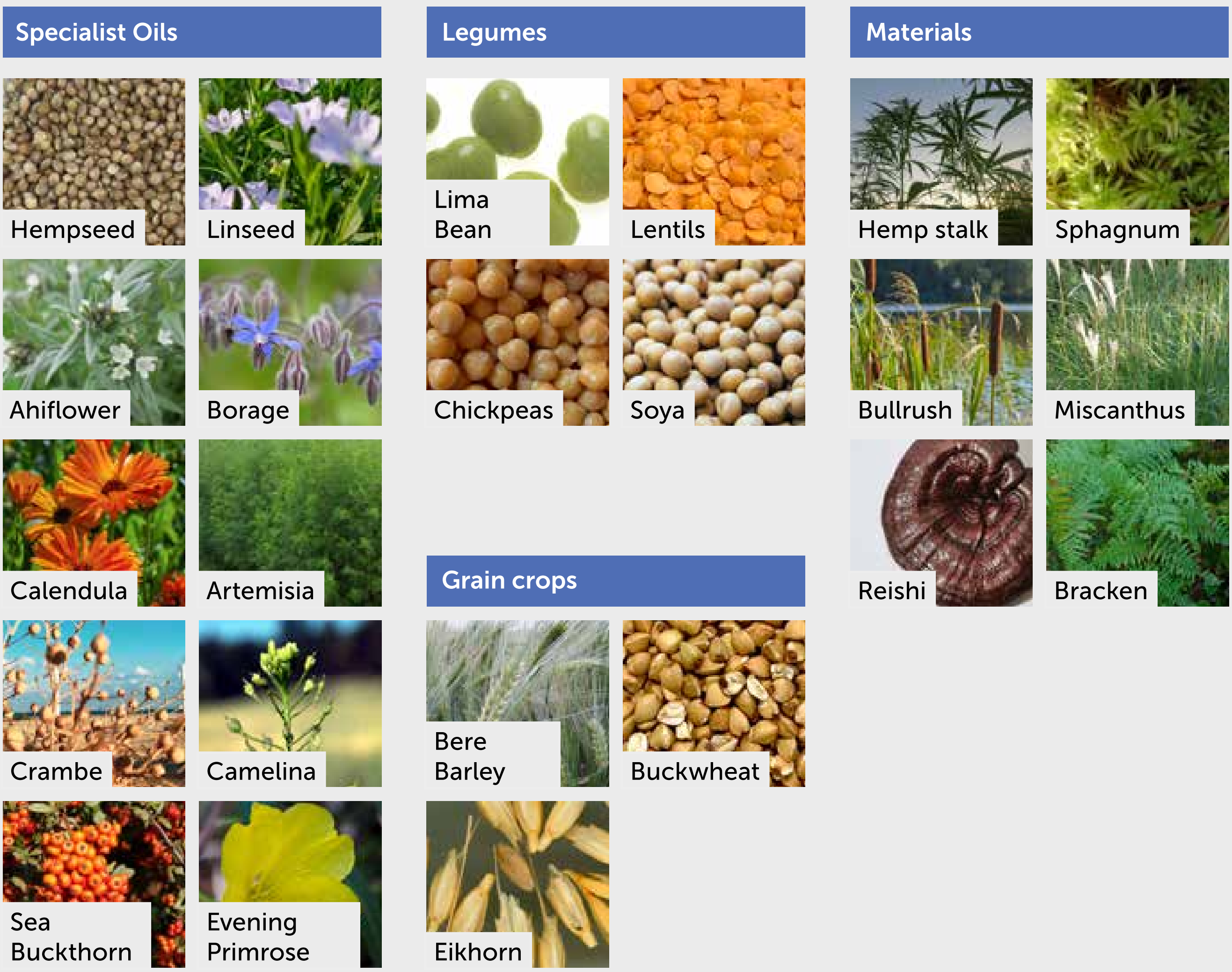
Two areas where supply chain co-ordination is emerging in the UK are specialist fatty acids and perennial energy biomass. Companies are contracting farmers to grow crops from their supply of seed or plant stocks, and then buying back the harvest to process and sell end-products. Examples of this model include the miscanthus company Terrevesta; and De Wit Speciality Oils which is headquartered in Holland and owns New Holland Extraction, the UK based oil extraction facility. They contract 100's of UK farmers to grow specialist oilseed crops, such as echium, blackcurrant, and borage

3. Emerging and underutilised UK crops

There is significant effort under way to develop more diverse crops suited to the UK climate. More cold-tolerant soy, chickpeas and lentils are being bred to replace imports. Development of old wheat varieties such einkorn would offer greater range of food crops with broader genetic diversity. NIAB has undertaken an extensive review of opportunities for diversifying UK agriculture and horticulture through investment in underutilised crops, for food, feed, forage, and pharmaceutical uses. The project will report towards the end of 2022.

In addition, there is growing use of cover and catch crops, which are used to protect and enhance the soil and manage nutrients between main crops. These often consist of brassicas such as mustard, radish or forage rape, legumes such as clovers, lucerne and vetch, and others like phacelia (a relative of borage) which grow quickly in the autumn. The potential for harvesting some of these crops for extraction of natural ingredients and compounds could be explored further.

Figure 3.1. Examples of emerging and underutilised UK crops



Beyond bulk food crops, there are opportunities for niche and specialist crops with higher value uses, some from native plants which have not yet been developed for cultivation. Table 3.1 gives some examples of these.

Table 3.1. Examples of native and wild plants and fungi with higher value compounds

Plant/Fungi	Target	Uses
Ahiflower	Seed oils	Omega-3 fatty acids, particularly stearidonic acid (highest content of any plant), and an excellent source of omega-6 gamma linolenic acid.
Alexanders	Petroselenic acid	Palm oil alternative due to melting point. Source of linoleic acid for bioconjugation for use in industry and food applications.
Artemisia	Artemisinin	Malaria (more suited for growing in other regions). Also investigated for anti-protozoal, anti-bacterial activities in livestock (Purdue University, 2009).
Bilberry and heather	Antioxidants	Catechin and epicatechin content. Derivatives implicated in anti-tumour, anti-colitis, insulin benefits. Suggestion that heather and bilberry are both potential candidate sources of polyphenolic precursors for production of high-value pharmaceutical compounds (Nottingham University, 2006).
Bird cherry tree	Fruit polyphenols	Native tree, enzyme extraction of polyphenols documented (Lemes, et al., 2022).
Bulrush	Pollen	Protein.
Daffodil	Galantamine	Galantamine is marketed by Janssen as Reminyl. It was originally isolated from several plants, including daffodil bulbs, but is now also synthesized, as an acetylcholinesterase inhibitor (Olin, et al., 2004).
Elder	Seed oil	Seed oil has carotenoids, gamma tocopherol and alpha linolenic acid (De Wit Specialist Oils, 2022).
Feverfew	Pyrethrins	AApproved by the European Medicines Agency for migraine headache (Holland and Barrett, 2022). A Cochrane review, published in 2015, found that feverfew was effective in preventing migraine in four out of six clinical trials (Cochrane Library, 2022). Pyrethrins are also known as insecticidal.
Hawthorn	Berry extract	Various studies for heart and cardiovascular conditions, with mixed results. A meta-analysis of randomised clinical trials found adjuvant treatment with standardized hawthorn extract is superior to adjuvant treatment with placebo in chronic heart failure (Pittler, 2005).
Hops	Various bioactives and tannins	Under exploration for potential medical uses such as weight control and treating depression, anxiety, stress, menopausal symptoms and insomnia, (Bolton, 2019). The beta acids have antimicrobial properties.
Horse chestnut	Seed	Natural surfactant properties.
Ivy	Leaf extract	Surfactant properties.
Lavender	Essential oil	Traditional UK crop for flavour and fragrance in food, home and personal care sectors. Oil contains monoterpeneoids and sesquiterpeneoids.
Lucerne	Whole plant	A catch and cover crop used to protect and enhance soil between main crops. Gaining attention in the search for natural antioxidants for use in animal feeds, human foods and nutraceutical formulations due to polyphenol content. Lucerne (11.29 ± 0.25 mg AAE/g DW) showed high values for hydroxyl (OH-) radical scavenging activity (Iqbal, et al., 2021).
Deadly nightshade	Atropine, scopolamine, and hyoscyamine	Contains atropine, scopolamine and hyoscyamine used as pharmaceutical anticholinergics. Donnatal is a prescription pharmaceutical that combines natural belladonna alkaloids in a specific, fixed ratio with phenobarbital to provide peripheral anticholinergic or antispasmodic action and mild sedation.

Plant/Fungi	Target	Uses
Sphagnum	Sphagnan	Johnson & Johnson patent for use as absorbent in nappies. Used as wound dressing and for antimicrobial properties (ADAS, UKCEH, 2020).
St John's Wort	Hypericin and hyperforin	Many active substances, including hypericin and hyperforin, which are thought to affect mood. 150 different compounds have been identified. Sold as treatment for mild anxiety and low mood (Holland and Barrett, 2022).
Oak Tree	Tannins from bark	Tannins used for brewing, dying, leather and other industries.
Turkey tail fungus	Polysaccharide Dye compounds	A protein-bound polysaccharide called PSK (Krestin) has been developed in Japan for cancer therapy (Kobayashi, et al., 1995). Can be used to dye fabrics various colours.
Valerian	Root	EU approved use for sleep disorders and anxiety.
Watercress	Isothiocyanates	Potential cancer prevention (Watercress Company, 2022). Urease inhibition to reduced nitrate emissions (Watercress Research, 2022).
Weld	Leaves and flower stalks	Natural yellow dye.
Willow	Salicinoids	Scientists from Rothamsted Research have demonstrated the anti-cancer activity in cell-lines of miyabeacin, a new cyclodimer from willow (Ward, et al., 2020) .
Woad	Leaves	Natural blue dye traditionally grown in UK. The UK market is estimated to be 40 million tonnes/year, which would require about 1,000-2,000 ha to supply (Yara, 2022).
Vetch, common	Whole plant	Becoming more widespread as a cover or catch crop, sown between main crops to protect and improve soil. Lack of phytochemical data, but a study has found nine known compounds, two flavones (2-3), one coumarin (4), and six oleanane triterpenoids plus one new flavanol (Liu, et al., 2019).
Yellow horned-poppy	Glaucine from roots	Currently used as an antitussive agent in Iceland, as well as Romania, Bulgaria, Russia and other eastern European countries. Bulgarian pharmaceutical company Sopharma sells glaucine.

Figure 3.2. Examples of semi-wild and native UK plants and uses

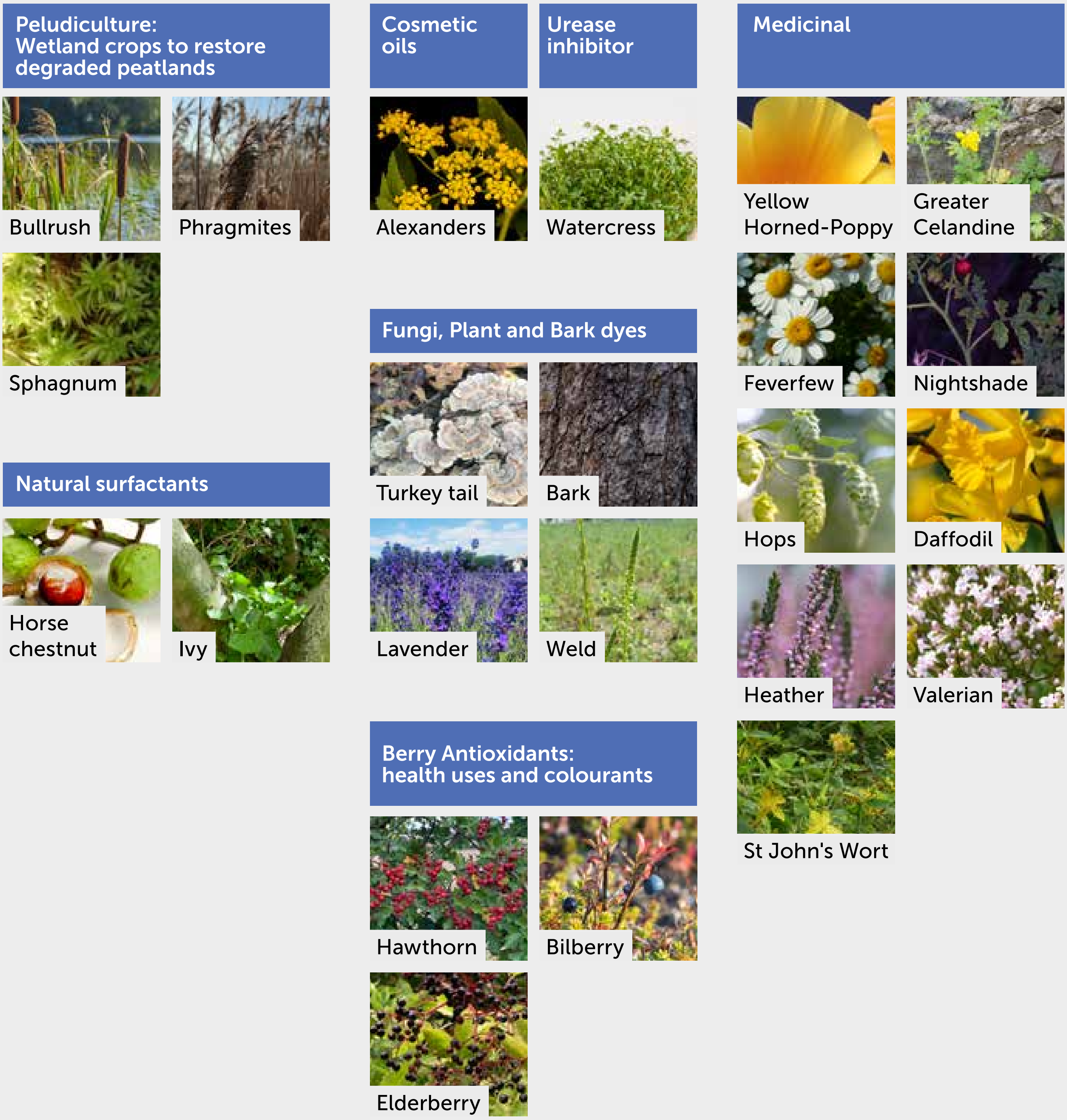


Table 3.2. Summary of selected plants and fungi by type and application

CROP TYPE	APPLICATION: Medical and Pharmaceutical	Consumer healthcare/ Nutraceutical	Functional food ingredient	Cosmetics and Consumer Goods	Industrial and Enablers*	Agriculture (crop protection)
Fungi	▪ Reishi extracts	▪ Reishi extracts		▪ Various crop dyes	▪ Various crop dyes	▪ Mycorrhizal fungi
Horticulture/ Herb/ Vegetable	▪ Potato, solanesol ▪ Potato/tomato, GA ▪ Onion, Quercetic	▪ Potato, solanesol ▪ Potato/tomato, GA ▪ Onion, Quercetic ▪ Various Aox/ colours ▪ Rosemary and Sage, cineol ▪ Brassica GS	▪ Potato enzymes ▪ SB Arabinose and GL ▪ Various Aox/ colours ▪ Rosemary and sage, cineol ▪ Brassica GS	▪ Potato enzymes ▪ Various Aox/ colours ▪ Rosemary and sage, cineol	▪ Potato enzymes ▪ Potato, solanesol? ▪ Potato/tomato, GA	▪ Potato/tomato, GA ▪ Brassica GS
Forestry and perennial Bioenergy		▪ Pine α-terpineol ▪ Pine stilbenes ▪ Various crop tannins	▪ Pine α-terpineol ▪ Pine stilbenes ▪ Pine vanillin ▪ Various crop tannins	▪ Pine α-terpineol ▪ Pine stilbenes ▪ Pine vanillin	▪ Pine α-terpineol ▪ Various crop tannins	▪ Pine α-terpineol ▪ Pine stilbenes ▪ Various crop tannins
Cereals and Oilseeds and their residues	▪ Amaranth, Squalane ▪ Various crop, FAs/ sulfolipid/ phospholipid ▪ OSR GS	▪ Amaranth squalane ▪ Various FAs ▪ OSR GS	▪ Various crop FAs ▪ Various crop erucic acid ▪ OSR GS	▪ Amaranth squalane ▪ Various crop FAs ▪ Various crop erucic acid	▪ Various crop FAs/sulfolipid/ phospholipid ▪ Various crop erucic acid	▪ Amaranth squalane ▪ OSR GS
Other	▪ Poppy, alkaloids ▪ Sphagnum, sphagnan	▪ Hops, flavonoids ▪ Various crop, hydrocolloid gels	▪ Stevia, RebM	▪ Hemp/flax fibres ▪ Woad/weld/ madder dyes ▪ Various hydrocoloid gels	▪ Hemp/flax fibres ▪ Woad/weld/ madder dyes	▪ Hemp/flax fibres ▪ Chrysanthemum spp pyrethrins

*enablers such as biosolvents, biocatalysts, biosurfactants etc.

Aox	antioxidants
FAs	fatty acids
GA	glycoalkoloid
GL	galacturonic acid
GS	glucosinolates
OSR	oil seed rape
SB	sugar beet

4. Higher value markets for biorenewables

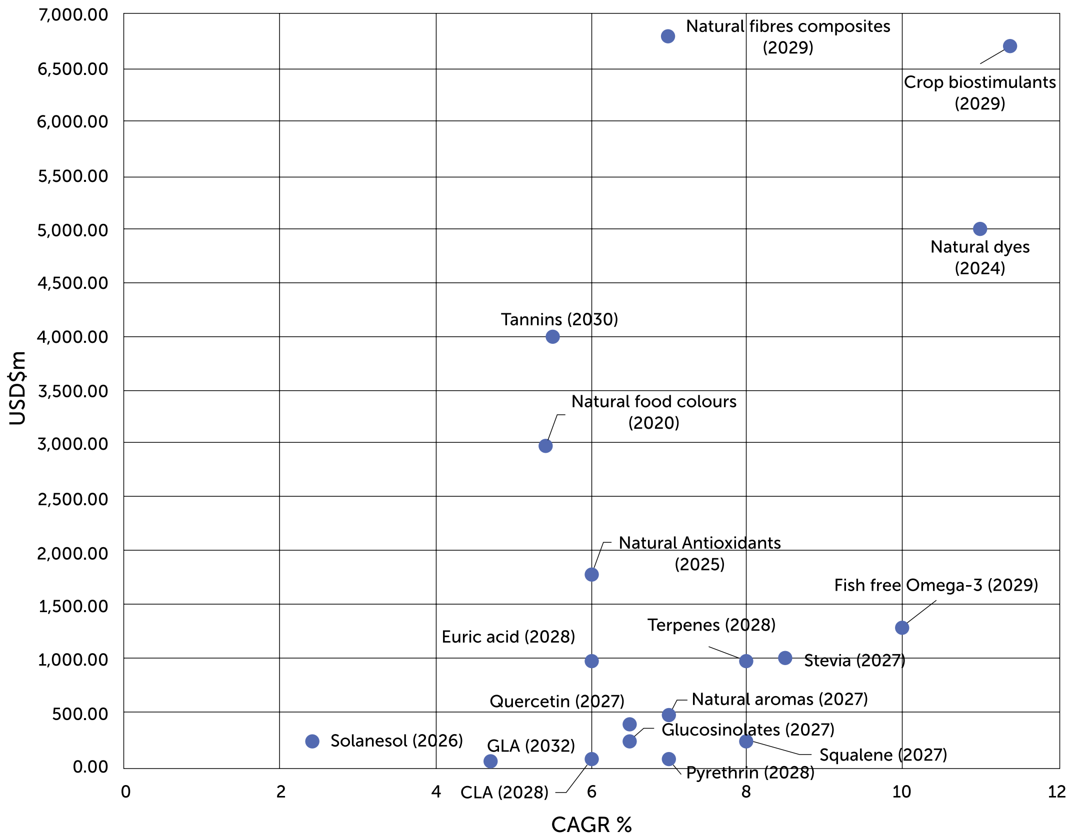
The table below shows market size and compound annual growth rate (CAGR) for various products investigated during the course of this review. The largest markets in terms of scale include natural fibre composites, natural dyes and crop biostimulants. Dyes and composites are existing large markets where synthetic and fossil fuel derived materials are the main resources, but interest in natural biorenewables that are less harmful to the environment and have a lower GHG footprint is driving significantly large and growing markets. Many of these natural dye and composite products are below the value of the scope of this project ($10/kg), but there are likely to be niches whereby higher quality or specialist requirements drive a higher value market.

The crop biostimulants market is emerging and growing exceptionally fast, valued at $2.85 billion in 2021 and growing to $6.69 billion by 2029 with a CAGR over 11%. The natural dyes market is also seeing similar growth rates of over 10%.

The healthcare sector is also driving growth in several bioderived markets. This includes the fast-growing fish-free omega-3 market, and the natural antioxidants market. More niche areas within these are the gamma linoleic acid from oilseed crops, glucosinolates from brassicas, quercetin from onions and solanesol which is primarily derived from potatoes and tobacco plants. Terpenes are used in multiple products, including insect repellents and crop protection, as well as in healthcare, flavour and fragrances applications and have potential as a green solvent. Terpenes can be made synthetically from petrochemicals, but are also still derived from natural sources including wood, particularly pine, and can be sourced from existing large scale paper mill and tall oil industries.

Functional food and beverage ingredients, alongside natural aromas for broader applications, are also key markets for higher value biorenewables. Particularly notable is the natural food colourants market, which reached $3 billion globally in 2020 and continues to grow in a positive trajectory.

Table 4.1. Forecasted global market size and growth rate (CAGR) for selected products

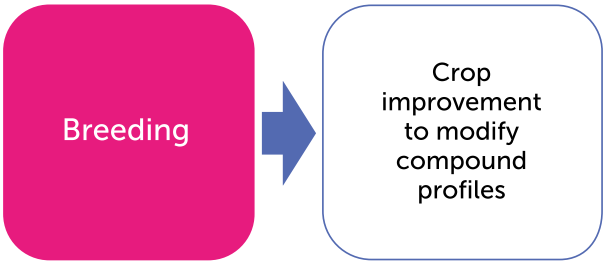


Notes:
Year noted against product is forecast date
GLA = Gamma linolenic acid
CLA = Conjugated linoleic acid

5. Highlighted opportunity areas for industrial biotechnology

This section of the report explores areas where the review has identified opportunities for industrial biotechnology to produce higher value renewables using UK-grown resources. The opportunities are grouped into four main areas: plant breeding for specialist compound profiles; crop, seed and soil treatments; biotechnology-based extraction; and biotransformation of plant extracts. For each area, market opportunities and risks are discussed and examples of existing research, products and processes are presented from within and beyond the HVB network.

5.1 Plant breeding for specialist compound profiles



5.1.1 Breeding for fatty acids

Description	Specialist fatty acids such as plant-derived omega-3s and omega-6s are sold into healthcare, food additives, nutraceutical and personal care markets.
Market	In 2019 the size of the global fish-free omega-3 ingredients market was $590 million and growing rapidly, expected to reach $1.3 billion by 2029 (Transparency Market Research, 2019). The omega-6 gamma linolenic acid (GLA) market is growing at a CAGR of 4.7%, and projected to grow from a valuation of US$ 20 million in 2022 to US$ 31.6 million by 2032 (Future Market Insights, 2022). Indicative wholesale prices for GLA of up to £30/kg and eicosapentaenoic acid (EPA)/ docosahexaenoic acid (DHA) at £15–20/kg.
Opportunity	▪ Fits with plant-based and vegan food and cosmetics trends, and reduced fish stocks in the case of DHA/EPA sources. ▪ Beneficial for crop rotation diversity to reduce inputs, improve soil health and break pest and disease cycles. ▪ Growing evidence and awareness of health benefits of specialist fatty acids. ▪ Breeding efforts have improved yield and efficiency of crop production: UK has excellent track record and expertise to commercialise these crops. ▪ UK produces higher concentration and/or quality of target compounds for some crops than some other countries (e.g. borage GLA).
Risks	▪ Highly competitive global market with international supply (e.g. DSM and Merck are key players for GLA). ▪ Countries with lower concentration of fatty acids in their crop oils will periodically make high purchases of UK stocks of certain oilseeds (e.g. high GLA borage), making the UK growers market and supply chain volatile from year to year. End users who are reliable, demand high quality and commit to purchasing in advance are required to stabilise the market. ▪ The end-user awareness is still low. Understanding of omega fatty acids is growing, but still only few people understand benefits of specific compounds such as GLA and SDA. More end-user education required.

Example 1: Ahiflower™ omega fatty acids, Natures Crops International

AhiflowerTM is derived from a native UK plant in the borage family, *Buglossoides arvensis*, which was discovered growing in a hedgerow in the UK countryside. Conventional selection and breeding efforts over 15 years by Natures Crops International in collaboration with NIAB, with support from Biotechnology and Biological Sciences Research Council (BBSRC) funding, have resulted in a cultivated non-GMO agricultural crop which is grown and processed as a plant-derived alternative to fish oil. It has a uniquely balanced omega profile, is high in omega-3 fatty acids – its 18–20% stearidonic acid (SDA) is the highest content of any non-GM plant) – and is an excellent source of omega-6 GLA. According to Natures Crops, Ahiflower's SDA content means it can be converted by the body into EPA up to four times more efficiently than flaxseed oil can, therefore Ahiflower gives the combined benefits similar to fish oil and evening primrose. The team is continuing to develop the crop to enhance its yield, quality and disease resistance. They work closely with their farmers, and all the products are 100% traceable back to the field.

Crop: Several thousand hectares are grown by farmers across the UK on a range of heavy and light soils, as a break crop in arable rotations. Ahiflower fits well into rotation to help control pest and disease. According to NIAB trials it requires only moderate inputs and low fertilizer, suffers little from pest attack, and has a higher yield and is easier to harvest (no special equipment required) than the alternative SDA crop echium. One hectare of Ahiflower is said to yield the equivalent omega-rich oil as 20 tonnes of fish (Oils and Fats International Magazine, 2016). Harvesting is typically in late June/early July.

Extraction: Natures Crops International manages the entire production supply chain, buying back seed from contracted growers to process into the Ahiflower oil. The company has a manufacturing site in Prince Edward Island, Canada, where the seed is pressed in small-scale expeller presses and gently refined.

Formats: The oil is available in softgels, powder, pure oil and gummies under the brand Natralipid® (Natures Crop International, 2022).

Markets: Applications include food, beverages and personal care. Ahiflower has been approved in many regions, including the United States and the European Union as a novel food. Ahiflower is claimed to combine the anti-inflammatory skin health benefits of evening primrose and echium oils. It is supplied and sold directly and by distributors such as Stratum, Lamotte, Cambridge Commodities and De Witt specialist oil company. In addition, there is an equine supplement market. One challenge has been education of the public, and how to convey the benefits it confers versus other oils.

Example 2: Fish oils from GM camelina, Rothamsted Research

Professor Johnathan Napier and colleagues at Rothamsted Research in Hertfordshire have conducted field trials of their genetically modified camelina plant which provides a plant-based source of omega-3s EPA and DHA, to replace fish-derived sources. These are proven to be health-beneficial, reducing the risk of cardiovascular disease (CVD) and other metabolic diseases such as obesity and type-2 diabetes.

Genetic modification (GM) field trials have shown the accumulation of EPA and DHA in seed oil is a stable trait, while animal feeding studies have determined the efficacy of this plant-based source of EPA and DHA. Further enhancement of EPA and DHA levels in camelina has been explored through the CRISPR-Cas9 inactivation of the competing FAE1 pathway (Han, et al., 2022). All of these studies confirm the promise and utility of this terrestrial source of omega-3 fish oils.

The current focus is to provide a fish feed supplement for fish farms, so the team added an additional trait of the ketocarotenoid astaxanthin biosynthesis, a red natural colourant which gives salmon its pink flesh. The astaxanthin partitions out with the extracted oil. This is also a GM trait. However, ultimately the oil may be used directly in food or supplement products.

Due to the current GM regulations in Europe, which the UK has adopted since Brexit, the main end-market focus of the group is in North America, where the GM regulatory pathway is clear. However, trials are being conducted in the UK.

The seed and oil yield is still under investigation, but trials to date indicate that the crop is economically viable.

Crop: Growing efforts for this GM camelina have been mainly focused on North America for the GM variety. Yara reports a few hundred hectares of conventional camelina are being grown in the UK, with yields of 2.5–3 tonnes/ha. The crop requires a modest 75–120kg/ha of nitrogen (Yara, 2022). It grows in a variety of situations and copes in arid conditions. The crop has not undergone much breeding and development.

Extraction: Standard processes such as screw press and hexane solvent.

Markets: Fish feed supplement for farming. Nutraceutical and dietary supplements as a direct replacement of fish-derived EPA/DHA oils in foods and supplements.

Example 3: Hemp seed fatty acids, University of York

Using non-GM, molecular breeding tools, Professor Ian Graham's laboratory in the Centre for Novel Agricultural Products (CNAP) at the University of York has developed a suite of novel hemp lines with bespoke seed oil profiles to suit a variety of dietary or industrial uses (Bielecka, et al., 2014).

The portfolio includes CNAP1HOH, which was recently registered in the UK as a dual-purpose, high oleic acid variety that produces seed and biomass (shiv and fibre). The novel high oleic acid seed oil trait is five times more stable than conventional hemp seed oil at 20°C, offering new functionality and opportunity to the food processing industry. Additional novel seed oil traits are already confirmed in other lines, including elevated GLA, with oil profiles to compete with speciality oils such as borage, evening primrose and blackcurrant oils. The oil profiles are defined at the genetic level, giving the product a strong Intellectual Property position.

Crop: Hemp seed has a yield of approximately 1.2 tonnes/ha. Hemp is an excellent break crop and does not greatly suffer from pests and diseases, so it requires few inputs. Some nitrogen may be needed to optimise yield. Hemp can improve soil health owing to its deep root systems and carbon exudates and can suppress weed growth.

Extraction: Cold pressing or solvent extraction.

Markets: Nutraceutical and dietary supplements. Competes against evening primrose oil, blackcurrant seed oil and borage seed oil. The high-GLA UK borage seed market (i.e. 20–25% GLA) has been volatile in recent years, as other countries whose producers do not achieve the 20% needed for most GLA supplements have to buy a higher content oil to blend. This makes crop market prices very variable from year to year. The market is relatively small, so only a very small acreage is required to meet market demand. Currently, most people are only aware of omega fatty acids as a whole category, and less informed regarding the benefits of specific fatty acids.

Table 5.1. Other specialist fatty acid crops suited to the UK

Crop	FAs	Known Breeding/Research Efforts
Borage	20–25% omega-6 GLA	Fairking have successfully grown borage in the UK for almost 30 years (Fairking Seeds, 2022). Rothamsted breeding programme in 2000s. UK-listed varieties are under Bioriginal Food and Science Corp, Canada (DEFRA, 2022). De Witt Speciality Oils processes UK grown borage at their New Holland extraction facility in the UK.
Blackcurrant seed	12–17% omega-6 GLA; 12–16% omega-3 ALA and 2–4% omega-3 SDA	Ribena (Suntory) listed against the two varieties on the UK listing (DEFRA, 2022). De De Witt Speciality Oils processes Suntory derived blackcurrant seeds at their New Holland extraction facility in the UK.
Calendula	60% omega-6 calendic acid	European breeding programmes. NF0503: Calendula as Agronomic Raw Material for Industrial Applications, ADAS 1998.
Crambe	Erucic acid	Sweden, Netherlands, Germany development of ultra-high erucic acid crambe (Li, et al., 2012). Competes against high erucic acid rape (HEAR).
Echium	11–15% omega-3 SDA; 6–33% omega-3 ALA and 10-13% omega-6 GLA	230ha was grown at one farm in UK in 2021 for cosmetic market, requiring 50kg/ha nitrogen, with yield of 330kg/ha and sold for £3800/tonne of seed (Farmers Weekly, 2020) (Fairking Seeds, 2022). De Witt Speciality Oils processes UK grown echium at their New Holland extraction facility in the UK.
Evening Primrose	9–10% omega-6 GLA	(Sold by New Holland and Kerfoot specialist oil suppliers in UK).
Linseed	Up to 64% α-linolenic acid (ALA)	Considerable progress has been made in understanding and enhancing the metabolic pathways leading to ALA and polyunsaturated fatty acid synthesis in flax (Linda M., Hall et al., 2016). Major breeding efforts in Canada and France.
Meadowfoam	Over 98% long chain fatty acids. Very high level of cis-5-eicosenoic acid (up to 65%), alongside 14–21% cic-5, c13 docosadienoic acid and up to 15% erucic acid.	An established personal care ingredient that is a very stable cosmetic carrier oil. Has replaced sperm whale-derived oil and supplements jojoba oil production. Natures Crops is developing varieties better suited to the UK in collaboration with NIAB.
Honesty (Lunaria)	30% of dry seed is fatty acids with 23% of this being oleic acid, 46% erucic acid and 20% nervonic acid. Nervonic acid has potential as a medicine for multiple sclerosis.	Trials in England and Scotland conducted in 2003. Breeding research in Lunaria has been performed in Wageningen, the Netherlands (Mastebroek, et al., 2000).
Sea buckthorn	106–135g/kg total oil in the seeds, of which 35% palmitoleic acid, 17% oleic acid, 34% omega-3 (ALA) and 31% omega-6 (linoleic) (Gatlan, et al., 2021).	UK trials on the Essex coast of a number of different varieties from across Europe and Russia since 2009 (British Sea Buckthorn Company, 2022). Kerfoot markets the oil from seeds. Also of interest for other phytochemicals.
Wheat	Bran 3% oil and germ 7% oil: >50% omega-6 linoleic acid plus small amounts of omega-3 fatty acids.	

Notes:

- Omega-3 and omega-6 fatty acids sit within the PUFA group of polyunsaturated fatty acids, and are important for health and industrial applications.
- The two dietary essential fatty acids are alpha-linolenic acid (an omega-3 fatty acid) and linoleic acid (an omega-6 fatty acid). "Conditionally essential" fatty acids include omega-3 docosahexaenoic acid (DHA) and omega-6 gamma-linolenic acid (GLA). SDA provides a precursor for the body to make EPA and DHA.

5.1.2 Breeding for blue

Example 1: Natural blues, John Innes Centre

Professor Cathie Martin and colleagues at the John Innes Centre in Norwich are investigating the effects of chemical modifications, co-pigments and pH on colour and stability for developing new plant sources of natural colourants and new natural colours. As well as considerable work on transgenic purple tomatoes, for which the group are currently seeking USDA approval, they have also explored the challenges and opportunities for natural blue colourants (Houghton, et al., 2021). They outline the challenges for commercial natural blue colourants, including:

- Low occurrence of natural blue pigments in nature, and often have low stability in solution.
- Reconstituting metal complexing with anthocyanins has been explored by industry, but the use of iron has taste and cost implications, and still requires co-pigmentation.

The group concludes that further screening of plants could be conducted to find a wider range of more stable natural blue tones. They have found that the butterfly pea (*Clitoria ternatea* or blue pea) may provide a solution. The ternatin extracts produced have better stability even at a high pH and in cooked goods than spirulina natural blue and the beetroot red betacyanins. However, butterfly pea plants do not produce many flowers and those flowers are ephemeral, lasting little longer than a day with their full blue colour (Houghton, et al., 2021). The researchers have explored cell lines, but issues with loss of the ability to produce anthocyanins over time presents a challenge. Gene editing is not considered by the team to be a valid approach for anthocyanin production. Transgenic approaches are likely to be more successful, but restrictions on GM foods in the UK and Europe limits this approach. Considered a holy plant in India, the flower is used across Southeast Asia as a natural food colouring to colour rice and desserts and in Ayurvedic medicine. The pigments have also been used in Sharish Blue Magic Gin, which turns from blue to pink when tonic is added due to the change in pH.

Crop: Butterfly pea is a tender leguminous vine, currently supplied as a garden plant for growing under glass in the UK (Special Plants Nursery, 2022). It is cultivated on a large scale in Southeast Asia and Portugal.

Markets: Approaches to improving the availability of natural blue colourants are largely focused on scaling up specific natural sources and improvements in formulations. Scale-up has been possible globally from black or purple carrots, purple sweet potato, and blueberries, because such plants are already cultivated widely and, for some, colour extraction may offer sustainable ways of using waste material from mainstream commercial use, such as the use of skins of red grapes from the wine industry for colourant production.

See also Section 5.4.1 biotransformation of colourants section for market information.

5.1.3 Breeding for pharmaceutical bioactives and consumer healthcare

Description	The use of naturally occurring health and pharmaceutical compounds. Cancer is a particular target for plant-derived agents. 19 million new cancer cases were diagnosed in 2020 (WHO, 2020), and several plant-derived anticancer agents are in clinical use, including taxol, vinblastine, vincristine, camptothecin and topotecan. The National Cancer Institute of the United States has screened over 110,000 extracts from plants (DataM Intelligence, 2021).
Market	▪ The plant-derived anticancer agents market is growing and is worth over $1 billion (DataM Intelligence, 2021). ▪ The natural antioxidant market is predicted to reach $1.8 billion by 2025 and $1.9 billion by 2027, exhibiting a CAGR of 5.81% during 2022–2027 (PR Newswire, 2020). ▪ Indicative wholesale price for anthocyanins of up to £250/kg, but many products are sold at lower prices.
Opportunity	▪ Established plant-derived compounds for anti-cancer. ▪ High demand for natural products and novel anti-cancer solutions. ▪ Can have fewer side-effects than synthetic drugs. ▪ High demand for traceability and quality assurance for health products.
Risks	▪ The global market for plant sources of anti-cancer agents is quite competitive, with some key actors including Phyton Biotech, Novasep and Pfizer. ▪ In many instances, the pharmaceutical actives would be transferred to fermentation or synthetic production wherever possible. ▪ High barrier to entry owing to costs of trials and regulatory frameworks. ▪ Despite precedent of plant agents, the lack of awareness around phytochemical actives is said to restrict market growth.

Example 1: Willow miyabeacin, Rothamsted Research

Rothamsted Research has a long history of willow research and manages the National Willow Collection, one of the largest ensembles of *Salix* germplasm in the world, with 1,500 accessions and over 100 pure species of *Salix* represented. To date, breeding efforts have been focused on increasing growth rates and yields and conferring disease resistance. However, more recently attention has turned to higher value compounds and bioactives that can add value. Screening conducted by Dr Jane Ward and Professor Mike Beale has revealed both high concentrations (up to 15% of total dry matter) and huge diversity of compounds, with significant variation between willow species. For instance, in screening work on a natural hybrid of *Salix triandra* and *S. dasyclados*, 22 phenolic glycosides, including 18 that are new to the Salicaceae, were identified (Noleto-Dias, et al., 2019).

Although there is a long history around salicin and aspirin, much of the pharmacology of the diverse willow collection is yet to be determined, but Rothamsted have identified a novel molecule, miyabeacin, which has shown anti-cancer properties in several cell lines. The production of this cyclodimeric salicinoid from *S. miyabeana* and *S. dasyclados* is a heritable trait, and thus could be selectively bred for. Variation in structures of natural miyabeacin analogues is derived via cross-over Diels-Alder reactions from pools of ortho-quinol precursors. These transient ortho-quinols have a role in the as-yet uncharacterised biosynthetic pathways around salicortin, the major salicinoid of many willow genotypes. Selection of differential chemistry of parents could generate hybrids with variations of molecules to improve anti-cancer activity (Ward, et al., 2020).

In addition to these potential novel pharmaceuticals, there is interest in options for expanding the use of willow extracts in herbal remedies, for long-term pain management in chronic disease, for example. The Rothamsted team are also investigating extracts from different species and agronomic cycles, as well as engineering the biosynthetic pathway by hybridisation in willow and GM/GE in the closely related poplar tree (*Populus* species), which also contains the salicinoid pathway.

In addition to work at Rothamsted, other research is under way in other countries on *Salix* bioactives such as for anthelmintic properties to reduce or replace the use of insecticidal wormers in livestock (Hernandez, et al., 2014). This could help with worm resistance as well as damage of the insecticides to beneficial insect populations.

Crop: Willow species are a key target of the UK's growing biomass market and can also be utilised for flood defences and mitigation. Willow grows vigorously in the UK as a perennial. Total short rotation coppice of willow was estimated to cover 2,250 ha in 2019 with over 270 commercial growers (DEFRA, 2019).

Extraction: The team are currently working to explore the extraction process with an on-farm aqueous extraction pilot project and exploring extracts from different species and accessions.

Market: Huge demand for anticancer agents, especially plant-derived sources.

Product: Requires extensive further trials and research, including clinical trials, alongside regulatory approval processes.

Example 2: Golden flax podophyllotoxin (PPT), De Montford University

Podophyllotoxin (PPT) is the unique natural precursor of etoposide, used in various anticancer chemotherapy treatments. PPT is still exclusively extracted from the rhizome of *Podophyllum peltatum*, which grows in the United States and Canada. The supply of podophyllum plants is limited, and collection has resulted in its endangered listing. A number of alternative plants have been identified as potential sources for PPT, including yellow flax, *Linum flavum*. Professor Randolph Arroo and colleagues at De Montford University in Leicester have explored the mechanisms for biosynthesis of PPT in root cells of yellow flax, *Linum flavum*, in order to optimise cell culture productivity (Mikac, et al., 2020). This may open the route for other breeding or plant screening opportunities.

Crop: *Linum flavum* is more suited to warmer climates, so is likely to be grown under glass if utilised for PPT extraction in the UK. Currently the plant has low productivity due to its slow growth.

Market: Huge demand for anticancer agents, especially plant-derived sources. See table above.

Product: PPT is a known chemotherapy treatment, which should reduce some of the hurdles in bringing this source to market.

Example 3: *Euphorbia millii* anticancer activity, Huddersfield University

Dr Talha Ali Chohan and colleagues of the University of Huddersfield used phytopharmacological and advanced computational techniques to study the anticancer potential of *Euphorbia milii*. They found activity against hepatocarcinoma cell line (HepG2). They concluded that the major extract components of cyclobarbital and benzodioxole derivative from the plant may be responsible for anti-invasive activity against HepG2 cells (Chohan, et al., 2020). The plant latex and niclosamide has also been used as a pesticide, particularly for snail control.

Crop: *E. milii* is a shrub native to Madagascar and is not hardy, but grown as a horticultural plant in the UK. It does not tolerate temperatures below 10°C (50°F). In temperate areas it needs to be grown under glass in full sun. During the summer it may be placed outside in a sheltered spot, when all risk of frost is absent.

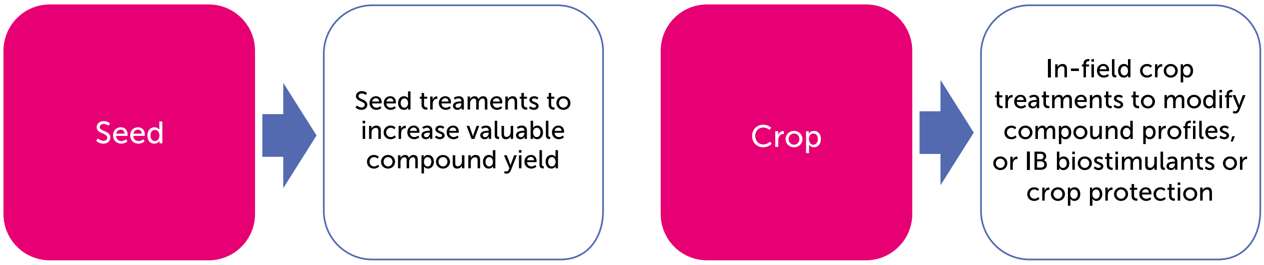
Market: Huge demand for anticancer agents, especially plant-derived sources. See table above.

Product: Requires extensive further trials and research, including clinical trials, alongside regulatory approval processes.

Table 5.2. Other examples of plant-derived anti-cancer agents

Drug Type	Source	Example Players	Recent Development
Paclitaxel	Bark and leaf *of Taxus brevifolia* (Pacific yew tree), *T. Canadensis* and Corylus avellana	Rigel Pharmaceuticals	Combined fostamatinib and paclitaxel phase 1 clinical trials 2022
Vinca alkaloids	*Periwinkel C roseus* (was *Vinca rosea*) and other Vinca species	Pierre Fabre	Navelbine drug generic in US 2003
Docetaxel	*Taxus baccata* (European yew tree)	Sanofi-Aventis, Sun Pharma Global, Zydus	Patented in 1986 and now generic
Camptothecin derivatives	Bark and stem of *Camptotheca acuminata* (happy tree)	Yakult Honsha	Identified in the 1960s. Many analogues have been synthesized, such as irinotecan and hydroxycamptothecin

5.2 Crop, seed and soil treatments using biostimulants



Description	The Agriculture and Horticulture Development Board (AHDB) defines a plant biostimulant as a formulation which contains substances and/or microorganisms that stimulate natural plant processes, beyond basic fertilisation or pesticidal activity. Indeed, fertiliser and pesticide activity are regulated separately. The use of microbes to support crop growth and health is a growing area of interest. Products are entering the market from mainstream companies such as Syngenta.
Market	A new, rapidly evolving market, still being defined and with little regulation currently. The global biostimulants market size was valued at USD 2.85 billion in 2021. The market is projected to grow from USD 3.14 billion in 2022 to USD 6.69 billion by 2029, exhibiting a CAGR of 11.43% (Fortune Business Insights, 2022).
Opportunity	▪ Rapidly growing, novel market with huge scope for innovation. ▪ Strong interest from large companies. ▪ The rising cost of nitrogen fertiliser, increased regulations controlling the use of organic and synthetic fertiliseron farms and a transition to min-tillage and no-tillage systems are all increasing interest among farmers to find alternative ways to support crop health and yields. ▪ Growing pool of data providing evidence of efficacy is helping develop trust among end-users.
Risks	▪ Lacks clear regulations currently, but likely to become regulated in next few years. ▪ Soil microbes and ecosystems poorly understood, so high risk of unintended consequences. ▪ Strong competition. ▪ Lack of farmer education. ▪ Scepticism among end-users due to some unproven early entrants into market.

Emerging interest in biostimulants

Interest in the role of soil microbes in plant health and biochemistry has been rekindled in recent years, particularly with the wave of regenerative agriculture, which focuses its principles on soil health. Soil constitutes a set of ecosystems that are quite distinct from the above-ground habitats that have been deeply studied. Healthy soil is a fractural system, with structures at different scales serving many functions and providing ecological niches for different cohorts of species. The vast surface area of this mosaic of pores of different sizes in healthy soils provides an extraordinarily diverse habitat that can sustain a water film and humidity to support a hugely complex and abundant range of microorganisms and fauna. New approaches to protection and management of soil consider it in terms of landscape ecology, but on a micro-scale (Stockdale, et al., 2018) (Harris, et al., 2022).

Microbes and soil fauna represent reservoirs of carbon, nitrogen and phosphorous along with other micronutrients, and are fundamental to the natural cycling of these essential energy and nutrient components.

Regarding biotechnology, particularly synthetic biology interventions, it should be noted that our understanding of soil is extremely limited. The diversity and roles of species are not well described, and there is even less knowledge of the structural, dynamic and functional aspects of soil systems. Therefore, the risk of unintended consequences from introducing functionality via a synthetic organism into the system is high, and control over the spread of genetic material very low.

However, as the understanding of mycorrhizal fungi and beneficial microbes grows, researchers are beginning to explore the potential to develop treatments for seeds, soil or crops using known organisms from healthy systems.

Current inoculants and biostimulants are not well regulated, and the quality and quantity of active microbes has been questioned for some products. New EU legislation, due in 2022, should tighten up the requirements and help shift from a commercial to a technically driven market. There are, to date, no specific regulations for soil conditioners, soil improvers or biostimulants in UK domestic legislation (Biostimulants Legislation, 2022). It is likely that this will change over the next few years.

In 2016 the AHDB reviewed biostimulants for horticulture and arable crops and found low to moderate evidence for the efficacy of most microbial biostimulants, with the exception of plant growth-promoting bacteria, which provided good evidence for boosting growth and yield (AHDB, 2016). However, more recent research efforts have shown a beneficial effect, as shown in some of the examples below.

Box 5.1. Definition of Biostimulants

A plant biostimulant contains substances and/or microorganisms that stimulate natural plant processes. The effect will be independent of its nutrient content and will improve one or more of the following characteristics of the plant, or the plant rhizosphere:

- Nutrient-use efficiency
- Tolerance to environmental stress
- Quality traits
- Availability of nutrients in the soil or rhizosphere

The main role of a biostimulant should not be to provide fertilisation or pesticidal activity. Any product marketed as a pesticide must have a Ministerially Approved Pesticide Product (MAPP) number.

(AHDB, 2022)

Table 5.3. Types of microbial biostimulants

Microbe Type	Description
Growth promoting bacteria	Bacteria that support crop growth, such as nitrogen-fixing *Rhizobia* or *Bacillus* species, which can act as endophytes in plants where they can play a role in their immune system, nutrient absorption and nitrogen-fixing capabilities.
Beneficial non-mycorrhizal fungi	Fungi play important roles in decomposition, nitrogen cycling and accessing trace minerals. Some fungi can deter pathogenic organisms (e.g. *Trichoderma* has been developed as a biocontrol against root and foliar disease).
Arbuscular mycorrhizal fungi	A common category of endomycorrhizal fungi (i.e. grows into root cells) that forms a symbiotic association with plant roots (e.g. *Rhizophagus irregularis*).
Protozoa	Protozoa are single-celled organisms which include amoeba, ciliates and flagellates. They play a significant role in carbon and nitrogen cycling and control of bacteria in soil.
Nematodes	Soil nematodes are non-segmented microscopic worm-like organisms, which, depending on the species, will feed on bacteria, fungi, protozoans, other nematodes or plant roots. They can be beneficial or detrimental to crop health, depending on the species.

Example 1. Bayer Novozymes biostimulants

Bayer and Novozymes have collaborated to launch two biological biostimulant seed treatments, JumpStart and ProStablish, which can help increase cereal yields by establishing better rooting.

JumpStart contains the natural soil fungus *Penicillium bilaiae*, making soil phosphate more soluble and biologically available to plants. ProStablish is a lipo-chitooligosaccharide (LCO), derived from crustaceans, which is a key biologically active signal molecule that stimulates spore germination of mycorrhizae fungi and colonisation of plant roots. The team conducted trials across 94 locations over two seasons in Europe and Ukraine for different varieties and cropping patterns. Results included a 3.3% yield increase in winter wheat, with a positive yield response in 60% of trials (Bayer, 2020).

Example 2. Corteva organic pest control from soil bacteria

Qalcova™ Active (spinosad) and Jemvelva™ Active (spinetoram) are both molecules extracted from sugar-based fermentation of the soil bacterium *Saccharopolyspora spinosa*. Developed by Corteva, they are used to control lepidopteran species and thrips, with safety for most beneficial insects. The spinetoram is a more effective chemically modified compound. These products have received multiple recognitions, including the US Environmental Protection Agency Green Chemistry Awards for products that reduce negative impacts on the environment. Because of its natural origin, certain products containing Qalcova can be certified for organic production, pending local regulation (Corteva, 2022).

In Brazil a microbiological nematicide, Inlayon™, has been developed from a Brazilian soil microbe for the control of the *Pratylenchus brachyurus* parasite and *Sclerotinia sclerotiorum* fungus. In the United States, Corteva has developed a virus-based biological insecticide that infects moth larvae and can be used for organic farming in that country (Corteva, 2022).

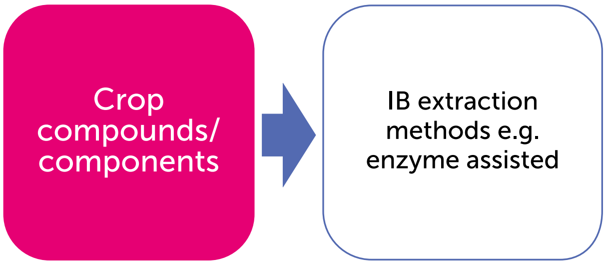
Example 3. Syngenta carbon and amino acid biostimulants

Syngenta is developing carbon and amino acid-based biostimulants to help UK crops cope with heat stress. Following the UK's most extensive research field trial of a biostimulant, analysis has revealed significantly increased yield for potato crops that had been under prolonged or extreme heat stress (Syngenta, 2022).

Example 4. Azotic nitrogen-fixing bacteria for crops

Azotic Technologies Ltd is a UK company that produces Envita™ and N-Fix® nitrogen-fixing bacteria. These products can be used for multiple crops, are applied in liquid formulation and are reported to reduce synthetic nitrogen fertiliser use by 25–50% while maintaining yield (Azotic Technologies, 2022).

5.3 Enzyme-assisted extraction



Example 1: Rosmarinic acid from sage, Ming Chi University, Taiwan

Enzyme assisted extraction (EAE) can enhance the mass transfer in extraction processes by breaking the cell walls of the vegetable matrices (Krakowska, et al., 2018). EAE of rosmarinic acid from sage (*Salvia officinalis*) has been demonstrated by Chia-Hung Su at Ming Chi University in Taiwan. Cellulase A and Novozyme's Protamex mixture (1:1, w/w) exhibited maximum effectiveness in the extraction (Chia-Hung, et al., 2020). Rosmarinic acid has a number of biological activities (e.g. antiviral, antibacterial, anti-inflammatory and antioxidant), making it an interesting target.

Example 2: Betalain from beetroots, Tuscia University, Italy

The recovery of betalain pigments from beetroots was carried out by a team at Tuscia University, Italy, using a tailored enzymatic mix, blended to target the polysaccharide composition of a beetroot cell wall. The mix consisted of cellulase (37%), xylanase (35%) and pectinase (28%). The enzyme-assisted extraction protocol was optimized, and the most suitable conditions for pigment yield and colour were found to be 25 U/g total dose of enzymatic mix at 25°C, with a processing time of 240 minutes (Lombardelli, et al., 2021). (See also Section 5.4.1 on biotransformation of colourants).

EAE can be used to remove non-phenolic compounds (e.g. pectin) from apples or assist the elution of the phenolic compounds (Wikiera, et al., 2015), which could be a suitable biomass pre-treatment to improve the phenolics' extraction selectivity (Silva, et al., 2021).

Example 3: Carotenes from carrot residues, Aromes de Bretagne, France

Carotenoids, which are isoprenoids, show yellow-to-red colouration, and include carotenes and are used as a colourant in food and beverages, as the additive E160a. The UK has a large carrot crop of which up to 20% does not meet the quality standards as fresh produce and so is sent to anaerobic digestion or animal feed, or is composted (WRAP, 2017) A French firm, Aromes de Bretagne, filed a patent in 1985 for a process for extracting carotene from carrots using a pectolytic enzyme. A schematic comparing the patented enzymatic extraction method with the standard solvent extraction method is shown in Figure 5.1.

Figure 5.1. Two carotene extraction processes

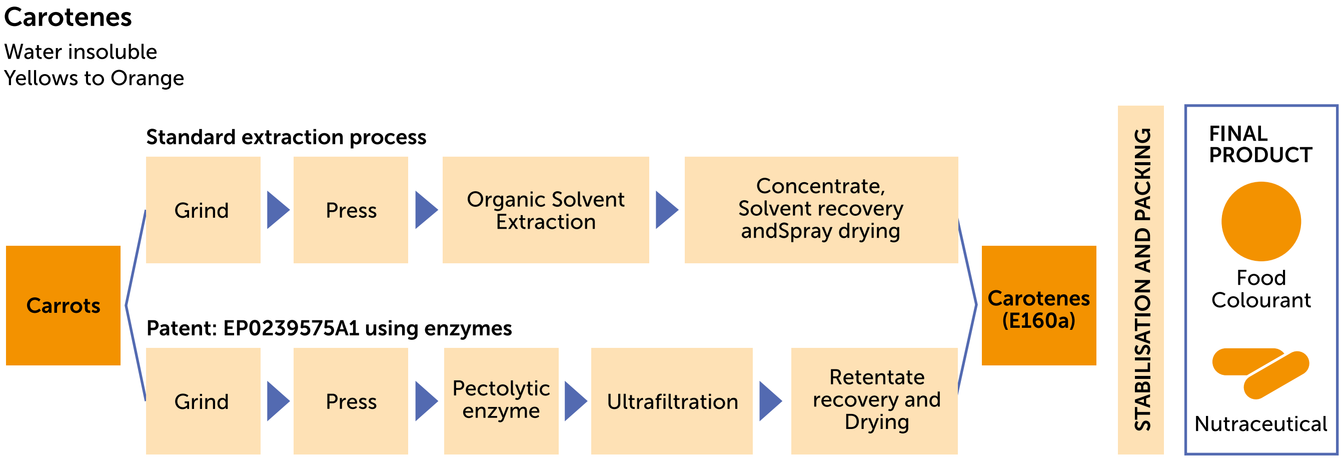
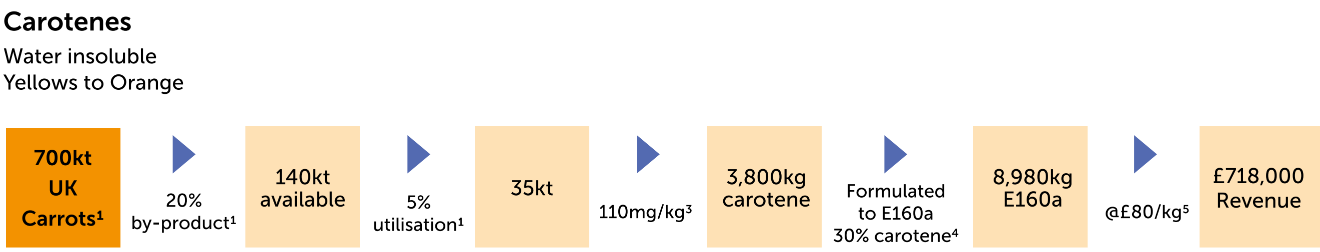


Figure 5.2 shows an example scenario for revenues from using a small proportion of UK-grown fresh carrot rejects to produce carotene additive E160a.

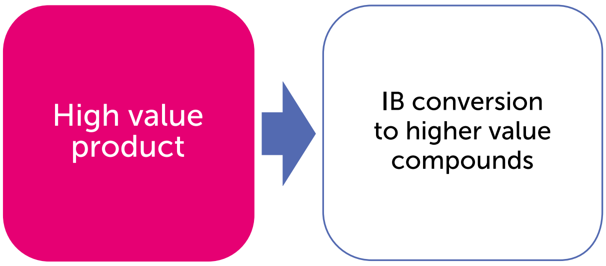
Figure 5.2. Modelled revenue from producing carotene using enzymes



Notes:

1. Carrot waste volumes: WRAP Fresh Produce By-Products Valorisation 2017, British Carrot Association
2. Utilisation: example scenario for demonstration
3. McCance Widdowson Food Composition Dataset (McCance, et al., 2021)
4. 30% based on specifications of commercial carotenes in E160a
5. Small-scale wholesale price for FDA and EU food grade product

5.4 Biotransformation of plant extracts



5.4.1 Biotransformation of colourants

Description	Flavonoids, betalains and carotenoids are major categories of botanical pigments that can be used to derive natural colours. There are few examples of enzymes or synthetic biology being used to transform the colour profiles of extracted compounds, but much work has been conducted to profile the synthesis pathways and explore fermentation options, which potentially could be used to tailor or stabilise naturally extracted pigments (e.g. from crop residues).
Market	The global natural food colours market was worth $2.1 billion in 2021 and is forecast to grow to over $3 billion by 2028 with a CAGR of 5.4% (GlobalInfoResearch, 2022).
Opportunity	▪ Biotransformation of natural extracts offers a clean label option for use in food and food-contact packaging. ▪ Demand from the food and cosmetics industries for naturally derived colourants. ▪ Availability of off-cuts and residues from fruit and vegetable processing may provide a ready source of materials. ▪ Established natural colourant suppliers in the UK such as Fast Colours LLP
Risks	▪ Competition against microbial biosynthesis. ▪ Low concentration of target compounds can make extraction inefficient prior to biotransformation. ▪ Requirement to stabilise target compounds in formulations.

Example 1. Anthocyanins and betalains from soft fruit and beetroot residues

The UK grows various crops containing anthocyanin and betalain pigments. This includes annual production of:

- 12,000 tonnes blackcurrants (90% used in Ribena) (International Blackcurrant Association, 2021);
- 12,500 tonnes raspberries (British Berry Growers, 2022);
- >30,000 tonnes beetroot (Beetroot UK, 2022).

Several companies in the UK are using naturally derived colourants in cosmetic and hair products. For example, Keracol Ltd, a spin-out from the University of Leeds, has developed a hair dyeing technology to utilise anthocyanins from blackcurrant skins that are by-products from Suntory Ribena processing in the UK. Synthetic hair dyes are known irritants and can trigger severe allergic reactions. There is also much debate whether these ingredients also cause cancer, and up to 95% of all dye is washed down the drain (Food & Drink Federation, 2018).

Seeds of Colour (SoC) is manufacturing clean and natural labelled cosmetic products using a novel extraction process. Their ingredients are sourced from UK organic growers and include beetroot extract, rosemary leaf extract and blackcurrant seed extract. SoC started in the NIAB laboratories at the Eastern Agritech Innovation Hub, where its pigment extraction technology was developed.

Dr Freitas-Dörr and colleagues at the University of São Paulo, Brazil, have developed a photostable and metal-free blue chiral dye which is synthesized from betalamic acid. The acid can be obtained from hydrolyzed red beetroot juice or from enzymatic oxidation of the amino acid levodopa. BeetBlue is blue in the solid form and in solution of acidified polar molecular solvents, including water. Its capacity to dye natural matrices makes BeetBlue the prototype of a new class of low-cost bioinspired chromophores suitable for many applications (Freitas-Dorr, et al., 2020).

In terms of biotechnology potential in this space, ColourFix in Norwich is using synthetic biology approaches to assemble pigment pathways from nature for use in industrial textile dyeing.

In addition, research efforts may give rise to new breeding and crop-extract biotransformation opportunities. Lombardelli and colleagues used cellulase, xylanase and pectinase to extract betalains from beetroot at an enzyme loading of 24 U/g over 4 hours, in combination with acetate solvent extraction at solvent-biomass ratio of 15 ml/g, pH 5.5 and 25°C (Lombardelli, et al., 2021). A 2022 review examines anthocyanin synthesis via triggering transcription genes that code for anthocyanin-producing enzymes (Sunil, et al., 2022). Tanaka et al. describe the chemical structures and biosynthesis pathways of various plant pigments including anthocyanins, betalains and carotenoids (Tanaka, et al., 2008).

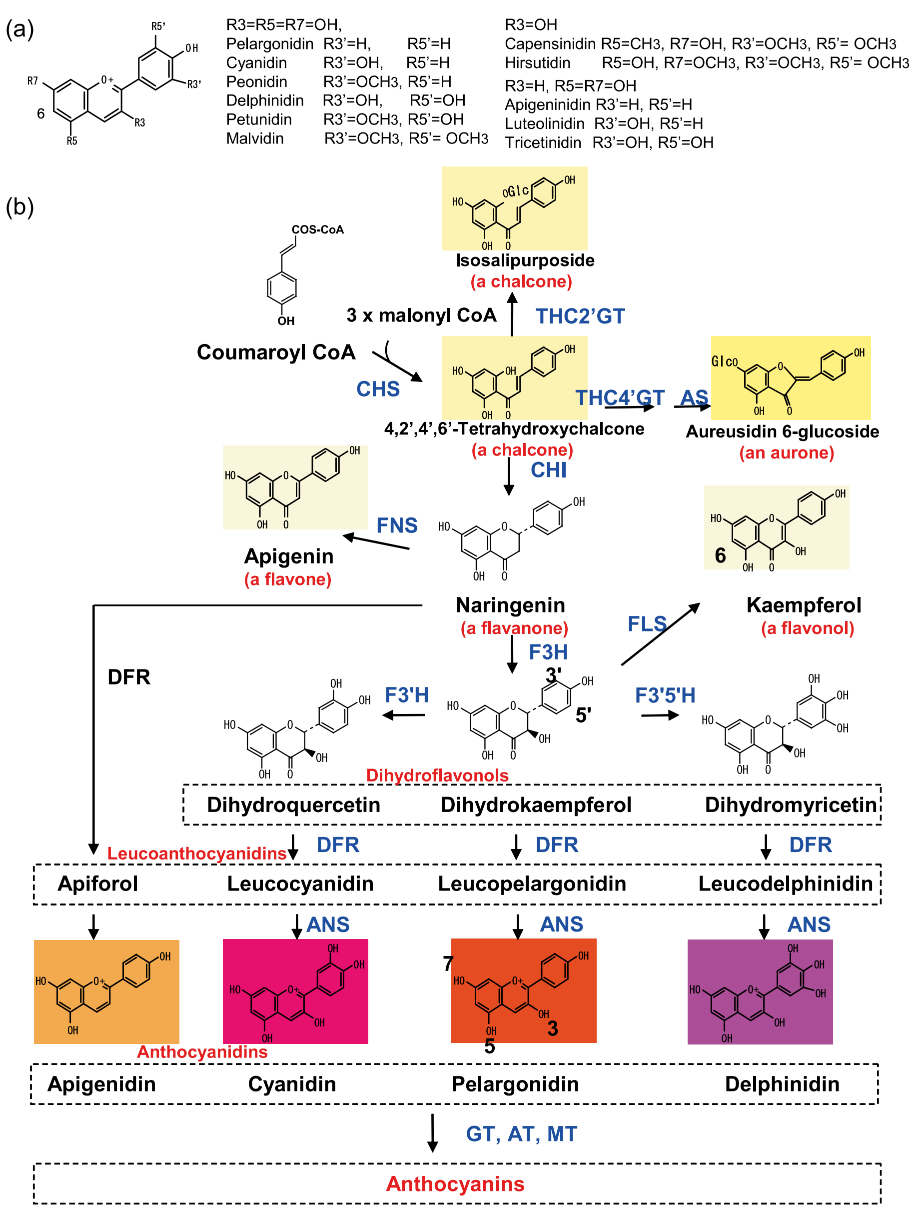


Figure 5.3. Anthocyanidin structures and flavonoid biosynthetic pathways relevant to colour

Notes:

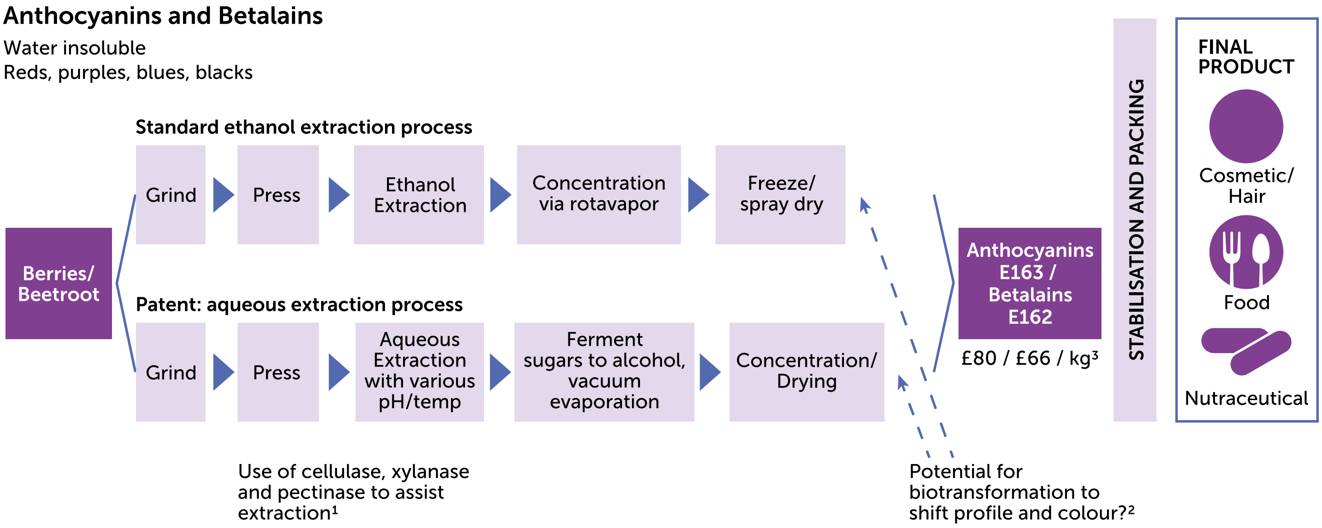
(a) Structures of major anthocyanidins (R groups listed on the left) and some minor anthocyanidins (R groups listed on the right). The basic structure is shown on the far left.

(b) The biosynthetic pathway leading to the biosynthesis of anthocyanidins. Anthocyanidin is further modified with glycosyl, acyl or methyl groups, catalyzed by glucosyltransferases (GT), acyltransferases (AT) and methyltransferases (MT). Enzymes and flavonoid classes are indicated by blue and red letters, respectively. The typical colours of compounds are also shown, but the actual colour depends on various factors as described in the text. CHS, chalcone synthase; THC2'GT, UDP-glucose:tetrahydroxychalcone 2'GT; CHI, chalcone isomerase; THC4'GT, UDP-glucose:tetrahydroxychalcone 4'GT; AS, aureusidin synthase; F3H, flavanone 3-hydroxylase; F3'H, flavonoid 3'-hydroxylase; F3'5'H, flavonoid 3',5'-hydroxylase; DFR, dihydroflavonol 4-reductase; ANS, anthocyanidin synthase; FNS, flavone synthase; FLS, flavonol synthase; Glc, glucose.

Source: (Tanaka, et al., 2008)

A schematic for ethanol and aqueous extraction and is shown in Figure 5.4 for anthocyanins and betalains, with suggested roles for biotechnology to enhance extraction or manipulate pigment profiles of extracts.

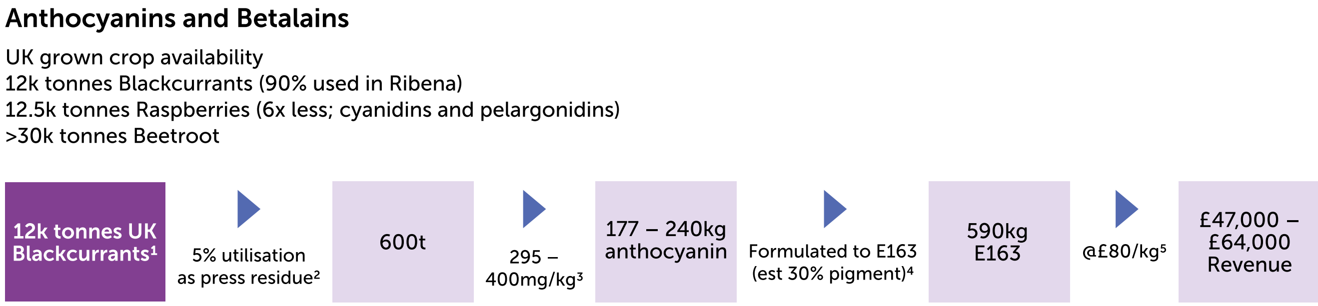
Figure 5.4. Two processes for extracting anthocyanins and betalains



Notes:

1. (Lombardelli, et al., 2021)
2. Regulations on processing technologies must be observed for specific applications
3. Based on small-scale wholesale FDA & EU Food grade

Figure 5.5. Modelled revenue scenario from extracting anthocyanins and betalains



Notes:

1. UK harvest 2021. Volumes are for UK-grown crop, and do not include imports for processing (British Berry Growers, 2022), (Beetroot UK, 2022), (International Blackcurrant Association, 2021).
2. Utilisation: example scenario for demonstration.
3. McCance Widdowson Food Composition Data (McCance, et al., 2021).
4. Specification for concentration in E163 unknown.
5. Based on small-scale wholesale FDA & EU Food grade.

5.4.2 Biotransformation of antioxidants, flavours and fragrances

Description	The natural flavours and fragrances industry is segmented into food and beverage, pharmaceutical, cosmetics, home and health care applications (GlobalInfoResearch, 2022). Major companies that produce natural flavours and fragrances include Givaudan, Firmenich, Sensient Technologies Corporation, International Flavors & Fragrances, Symrise and Kerry Group (GlobalInfoResearch, 2022), Antioxidants are used in similar applications, including packaging. Derivatives such as 1,8 cineole, from herbs in the mint family including lavender, sage and rosemary, have an established global market, being used in flavours, fragrances, medicines as well as insecticide and insect repellent. These herbs grow well in the UK, typically for culinary purposes. For example, the wholesale supplier Herbs Unlimited in Yorkshire produces mint, rosemary, sage and thyme amongst many other herbs and edible flowers from 100 acres of field crops, including 10 acres of polytunnels.
Market	▪ The natural flavours and fragrances market is growing at a fast pace with substantial growth rates over the last few years (Verified Market Research, 2020). The global natural aroma chemicals market for the flavours industry is estimated to surpass $470 million by 2027 with a CAGR of over 7% (Global Market Insights, 2022). ▪ The botanical naturals segment of the market is forecasted to achieve the fastest growth. ▪ The food antioxidant market is forecasted to be worth $1.8 billion by 2025 and to grow to $1.9 billion by 2027, exhibiting a CAGR of 5.8% during 2022–2027. Natural antioxidants are driving this growth (PR Newswire, 2020). ▪ The global terpene market was worth $536m in 2020 and is expected to grow to $1 billion by 2028 – a CAGR of 8% (Verified Market Research, 2020). ▪ The global eucalyptol market is estimated to have been worth $382 million in 2021 and is forecast to grow to $492 million by 2028 with a CAGR of 4.3% (Market Reports World, 2022).
Opportunity	▪ In general, increased demand for products free from artificial flavour and colour and tightened regulation of synthetic additives both present opportunities for natural alternatives. ▪ Growing awareness of the importance of eating natural and healthy food products has boosted demand for natural aroma chemicals. ▪ Increased production of natural personal care products with essential oils and exotic aroma will drive product demand, ▪ Large investment by major players. For instance, in November 2018, Symrise AG opened a site for high-quality natural food ingredients in the US state of Georgia. The group invested €50 million in the facility, which follows high technological and sustainable standards. Blue Pacific Flavors and McCormick entered into partnership for marketing , non-GMO, natural flavours with FlavorCell® encapsulated flavour delivery. ▪ Growing awareness among populations related to health and hygiene is expected to drive the natural flavours and fragrances market. ▪ Consumer demand for essential oils in cleaning products is expected to grow. ▪ Growing use of antioxidants in the meat and poultry. For instance, natural antioxidants such as plum products, grape seed extract, cranberry, pomegranate, bearberry, pine bark extract, rosemary extracts, oregano and various spices function as antioxidants in meat and poultry products.
Risks	▪ Eucalyptol can be derived from eucalyptus, which is grown in large quantities globally and is likely to be competitive against UK-grown extracts. ▪ Competition against microbial biosynthesis. ▪ Achieving purity and consistency of extracts to meet specifications is challenging.

Example 1. Mint family monoterpenes, University of York

A high level of monoterpenes is found among plants in the mint family, which includes sage, rosemary, thyme, catnip, lavender and mints. Dr Benjamin Lichman's laboratory at the University of York is working on synthetic biology platforms for natural product production and industrial biocatalysis, with an emphasis on monoterpenes from this plant family. The focus is on elucidating the compound profiles and enzymatic biosynthetic pathways across species and cultivars expressing different monoterpenes, and the team have seen significant diversity. For example, they have identified a class of nepetalactol-related short-chain dehydrogenase enzymes (NEPS) from catmint (*Nepeta mussinii*) that capture a reactive enol intermediate and catalyze the stereoselective cyclisation into distinct nepetalactol stereoisomers. Subsequent oxidation of nepetalactols by NEPS1 provides nepetalactones, metabolites that are well known for repelling insects and producing euphoric effects in cats. These discoveries will complement metabolic reconstructions of iridoid and monoterpene indole alkaloid biosynthesis (Lichman, et al., 2019). The group in York is also exploring the genetics of iridoid biosynthesis in catnip related to nepetalactone (Lichman, et al., 2020). Meanwhile, researchers at the Mint Genome Project in the United States are studying the evolution of specialized metabolite biosynthetic pathways in the broader mint family of Lamiaceae (The Mint Genome Project, 2022). Collaborative efforts between Dr Lichman and researchers at the University of California explored how catnip enzyme could help make high-value compounds, exploring one-pot, cell-free enzymatic synthesis of nepetalactol starting from the readily available geraniol (Bat-Erdene, et al., 2021). This research is currently at an early stage.

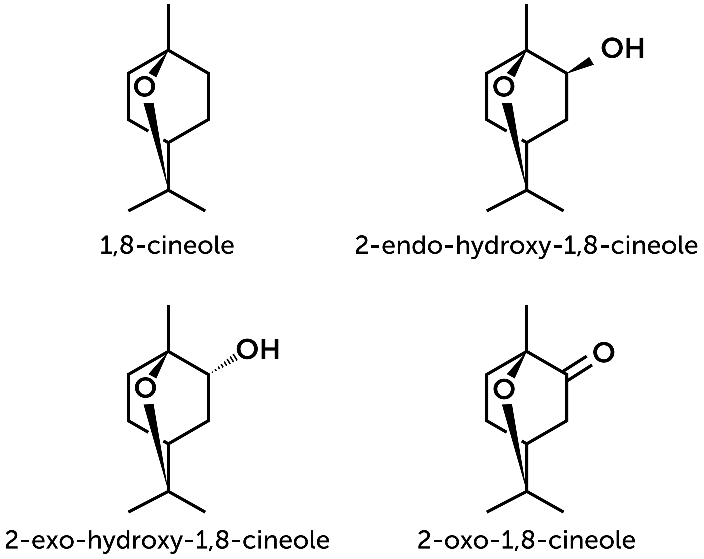
A US company, Entomol, is using catnip extract nepetalactone for an insect repellent, which has been shown by researchers at Iowa State University to be as effective as DEET for cockroaches and mosquitoes. These discoveries resulted in three patents on those natural terpenes as repellents, and the rights were licensed by Entomol. The group has tested more than 300 closely related chemicals derived from the best of the natural repellents like citronellol, menthol and thymol (Wisconsin University, 2018) (Coates, 2007). Indeed, Du Pont has patents for catnip-derived insect repellent and a catnip variety with high oil yield. Similarly, Professor Florence Dunkel of Montana State University has patented natural mosquito-repellent compounds, also from mint plants, with two patents sub-licensed to biotech firms (Montana State University, 2022).

Crop: mint (Menth sp.), rosemary (*Rosmarinus officinalis*), thyme (*Thymus vulgaris*), and sage (*Salvia officinalis*) are established UK herb crops grown for culinary purposes. For example, Herbs Unlimited in Yorkshire is a wholesale supplier with 100 acres of field crops, including 10 acres of polytunnels, and supplying mint, rosemary, sage, thyme amongst many other herbs and edible flowers.

Example 2. Biotransformation of 1,8-cineole, Universidad de la Republica Uruguay

Another compound of interest is 1,8 cineole, which is the main component of eucalyptus essential oil, but is also found in rosemary, sage, lavender and other aromatic mint family herbs. This monoterpene is easily obtained from distillation. The oxidized derivatives of 1,8-cineole have been reported to represent a set of compounds of high potential as chiral synthons for organic chemistry, and several oxygenated terpenes have shown wide utility in the scent industry as fragrances. To this end, biotransformation has been explored in some early-stage research. A *Rhodococcus sp*. strain capable of metabolizing 1,8-cineole was isolated from soil beneath *Eucalyptus sp*. Three compounds were obtained from the biotransformation of 1,8-cineole with this strain and they were identified as 2-endo-hydroxy-1,8-cineole, 2-exo-hydroxy-1,8-cineole and 2-oxo-1,8-cineole. The biotransformation conditions were optimized to reach 98% bioconversion with this strain (Rodriguez, et al., 2006).

Figure 5.6. Chemical structure of 1,8-cineole and the biotransformation products



Rhodococcus sp. (this work)	2-oxo-1,8-cineole 2-endo-hydroxy-1,8-cineole 2-exo-hydroxy-1,8-cineole	17 56 25 **Total: 98**

(Rodriguez, et al., 2006)

Example 3. Fermentation of Lavandin from Lavender, INRA UMR 1163, France

A 2015 study by Marine Bou and colleagues at the Biotechnology Research Institute INRA UMR, France, explored the potential industrial biotechnology applications for lavandin from lavender (Lesage-Meesen, et al., 2015). Lavandin essential oils, usually produced by steam distillation from the flowering stems, is characterized by the presence of terpenes (e.g. linalool and linalyl acetate) and terpenoids (e.g. 1,8-cineole). The researchers explored the possible uses of lavender and lavandin straws in fermentative or enzymatic processes involving various microorganisms, especially filamentous fungi, for the production of antimicrobials, antioxidants and other bioproducts with pharmaceutical and cosmetic activities. This appears to be at an early stage of research.

Crop: The UK has a strong tradition of growing lavender, with Yardley, Potter & Moore and other historic brands, and English lavender is still highly regarded as a sign of quality. Norfolk Lavender is one company which continues the traditional lavender growing industry with 100 acres and an oil distillery, and Mayfield Lavender is the largest organic lavender farm in the UK, based in a traditional Victorian growing area in Surrey.

Example 4. Biotransformation of eugenol, CSIR-Indian Institute of Integrative Medicine

Eugenol, found in various plants such as cloves and bay leaves, is used in perfumeries, flavourings and essential oils as well as medicines, plastics and rubber products. There are claims of eugenol possessing anaesthetic properties, indeed cloves were traditionally used for toothache, and several manufacturers including 3M use eugenol zinc oxide in dental cement.

Eugenol is biosynthesised from L-tyrosine and is also produced synthetically. The CSIR- Indian Institute of Integrative Medicine has developed a biotransformation pathway for eugenol by an endophytic fungus Daldinia sp. IIIMF4010 isolated from *Rosmarinus officinalis*. The biotransformation reaction of eugenol resulted in the production of eugenol-ß-D-glucopyranoside (6.2%) and vanillin (21.8%) (Lone, et al., 2022).

Example 5. Raspberry ketone, University of Kent

Raspberry ketone is a high-value (around £20,000/kg) fine chemical farmed from raspberry (*Rubeus rubrum*) fruit. Using a natural feedstock of L-tyrosine, Dr Simon Moore's group at the University of Kent has optimised a cell-free synthetic raspberry ketone biosynthetic pathway. They have refactored the raspberry ketone pathway from a low level of productivity (0.2 mg/L), to achieve a 65-fold (12.9 mg/L) improvement in production (Moore, et al., 2021). L-tyrosine can be derived from D-glucose, which is a target of the UK sugarbeet biorefinery model presented by the Biochemical Engineering Department of University College London (Cardenas-Fernandez, et al., 2017). The UK grows over 8 million tonnes of sugarbeet a year, and pulp is a major residue containing D-glucose.

5.4.3 Biotransformation of fatty acid bioconjugates

Description	Conjugated vegetable oils are attractive bioresources for use in paints, inks, coatings and plastics as well as ingredients for functional foods. In particular, conjugated linoleic acid (CLA) is marketed as a dietary supplement. Primarily an animal-derived compound, CLA can also be generated from plant-derived linoleic acid (LA) and alpha linoleic acid (ALA) by gut microbes. LA or ALA can be found in wheatgerm, blackcurrant seed oil, echium, linseed and safflower seeds. Also, studies have been conducted on production of CLA by *Bifidobacterium* in fermented milk supplemented with barley-derived prebiotic ß-glucan.
Market	The global CLA market size is predicted to reach $70 million in 2028, growing at a CAGR of 6.1% from 2022 to 2028 (LP Information, 2022).
Opportunity	▪ There exists a buoyant CLA market within the food, pharmaceuticals and healthcare, dietary supplement and feed industries. ▪ Rapid development and research interest in finding biocatalysis solutions. ▪ Synergies with probiotic markets. ▪ Drive for plant-based alternatives to dairy sources.
Risks	▪ Competition against established alkaline isomerization. ▪ Major established players already include Eastman, BASF (Cognis), Aiko Natural Products and Dalian Innobioactives (LP Information, 2022).

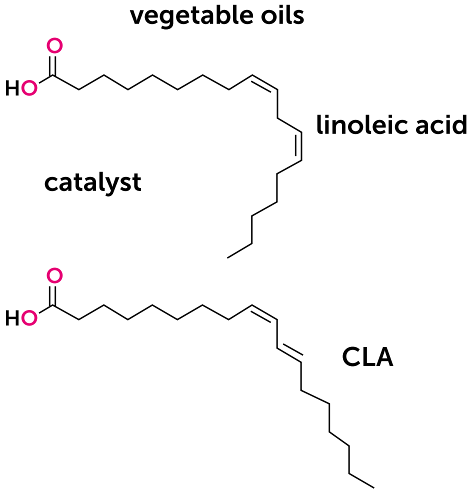
Enzymatic production of conjugated linoleic acid

Conjugated linoleic acid (CLA) is derived from linoleic acid (LA). LA occurs at high levels in various UK native plants and crops, including Alexanders (horse parsley), safflower and wheatgerm.

The high isomer selectivity of CLA, and elucidated isolation and purification processes, means that microbial CLA has become a research hotspot. In nature, enzymatic conjugation occurs by ruminant bacteria. For example *Megasphaera elsdenii* and *Butyrivibrio fibrisolvens* have been used frequently as a model for c9,t11 CLA production (Philippaerts, et al., 2011). In addition, human intestinal bacteria can convert LA to CLA and many food-grade bacteria such as *Lactobacillus* and *Bifidobacterium* have been reported to possess CLA-production ability. Particularly, *Bifidobacterium* has a high bio-conversion rate and enhanced CLA production and is considered one of the best and most promising CLA producers among microorganisms (Mei, et al., 2022).

Meanwhile, researchers at Nanjing Tech University in China have collaborated with Imperial College London to investigate the potential of biomanufacturing conjugated fatty acids using the oleaginous yeast *Yarrowia lipolytica* chassis, due to its high intrinsic lipogenesis ability (Wang, et al., 2022).

There is considerable interspecies variation, and thus each strain has its own specificity and productivity. It has been found that using washed cells circumvents the inhibitory effect of LA on cell growth, leading to higher CLA yields. Furthermore, immobilized *Lactobacillus reuteri* produced CLAs during five repeated cycles, with modest productivity of CLAs under optimal conditions of 0.003 g/l/minute. This value was 5.5 times higher than that obtained using free washed cells (Lee, et al., 2008). The challenges of efficient conversion makes enzymatic approaches challenging when competing with established alkaline isomerization of LA. Dr An Philippaerts et al. suggested that CLA levels in milk and dairy products can easily be raised by manipulating the diet of ruminants and by manufacturing fermented dairy products or cheese with starter cultures that have a high CLA-producing potential (Philippaerts, et al., 2011).



Example. ß-glucan prebiotic for conjugated linoleic acid, University of Tabriz, Iran

Beta glucan from oats has been used as a prebiotic to enhance CLA production in fermented dairy products. Researchers at the University of Tabriz, Iran, used *Bifidobacterium animalis* subspecies *Lactis* BB12 to test CLA production with and without barley-derived ß-glucan. C9, t11 CLA was 28% higher and c12, t10 CLA was 39% higher in the fermented organic milk than in the samples without ß-glucan (Moghadam, et al., 2022).

5.4.4 Biotransformation of glucosinolates

Description	Isothiocyanates are toxic to the plants that produce them. Because of this, they are stored in the form of larger molecules, glucosinolates, and as such are inactive. When the plant is attacked by a pest or microbe, it releases the enzyme myrosinase, which releases the isothiocyanate to deter the offending organism. Glucosinolates are typically found in brassicas, such as brussels sprout, broccoli, cabbage and mustard, among others. Research studies examining the health advantages of glucosinolates have found a link between high consumption of brassica vegetables and low cancer and heart attack risks. Rising awareness of the health advantages of glucosinolates has boosted product demand. Therefore, glucosinolates are of interest to health markets, pharmaceutical, food and cosmetics, as well as crop protection and insect repellent companies.
Market	In May 2021, Native Extracts, a key company in the glucosinolates space, launched a nutraceutical division to undertake research on the benefits of phytonutrients. Growing research activity has positively influenced the industry outlook for these products. ▪ The global glucosinolates market reached \$160 million in 2020 and is likely to record around 6.5% CAGR between 2021 and 2027 (Global Market Insights, 2021). ▪ The pharmaceuticals application segment of the brussels sprout glucosinolates market is anticipated to surpass a valuation of \$8.5 million by the end of 2027. ▪ In 2020, the food and beverages application segment was nearly \$13 million, and the cosmetics application segment held approximately 15% revenue share in the market in 2020.
Opportunity	▪ The trend towards regenerative agriculture and use of natural pest control methods in farming. ▪ Health trends, and growing fermented food (see Example 2 below) and supplements markets. ▪ Large quantities of brassica crop residues in the UK.
Risks	▪ Crowded Intellectual Property landscape. ▪ In poultry, glucosinolates cause nutritional disorders. Selection work in the 1980s and 1990s reduced the glucosinolate content five-fold in oil seed rape, in order to expand the market for oilseed rape oil cake residue left after oil extraction from the seed. FEDIOL, the EU vegetable oil and protein meal industry association, stipulates that members require their rapeseed suppliers to use certified seed of a variety with a glucosinolate level below 18mmol.

Example 1: Biofumigation for crop protection using glucosinolate derivatives

Biofumigation (a highly regulated sector under Plant Protection Product Regulations) is becoming increasingly popular as an alternative to synthetic agrichemicals. Natural compounds, mainly glucosinolates degradation products from brassica species, are used to prevent pests and microorganisms attacking crops. Researchers at the University of Massachusetts Amherst have investigated the use of plant material that, over the course of its degradation, releases glucosinolates that break down into nematotoxic isothiocyanates. It is possible that enzymes could be utilised to trigger degradation in a controlled release system to target pests and disease as needed in the field (Brennan, et al., 2020).

Example 2: Fermentation to enhance glucosinolates in broccoli puree

A collaboration between CSIRO, Australia, and Dongguan University of Technology, China, has explored lactic acid bacteria fermentation of broccoli puree, and found it to double the yield of the glucosinolate compound, sulforaphane, from 845 to 1617 µmol/kg dry matter, as well as increasing total polyphenol content by 85%, and ORAC antioxidant capacity by 70%. The researchers suggest that this sulforaphane-rich broccoli product can be used as a dietary supplement or potentially an ingredient in functional foods (XueCai, et al., 2019). Sulforaphane exhibits anticarcinogenic activity by induction of cell cycle arrest and apoptosis in various human cancer cells (Clarke, et al., 2008). Studies have also explored the therapeutic effects of sulforaphane in several pathologies impacted by hyperglycaemia that include damage to the brain, kidney, liver, heart and muscle (Wang, et al., 2016).

Table 5.4. Selected brassica glucosinolate-related patents for health and agronomic benefits

Number	Title	Assignee	Date
HEALTH			
DE102005033616A1	Production of brassica extracts with high anti-cancer sulforaphane content involves degradation of plant material in presence of myrosinase enzyme and glucosinolate	BIOPRO AG Biolog Products [Germany]	2005
FR2819376A1	New brassica plants having elevated levels of anticarcinogenic 4-methylsulfinylbutyl glucosinolates (4MSBG), or 3-methylsulfinylpropyl glucosinolates (3MSPG). Includes cabbage, broccoli, cauliflower, kale and brussels sprout	Plant Bioscience Ltd [UK]	1998
US2007033675A1 (B2)	Brassica plants with high levels of anticarcinogenic glucosinolates	Barten Piet [Netherlands]	2007
US2008312164A1	Isothiocyanates and glucosinolate compounds and anti-tumour compositions containing same	Rajski, Scott R. [US]; Mays, Jared Rae [US]	2008
CROP PROTECTION AND INSECT REPELLANT			
DE102006017831A1	Producing transgenic brassica plants with increased glucosinolate synthesis comprises causing overexpression of the gene coding for transcription factor MYB51 for Cytostatic; Virucide; Immunosuppressive; Insect repellent	University of Cologne [Germany]	2006
US2005055744A1 (B2)	Nucleic acids encoding glucosinolate biosynthesis enzymes and methods of their use	Carlos Quiros, Genyi Li	***2005***
US2010317518A1 (B2)	Meadowfoam-based bioherbicide products [particular aspects provide methods for converting glucosinolate in a glucosinolate-containing plant material to glucosinolate breakdown products	Stevens, Jan F. [US]	2010
WO2009087179A2	Amendment controlling soil-born pests and pathogens, use and using method of such amendment [ingredient assembly containing at least a glucosinolate and at least an enzyme selected in the group consisting of: glucosidasic enzymes and thioglusidasic enzymes; and to include an emulsified or dissolved liquid proteinic hydrolyzed agent]	Cerearltoscana SpA [Italy]	2008
CA3155397A1	Methods for weed growth control [the thiocyanate preparation or isothiocyanate preparation can be provided in the form of a glucosinolate hydrolysate]	MustGrow Biologics Corp [Canada]	2019

6. Conclusions and Discussion

This review has highlighted both commercialised and emerging opportunities where biotechnology can enable value creation from UK-grown crops.

It may seem like an unlikely time to focus on land use to grow biorenewables, with the current issues around food security and ecosystem losses, but there are several reasons why this is exactly the right time to increase biorenewable utilisation, so long as it is executed in the optimal locations and in the optimal way.

1. Our current food-cropping system is in significant difficulty. Challenges include deteriorated soil, increased incidence of pests and weeds with fewer agrichemical options to tackle them, and damaged ecosystem services, such as loss of pest-predators and pollinators and dysfunctional nutrient, carbon and water cycles. Many of the problems have come about from offering farmers incentives to grow in vast monocultures of limited crop types, and it is now realised that much of this can be remedied by increased diversity of farming rotations, for example through innovations in:

   - Break crops: a crop grown instead of a cereal crop to break up continuous cereal cropping and help manage pest and disease build-up. Oil seed rape was promoted on UK arable farms partly for this purpose, but has become such a widespread mono crop in itself that it has developed its own issues;
   - Cover and catch crops: grown between the cycles of main food crops to protect the soil, hold nutrients and prevent nitrogen losses, and to maximise productivity of the system. Cover crops are generally overwinter crops; catch crops are generally fast-growing plants that are grown between successive crops such as between spring harvest and autumn harvest;
   - Intercropping: multiple crops grown simultaneously on the same field to maximise productivity and, often, deliver mutual benefits such as nitrogen-fixing or disease or weed control;
   - Remedial perennial crops: grown for multiple years to help restore soil, remove pollutants, manage flood zones and provide a riparian buffer for agricultural run-off.

   These innovative cropping systems are being trialled and rapidly developed on UK farms, and new crops and markets are emerging. Many of these niche and emerging crops have higher value components such as specialist oils, antioxidants, flavourants and colourants which could be harnessed, and in turn, markets for those components can help to stimulate uptake of these beneficial, regenerative crops. There are many more semi-wild and native UK plants which could have potential in this area, as demonstrated by the development of the Ahiflower™ by Natures Crop. Wetland plants being explored for paludiculture (wetland and peatland agriculture), along with traditional medicinal and edible plants and fungi, are strong contenders for further exploration and development, as shown in the Appendix.

2. We urgently need to move away from synthetic fertilizers, fossil-derived chemicals and materials and transport-heavy global supply chains as far as possible. Well-managed, strategic, locally grown resources can deliver this. Large corporations have recognised this requirement, along with the benefits for quality and security of supply, and are setting high targets to diminish fossil fuel reliance. Many of these natural ingredients being sought after are of higher value.

As an alternative to growing crops in the ground, production methods of vertical farming and fermentation or cell-free synthesis certainly have a role to play in helping solve the land-use pressures we face. However, the full life cycle and technoeconomic impact of these approaches on resources across the supply chain must be factored in, and to the high levels of artificial inputs and environmental controls that they require may pose challenges for scaling up production. In addition, the low concentrations as well as challenging extraction and purification steps seen for many bioreactor systems can make processing resource-intensive and expensive. Therefore, these factory forms of production are unlikely to meet all market needs for scale and pricing so conventional crop-based production will continue to play an important part for many products. The options must be considered case by case with full lifecycle analysis considerations. Examples in this study have been seen where multiple production approaches are taken for different specifications of the same target product, to suit multiple markets and needs, suggesting continued co-existence of approaches in the foreseeable future.

Another route to low-impact higher value biorenewables is via field residues, crop off-cuts and rejects from current crops, particularly for vegetables, fruits, herbs and forestry. Antioxidants, functional proteins, flavours, colourants and dyes are all potential targets from established UK crops, with various enterprises already established in these areas, such as B-hive and Keracol. In biomass crops, work is under way to extract higher value compounds prior to biomass processing to enhance the economic value of the crop, as part of the biorefinery process. For instance, the ultimate aim for many growers of hemp is a UK-suited 'dual crop' where the whole plant is utilised: seed for food and stalks for industry uses (University of York, Centre for Novel Agricultural Products, 2022).

Ideally, all UK main crop materials that cannot be used on-farm would go through a biorefinery-type sequence of whole plant utilisation, whereby food and feed production takes precedence and residues or non-food resources undergo a multi-stage set of processes to extract valuable components for biorenewable applications where appropriate, with any eventual residues then being use for composting or anaerobic digestion. However, it is important to consider the existing role that field residues play in protecting and regenerating the soil. This must be considered. to prevent the development of a detrimentally extractive system whereby beneficial field residues are removed and then need to be replaced with more costly, resource-intense inputs.

The commercial case studies seen from Europe and North America in Section 2.7 demonstrate how co-operatives with public–private investment can lead to successful commercialisation of added-value products from crops. It seems that the UK is lacking this farmer–supply chain collaborative model and investment in most areas. One excellent exception is in specialist oil-seed breeding, growing and processing, where the UK is a leading player with international reach in some areas (e.g. Ahiflower™, hempseed, echium and meadowfoam). Meanwhile, expansion of biomass energy crops has stagnated in the UK and needs to increase 70-fold to meet government net zero targets for 2050 (Centre for Ecology and Hydrology, 2022). Experts interviewed for this review pointed to low confidence among growers and a need for greater knowledge on destination markets. The development of concerted cross-supply chain efforts to increase investment in, and expansion of, higher value crop products and markets could help drive these targets forwards.

The UK has significant biotechnology research expertise and capabilities related to deriving higher value from crops, and the current industry landscape offers multiple opportunities to harness this resource. Biotechnology can play a role at multiple points in the supply chain:

- **Breeding** can be used to modify the profiles of higher value compounds in crops, as well as increase the overall production to improve commercial viability. The emerging contributions of breeding to enhance high value components will be further unlocked by the current review in legislation of genome editing in the Genetic Technology (Precision Breeding) Bill, although many international companies are likely to avoid this approach as it does not align with rules in all other countries.
- The burgeoning market for crop **biostimulants** is a particularly exciting area of development and innovation, offering biotechnology-related opportunities for production of microbes as soil treatments. Regulations are likely to emerge for this sector, which will help build trust among end-users. There is a high requirement for fundamental research in this area, as soil biology and its relationship with crop health are highly complex and still poorly understood.
- **Enzyme assisted extraction** is already employed in some industries to extract juice or other components from plant materials. It seems to have attracted little attention within UK research but could offer interesting solutions to improve extraction efficiency for high value components such as colourants, flavours or antioxidants.
- **Biotransformation** of plant extracts into higher value compounds was the final area investigated in this review. This has been adopted for pharmaceuticals such as opium poppy alkaloids, and for food ingredients such as low-calorie sweeteners from stevia. In the latter case, the sweetener compounds are being produced using three approaches: full fermentation; via post-harvest biotransformation of crop extracts; and directly from crops without modifications. This example demonstrates the successful co-existence of different production approaches where there is sufficient volume and variety of market demand to warrant it.

Despite the strong biotechnology capability in the UK some experts interviewed for this review felt that more investment and technical expertise in extraction and processing for high value products was needed to transform innovation into commercially viable enterprises. This is a critical time for biorenewables, with synergies between the agricultural transition and industry's recognition of its own imperative role in greenhouse gas reduction. Commercialisation of higher value products is a vital piece of the puzzle to unlock development of multiple markets that can support the transition to Net Zero and towards regenerative, high diversity farming, thus supporting governments objectives, so long as commercialisation is executed with sustainable systems principles: fair share, with social and ecological benefits derived from the economic returns.

7. Appendix: Summary table of crops and their uses

The following tables summarise a long-list gathered and goes beyond the specific scope of this review. It highlights the uses identified during the research for various UK, and potentially UK-suited, plants and fungi, and does not represent a comprehensive review of all uses. This includes some which are less suited to the UK climate currently but have potential due to breeding efforts or climate change. In addition, some uses noted here are not particularly high value. It also includes some historic projects and not all the uses identified are economically viable. For further commentary and references please contact the author for further details. Latin or alternative common names have been provided in brackets where there might be ambiguity.

7.1 Native, semi-wild and wild plants

Plant	FOOD/FEED	AGRICULTURAL	BOARD, COMPOSITES, BUILDING AND INSULATION MATERIALS	CORDAGE AND SACKING	PERSONAL CARE AND COSMETICS	DYES, INKS AND COLOURANTS	ENERGY AND FUELS	INDUSTRIAL RAW MATERIALS	LUBRICANTS AND WAXES	PAINTS, COATINGS AND VARNISHES	PAPER AND PULP, PACKAGING	MEDICAL, PHARMACEUTICAL PRODUCTS AND NUTRACEUTICALS	PLASTICS AND POLYMERS	RESINS AND ADHESIVES	SOAPS, DETERGENTS, SURFACTANTS, SOLVENTS AND EMULSIFIERS	TEXTILES AND FURNITURE
Ahiflower™ (bred from Buglossoides arvensis)	✓											✓				
Alexanders (Smyrnium olusatrum, Horse parsley)	✓				✓											
Amaranthus	✓				✓							✓				
Annual wormwood (Artemisia annua)	✓	✓			✓							✓				
Bilberry	✓											✓				
Borage	✓				✓							✓				
Bracken																
Bulrush (Typha latifolia)	✓		✓								✓					
Calendula (pot marigold)					✓				✓	✓			✓		✓	
Camelina (Camelina sativa, Gold of pleasure)	✓											✓			✓	
Canary grass (Phalaris canariensis)	✓															
Caraway	✓	✓			✓							✓				
Castor (spurge family)	✓							✓	✓				✓		✓	
Celandine, Greater (Chelidonium majus)												✓				
Chamomile (Matricaria recutita)												✓				
Chia (Salvia hispanica)	✓				✓							✓				
Chicory	✓							✓				✓	✓		✓	

Plant	FOOD/FEED	AGRICULTURAL	BOARD, COMPOSITES, BUILDING AND INSULATION MATERIALS	CORDAGE AND SACKING	PERSONAL CARE AND COSMETICS	DYES, INKS AND COLOURANTS	ENERGY AND FUELS	INDUSTRIAL RAW MATERIALS	LUBRICANTS AND WAXES	PAINTS, COATINGS AND VARNISHES	PAPER AND PULP, PACKAGING	MEDICAL, PHARMACEUTICAL PRODUCTS AND NUTRACEUTICALS	PLASTICS AND POLYMERS	RESINS AND ADHESIVES	SOAPS, DETERGENTS, SURFACTANTS, SOLVENTS AND EMULSIFIERS	TEXTILES AND FURNITURE
Cordgrasses (Spartina spp.)							✓									
Coriander	✓				✓				✓				✓		✓	
Cotton			✓													
Crambe (Crambe abysinnica -Abyssinian mustard)								✓	✓				✓			
Cuphea	✓											✓			✓	
Daffodils												✓				
Echium (Echium plantagineum)					✓							✓				
Elder	✓											✓				
Evening primrose	✓				✓							✓				
Feverfew (Pyrethrum parthenium)		✓										✓				
Field scabious												✓				
Flax/Linseed	✓		✓		✓		✓		✓	✓	✓	✓		✓		✓
Gorse (Ulex spp)	✓					✓			~			✓			✓	
Hawthorn	✓											✓				
Heather (Calluna vulgaris)												✓				
Hemp (Industrial)	✓		✓	✓			✓				✓				✓	✓
Honesty (Lunaria)									✓			✓	✓			
Hop (Humulus lupulus)	✓											✓				
Horsetail		✓			✓								✓			
Jerusalem artichoke (Helianthus tuberosus)	✓											✓			✓	
Jojoba					✓											
Kenaf			✓	✓				✓			✓					
Lavender	✓				✓	✓						✓				
Lupin (Lupinus albus)	✓															
Madder (Rubia tinctorum)						✓										
Marsh mallow (Althaea officinalis)	✓											✓				
Meadowfoam (Limnanthes alba)									✓			✓	✓		✓	
Meadowsweet (Filipendula ulmaria)												✓				

Plant	FOOD/FEED	AGRICULTURAL	BOARD, COMPOSITES, BUILDING AND INSULATION MATERIALS	CORDAGE AND SACKING	PERSONAL CARE AND COSMETICS	DYES, INKS AND COLOURANTS	ENERGY AND FUELS	INDUSTRIAL RAW MATERIALS	LUBRICANTS AND WAXES	PAINTS, COATINGS AND VARNISHES	PAPER AND PULP, PACKAGING	MEDICAL, PHARMACEUTICAL PRODUCTS AND NUTRACEUTICALS	PLASTICS AND POLYMERS	RESINS AND ADHESIVES	SOAPS, DETERGENTS, SURFACTANTS, SOLVENTS AND EMULSIFIERS	TEXTILES AND FURNITURE
Millet	✓															
Miscanthus			✓				✓				✓					
Nettle				✓												✓
Nightshade																
Opium Poppy												✓			✓	
Petty Spurge (Euphorbia peplus)												✓				
Psillium (Plantago spp)	✓											✓				
Pyrethrum		✓										✓				
Quinoa (Chenopodium quinoa)	✓				✓							✓			✓	
Rain daisy									✓	✓				✓		
Reed, Common			✓				✓				✓					
Rosemary	✓				✓							✓				
Rye grass	✓				✓							✓	✓		✓	
Sage (Salvia officinalis)	✓				✓							✓				
Safflower (Carthamus tinctorus)	✓					✓						✓				
Sainfoin	✓	✓														
Sea Buckthorn	✓				✓											
Soya	✓		✓	✓						✓			✓	✓		✓
Sphagnum	✓	✓			✓							✓				
Stevia	✓															
St John's Wort (Hypericum perforatum)												✓				
Stokes aster (Stokesia laevis)			✓							✓			✓	✓		
Sunflower	✓		✓				✓	✓								
Sweetcorn/ Maize	✓				✓								✓			
Thyme	✓				✓											
Valerian			✓									✓				
Weld (Reseda luteola)						✓										
Woad (Isatis tinctoria)						✓										
Yellow Horned-Poppy (Glaucium flavum)												✓				

Descriptions for the native, semi-wild and wild plants described above:

Name	Description
Ahiflower ™ (derived from Buglossoides arvensis)	Bred from the weed, gromwell or wheat thief, Ahiflower is from the borage family. high Omega 3 FAs, particularly Stearidonic Acid (SDA) (highest content of any plant), and an excellent source of omega-6 Gamma Linolenic Acid (GLA). Natures Crops International, which has spent over 15 years developing the plant
Alexanders (Smyrnium olusatrum, Horse parsley)	Edible plant, native, mainly coastal. Biennial, leaves first year for salad, 2nd year oilseed. High petroselenic acid. Among fatty acids, petroselinic acid was the most abundant in fruits (67.5%), while linoleic acid (32.8–57.7%) was the main compound in the other parts. The levels of ascorbic acid detected and the nutritional profile exhibited partially supported the traditional use of Alexanders as an antiscorbutic remedy and suggest its re-acceptance as a vegetable would be worthwhile.
Amaranthus	Mostly food related uses currently, but Amaranthus sp. is now known to be the plant with the highest concentration of squalane in vegetal world, which can replace shark derived squalene. An extensive study conducted on 104 genotypes of 30 species of Amaranthus revealed concentrations of squalene between 10.4 and 73.0g/kg amaranth oil. However, Several microorganisms, such as bacteria, algae, and yeasts, synthesize and store squalene. It is also manufactured from olives.
Annual wormwood (Artemisia annua)	Specialist malaria crop - grow in malaria regions
Bilberry	Wild uplands plant, with high catechin and epicatechin content
Borage	Indigenous. high GLA oil crop, dietary, cosmetic and pharma
Bracken	The UK's most common fern and grows in dense stands on heathland, moorland, hillsides and in woodland.
Bulrush (Typha latifolia)	Wetland Reed, also known as cattail, reedmace, can be very vigorous. Being cultivated in Norfolk as part of Great Fen Project
Calendula (pot marigold)	A hardy biennial in temperate Europe, 60% calendic acid for paint, cosmetics, varnish, nylon. Historically been used for a host of different ailments, mainly those affecting the skin such as in the healing of wounds. The extreme reactivity of calendic acid makes Calendula oil interesting for several industrial applications but at the same time causes difficulties in processes related to extraction and refinement. Bioactive to treat eye disorders.
Camelina (Camelina sativa, Gold of pleasure)	Mediterranean plant, also known as false flax, giving Omega FA oil with CV benefits
Canary grass (Phalaris canariensis)	annual grass widely grown commercially in various parts of the world, including the UK, almost exclusively for the use of the seed for feeding ornamental birds, for hay and forage for animal feed and as an ornamental grass.
Caraway	Biennial of carrot family, growing in Western Asia, Europe, and North Africa
Castor (spurge family)	Castor is an ancient crop but its production now has been limited mainly to India, China and Brazil
Celandine, Greater (Chelidonium majus)	Native member of poppy family, a perennial, (not closely related to lesser celandine). When damaged the plant exudes a yellow/orange latex, which contains proteolytic enzymes and inhibitors. A toxic plant, containing high levels of isoquinoline alkaloids, mainly coptisine, and it was used in traditional medicine and Bayer's OTC drug "Iberogast"
Chamomile (Matricaria recutita)	Native annual plant of the composite family Asteraceae. Flowers contain many terpenoids and flavonoids, including Chamazulene and bisabolol are very unstable and are best preserved in an alcoholic tincture. The essential oil of Roman chamomile contains less chamazulene and is mainly constituted from esters of angelic acid and tiglic acid.

Name	Description
Chia (Salvia hispanica)	Native to central and southern Mexico and Guatemala.[2] It is considered a pseudocereal, cultivated for its edible, hydrophilic chia seed. 60% Omega-3 Alpha Linolenic Acid (ALA) and has an excellent proportion of Omega-3 to Omega-6.
Chicory	Sunflower family and well suited to Western Europe. High inulin to produce HMF platform chemical, plus food benefits. Big breeding program in ILVO Belgium, major grower. See also Jerusalem artichoke.
Cordgrasses (Spartina spp.)	Frequently found in coastal salt marshes, native to S Europe.
Coriander	Mediterranean plant, fatty acids of seed oil for plastics lubricant, nylons and cosmetics.
Cotton	Cotton plants are of the genus Gossypium in the mallow family, native to tropical and subtropical regions around the world, including the Americas, Africa, Egypt and India.
Crambe (Crambe abysinnica -Abyssinian mustard)	High erucic acid industrial oilseed, non-brassica, native to a variety of habitats in Europe, Turkey, southwest and central Asia and eastern Africa. Erucic acid (22 : 1) is a major feedstock for the oleochemical industry for manufacturing plastics, nylon13-13 and high temperature lubricants. HEAR rapeseed is the main crop source.
Cuphea	Tropical/warm genus, seed oil with medium-chain triglycerides, particularly capric acid, lauric acid. LA used in soaps/detergents. CA used in diets.
Daffodils	Native plant, producing galantamine (also called galanthamine, marketed by Janssen as Reminyl) which was originally isolated from several plants, including daffodil bulbs, but is now also synthesized. Galantamine is a specific, competitive, and reversible acetylcholinesterase inhibitor.
Echium (Echium plantagineum)	Genus of approximately 70 species of the Borage family. native to North Africa, mainland Europe to Central Asia. De Wit product, NEWmega™ Echium Oil contains 11-15% of the important omega-3 Stearidonic Acid (SDA). SDA only exists in a few plant sources. Echium Oil is second richest source, only Ahiflower Oil (oil from the plant Buglossoides arvensis) is higher in SDA. Echium Oil also contains 26-33% omega-3 Alpha Linolenic Acid (ALA), and 10-13% GLA.used in pharma, nutra, skincare
Elder	Common native fast growing shrub. Seed oil has carotenoids, gamma tocopherol and alpha linolenic acid.
Evening primrose	Introduced into the UK in the 1600s and has since become naturalised on dry waste ground, roadside verges, sand dunes and railway cuttings. Mentioned by multiple interviews. High GLA content: De Wit product NEWmega™ Evening Primrose Oil contains 9-10% GLA
Feverfew (Pyrethrum parthenium)	Native, traditionally used for headaches. Contains pyrethrins, (used as insecticide from Pyrethrum)
Field scabious	Native found in waste ground, grasslands and roadsides on calcareous dry soils. Sold as part of grass/pasture mixes.
Flax/Linseed	Traditional crop: fibre crops and seed crop with high alpha-linolenic (Omega 3), phospholipids, mucilage. Dries rapidly. Machine oil, paints, varnishes, energy feedstock. Enzymes been used to extract polyphenols and proteins. Already established industrial uses - anything new?
Gorse (Ulex spp)	Native plants comprises about 20 species of thorny evergreen shrubs in the subfamily Faboideae of the pea family Fabaceae. Gorse flowers are edible and the plant is high in protein, 17%, and was used for livestock fodder. "just by active removal from marginal land, there's enough gorse protein to easily feed [Scotland's] population." Prof Wendy Russell, at the University of Aberdeen, 2022
Hawthorn	Trials for CVD
Heather (Calluna vulgaris)	Native found widely in Europe and Asia Minor on acidic soils
Hemp (Industrial)	Botanical class of Cannabis sativa cultivars grown specifically for industrial uses. Oilseed with optimal balance of omega-3, omega-6 and omega-9 essential fatty acids. Fibres and shiv from stalks.

Name	Description
Honesty (Lunaria)	Cottage garden brassica genus with papery oilseed pods. 30% of seed DM was fatty acids with 23% of this being oleic acid, 46% erucic acid and 20% nervonic acid. . Trials in England and Scotland. Biennial with annual cultivars under development (2003)
Hop (Humulus lupulus)	Native climbing plant used primarily as a bittering, flavouring, and stability agent in beer, but also with medical and antibacterial applications
Horsetail	Native 'living fossil' in the Equisetaceae family of plants. It's also called "bottle-brush" or "horse herb." The crude cell extracts of all Equisetum species tested contain mixed-linkage glucan : Xyloglucan endotransglucosylase (MXE) activity.[11] This is a novel enzyme and is not known to occur in any other plants.Can be problem weed, difficult to eradicate.
Jerusalem artichoke (Helianthus tuberosus)	Horticultural UK crop. Annual herb and a close relative of the sunflower, and is a native of North America. Tubers with high inulin, at 0.36–12.6 Mg/ha, inulin yield per ha is often higher in Jerusalem artichoke than in chicory.
Jojoba	Desert and semi-desert crop, frost sensitive, hand harvested seeds, grown for liquid wax in seeds
Kenaf	wild plant in most African countries south of the Sahara, grown in tropcs and subtropics. tall annual herbaceous woody tropical plant. Fibre crop, remediation,
Lavender	Traditional English crop, still grown for flavour and fragrance, personal care industry. Oil contains monoterpeneoids and sesquiterpeneoids. Of these linalool and linalyl acetate dominate, with moderate levels of lavandulyl acetate, terpinen-4-ol and lavandulol. 1,8-cineole and camphor
Lupin (Lupinus albus)	High protein feed, soya alternative for vegan plant protein.
Madder (Rubia tinctorum)	Trailing perennial from central Asia. Madder roots have been used as a red/pink/orange dye for over 5,000 years, traditional in Ireland, Madder seems to have been first grown more for medicinal use – noted in Norfolk in 1274 – than as a dye
Marsh mallow (Althaea officinalis)	A native, herbaceous perennial with high mucilage.
Meadowfoam (Limnanthes alba)	Herbaceous winter annual in wet soils. The seed oil has high erucic acid (eicosenoic acid) similar to OSR - 65% . Use as liquid wax ester, replaces whale oil and jojoba oil. Can convert to solid wax sulphur polymer used in rubber industry or as a lubricant or detergent.
Meadowsweet (Filipendula ulmaria)	Native wetland plant used as a flavouring for drinks but also as a herbal remedy for fever and headaches. Contains rutoside, spiraeoside, and isoquercitrin.
Millet	Grown as overwinter bird feed
Miscanthus	tropical and subtropical grasses
Nettle	Perennial plant containing unlignified fibres
Deadly Nightshade (Atropa belladonna)	Poisonous plant of the same Solanaceae family as potatoes and tomatoes. Perennial growing up to 2m tall. It prefers calcareous soils in open woodland, field margins and hedgerows, but has been planted extensively. Contains tropane alkaloid toxins, including atropine, scopolamine, and hyoscyamine, which cause delirium and hallucinations, and are also used as pharmaceutical anticholinergics.
Opium Poppy	Naturalized across much of Europe and Asia, cultivated for food seeds, pharmaceutical opium, and other alkaloids, primarily thebaine and oripavine to convert to drugs hydrocodone and oxycodone.
Petty Spurge (Euphorbia peplus)	Native plant, very common on arable and brownfield sites. Sap from the plant Euphorbia peplus has been used for many years in Australia as a folk remedy to treat a number of skin conditions.
Psillium (Plantago spp)	Several species of plantago genus. Seeds produce mucilage used for gastric conditions and food thickener. Can cause allergies.
Pyrethrum	Main growers Australia Tanzania and Tasmania. Pyrethrins as natural insecticide made from the dried flower heads

Name	Description
Quinoa (Chenopodium quinoa)	ancient crop from South and Central America, generally grown at high altitudes. Food, feed and in industrial products, such as textiles, paper and cosmetics.
Rain daisy	Endemic in Africa. can be annuals or woody-based, evergreen perennials
Reed, Common	Genus of four species of large perennial reed grasses found in wetlands
Rosemary	Shrub with fragrant, evergreen, needle-like leaves, native to the Mediterranean region but commonly grown in the UK. Enzyme assisted extraction of rosmarinic acid demonstrated (also found in sage, mint and basil)
Rye grass	The main grass grown in the UK for livestock grazing. 2017 BBSRC IBTI Club study: fructans from rye-grass to produce novel biosurfactants and polymers as part of a rye-grass biorefinery. However, fructans and derivatives are relatively low value.
Sage (Salvia officinalis)	perennial, evergreen subshrub, with woody stems native to the Mediterranean region, though it has been widely naturalized and grows readily in the UK. Enzyme assisted extraction of rosmarinic acid demonstrated (see also Rosemary)
Safflower (Carthamus tinctorus)	Egyptian crop, oilseed for dye, high oleic and linoleic acid, biotech insulin, protein
Sainfoin	High protein legume forage crop. Tannin-rich giving anthelmintic (anti-worm) properties for livestock.
Sea Buckthorn	Native spiny, thicket-forming shrub of sand dunes on the east coast of England and widely planted elsewhere, with orange berries used to create jellies or syrups.
Soya	A legume native to East Asia, widely grown for its bean with high oil and protein content. Known to contain high levels of phytoestrogens
Sphagnum	over 30 species of sphagnum moss native in the UK found in wet places like peat bogs, marshland, heath and moorland.
Stevia	Stevia rebaudiana, a tender perennial, is native to Brazil and Paraguay, prefering humid climates, and produces compounds that act as a sweetener. Cultivated in Japan, SE Asia, US, Nepal and India. Cannot survive frost, so grown in greenhouses in Europe.
St John's Wort (Hypericum perforatum)	Very common native plant, with many active substances, including hypericin and hyperforin, which are thought to affect mood. 150 different compounds have been identified. AS of 216 it was estimated that 30% to 50% of the constituents needed to be definitively described.
Stokes aster (Stokesia laevis)	Hardy perennial oilseed crop for epoxy acid, native of South Carolina and Georgia, but said to grow well in the UK. Grows best in fertile, moist but well-drained, light, acid soil in full sun. Will tolerate partial shade, prone to damp
Sunflower	An oilseed plant native to the USA and developed as a crop in Russia in the 1800s, now grown extensively globally for vegetable oil
Thyme	Aromatic perennial evergreen herbs in the mint family Lamiaceae, native to mediterranean region
Valerian	Perennial native to Europe and Asia and has been cultivated in North America.
Weld (Reseda luteola)	A native plant, its foliage is harvested to give a yellow dye. It was grown as a crop, mostly in the south and east of England
Woad (Isatis tinctoria)	Biennial or short-lived perennial, native to southern Europe. It was grown in the UK until the 18th century for indigo dye
Yellow Horned-Poppy (Glaucium flavum)	Native toxic plant in poppy family with a waxy bloom mainly on coastal shingle. Main alkaloid is glaucine with respiratory and sedative effects

7.2 Main crops

Plant	FOOD/FEED	AGRICULTURAL	BOARD, COMPOSITES, BUILDING AND INSULATION MATERIALS	CORDAGE AND SACKING	PERSONAL CARE AND COSMETICS	DYES, INKS AND COLOURANTS	ENERGY AND FUELS	INDUSTRIAL RAW MATERIALS	LUBRICANTS AND WAXES	PAINTS, COATINGS AND VARNISHES	PAPER AND PULP, PACKAGING	MEDICAL, PHARMACEUTICAL PRODUCTS AND NUTRACEUTICALS	PLASTICS AND POLYMERS	RESINS AND ADHESIVES	SOAPS, DETERGENTS, SURFACTANTS, SOLVENTS AND EMULSIFIERS	TEXTILES AND FURNITURE
Wheat	✓								✓							
Barley	✓								✓							
Oats	✓								✓							
Oil Seed Rape	✓	✓					✓	✓	✓			✓				
Potato (tuber and tops)	✓	✓	✓		✓					✓	✓	✓	✓	✓		
Carrot	✓				✓	✓						✓				
Beetroot	✓				✓	✓						✓				
Parsnip	✓															
Sugar beet	✓				✓					✓			✓		✓	✓
Onion	✓				✓							✓				
Garlic	✓															
Other Brassicas (broccoli, cabbage, etc)	✓											✓				
Legumes	✓															
Leeks	✓															
Tomatoes	✓															
Apples	✓				✓	✓						✓				
Pears	✓															
Soft Fruits	✓				✓	✓										

7.3 Forestry and Tree Species

Plant	FOOD/FEED	AGRICULTURAL	BOARD, COMPOSITES, BUILDING AND INSULATION MATERIALS	CORDAGE AND SACKING:	PERSONAL CARE AND COSMETICS	DYES, INKS AND COLOURANTS	ENERGY AND FUELS	INDUSTRIAL RAW MATERIALS	LUBRICANTS AND WAXES	PAINTS, COATINGS AND VARNISHES	PAPER AND PULP, PACKAGING	MEDICAL, PHARMACEUTICAL PRODUCTS AND NUTRACEUTICALS	PLASTICS AND POLYMERS	RESINS AND ADHESIVES	SOAPS, DETERGENTS, SURFACTANTS, SOLVENTS AND EMULSIFIERS	TEXTILES AND FURNITURE
Walnut	✓															
Horse Chestnut																
Hazelnut	✓															
Sweet Chestnut	✓															
Oak										✓						
Pine trees	✓	✓	✓		✓	✓				✓	✓	✓	✓	✓	✓	
Yew (Taxus baccata)												✓				
Poplar								✓								
Willow		✓					✓					✓				
Cherry, Bird (Prunus avium)										✓						

7.4 Fungi

Plant	FOOD/FEED	AGRICULTURAL	BOARD, COMPOSITES, BUILDING AND INSULATION MATERIALS	CORDAGE AND SACKING	PERSONAL CARE AND COSMETICS	DYES, INKS AND COLOURANTS	ENERGY AND FUELS	INDUSTRIAL RAW MATERIALS	LUBRICANTS AND WAXES	PAINTS, COATINGS AND VARNISHES	PAPER AND PULP, PACKAGING	MEDICAL, PHARMACEUTICAL PRODUCTS AND NUTRACEUTICALS	PLASTICS AND POLYMERS	RESINS AND ADHESIVES	SOAPS, DETERGENTS, SURFACTANTS, SOLVENTS AND EMULSIFIERS	TEXTILES AND FURNITURE
Arbuscular mycorrhizal fungi		✓														
Turkey Tail						✓						✓				
Reishi (Ganoderma lucidum) and Artist's Bracket (Ganoderma applanatum)	✓		✓								✓	✓				✓
Shiitake mushrooms	✓	✓										✓				
Psilocybe genus												✓				

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NOTE: — indicates same author as previous entry.

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