Circular Bioeconomy Opportunities
Valorising Agricultural Wastes and Co-Products

SEFARI Fellowship with Zero Waste Scotland

Final Report

Professor Derek Stewart, FRSC
Director of the Advanced Plant Growth Centre
The James Hutton Institute
Invergowrie, Dundee
DD2 5DA
Scotland UK
Derek.Stewart@hutton.ac.uk

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About this Report

The production of this report was funded by the Scottish Environment, Food and Agriculture Research Institutes (SEFARI) Gateway, as part of their fellowship scheme, which are bespoke opportunities co-constructed with key partners to deliver solutions to priority policy and practice needs. This report received technical support from Zero Waste Scotland. The report is the independent view of SEFARI, and the views expressed do not necessarily represent those of Zero Waste Scotland or Scottish Government.

Executive summary

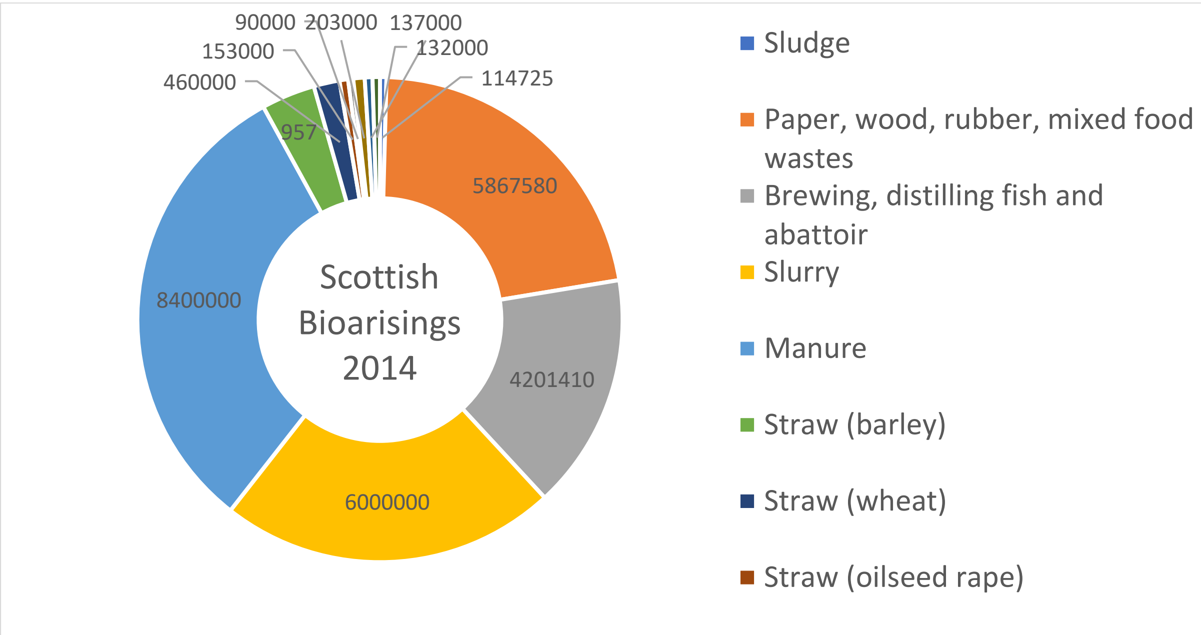
The landscape for society, industry and policy is ever evolving but the last few decades have seen a sharpening focus on the key issues of climate change and the sustainable use of resources. This has led to the development of policies and initiatives around factors mitigating and adapting to climate change and activities, particularly industrial, that deliver equivalent or enhanced outputs but with reduced greenhouse gas emissions. All of this highlights a shift away from fossil fuel-based feedstocks and the requirement for sustainable and renewable resources and processes. This shift to alternative resources means the feedstocks will need to come from land- and marine-based systems. These new feedstocks could be grown (or harvested) or, as discussed here, be bioarisings (wastes or co-products) from established rural economy processes such as crop and animal production.

Here we have utilised available Scottish bioarisings data for 2014 similar to that used in the Zero Waste Scotland (2017) report *Biorefining Potential for Scotland* to define the bioarisings available, or used in lower value uses, for "*conversion to higher value products*" (valorisation). This analysis examined bioarisings tonnage and location (local authority level) and, based on the macro- and micro-composition, identified viable opportunities for capturing value from these feedstocks at the (North East) Scottish level.

Findings

In 2014 there were 27Million Tonnes (MT) of bioarisings identified as being generated that had limited or no uses and values (Zero Waste Scotland, 2017). Within those bioarisings there are a large group of materials with established dedicated uses and valorisation routes such as sludges, paper wood wastes and brewing and distilling co products, and these did not form part of this study which focused on bioarisings from waste, by-products, agricultural residues and wastewater sludge.

Figure 1. The percentage of bioarisings identified as being generate that had limited or no uses in the Zero Waste Scotland (2017) report.



Further analysis of the agriculture-related bioarisings, identified that many held significant promise in terms of conversion to higher value products due to the quantities available and general and specific chemical composition.

Figure 2. The amount of bioarisings identified as being generate that had limited or no uses in the Zero Waste Scotland (2017) report.

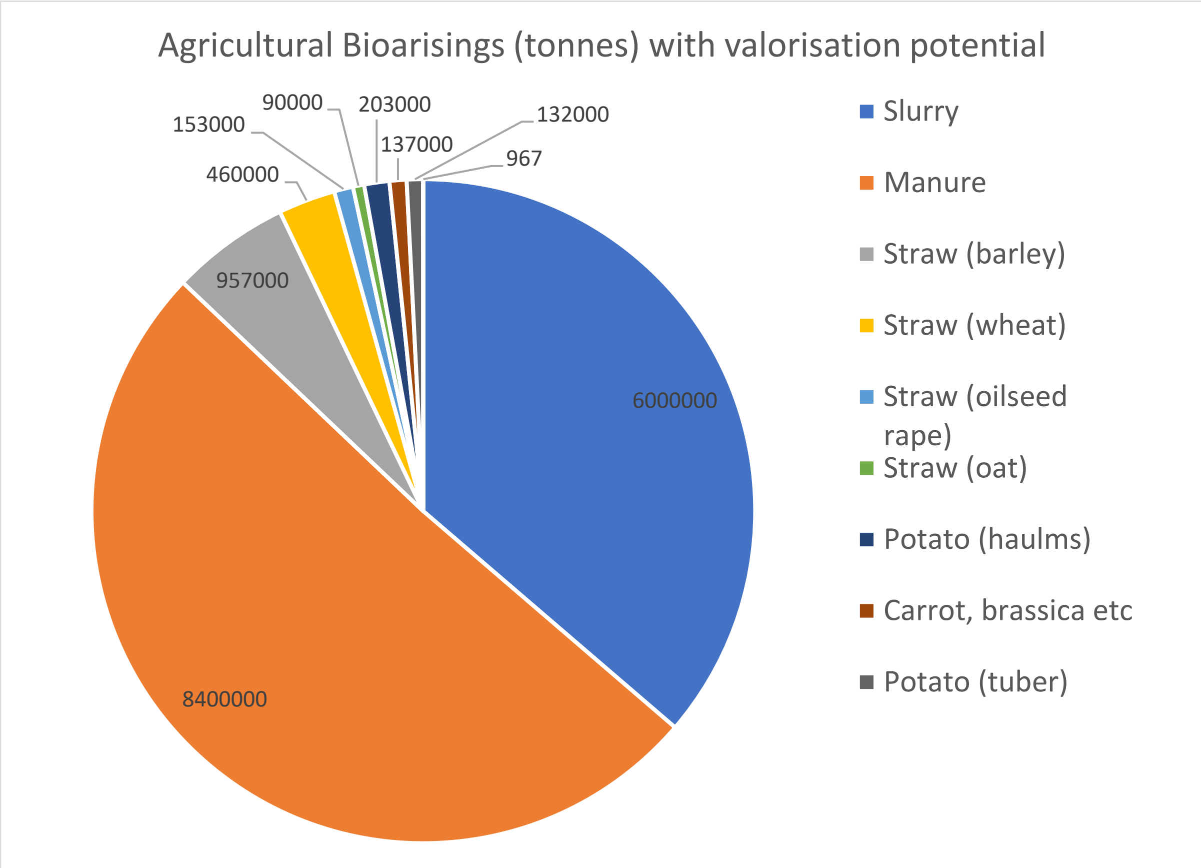


Table 1 below summarises these opportunities and the technologies needed to realise them. The opportunities to be realised are in both growing local and international markets representing significant value (£M/Bns).

It is clear that there are commonalities in the routes to valorisation identified in terms of the required technologies, and this offers up the potential of creating biorefining hubs to realise these and generate multiple opportunities from diverse feedstocks (both bioarisings and primary production).

Table 1. Summarises the bioarisings opportunities, their quantities, the valorised product and the technologies needed to realise them.

Bioarisings	**Quantity in 2014 (Tonnes)**	**Valorisation products**	**Process**
Slurry	6,000,000	i. Methane ii. Nutrient source (digestate: fertiliser)	Anaerobic digestor
Manure	8,400,000		

Cereal straw(barley)	1,500,000	i. Wax for cosmetics ii. Sugars, bioethanol iii. Methane	i. Milling, solvent (CO_2) extraction ii. Milling, fermentation iii. Anaerobic digestion
Straw (oilseed rape)	153,000	Horticultural substrate	Chopping, decortication
Potato (haulms)	203,000	Solanesol (cosmetics) Glycoalkaloids (IPM)	Milling, drying solvent (CO_2, ethanol) extraction
Carrot, brassica etc	137,000	i. Colourant (carrot) ii. Insect production feedstock	i. Milling, solvent (CO_2) extraction ii. Milling, maceration, heat treatments
Potato (tuber)	132,000	Energy and solvents	Bacterial fermentation
Soft fruit	967	i. Antioxidants ii. Colourants (food and non-food)	Milling, drying solvent (CO_2, ethanol) extraction

Conclusions

- Scotland has, based on 2014 data, significant levels of bioarisings from agricultural sources that currently have nil or low value uses.
- The cumulative total of agricultural-related bioarisings is 16.7Mt.
- These bioarisings can be used as feedstocks for a broad range of products across multiple sectors including, energy, food, cosmetics, pest and disease control, etc.
- There are significant opportunities for the valorisation of agricultural bioarisings into feedstocks, ingredients and products in global markets looking to deliver both economic returns ***and*** Net Zero emissions.
- For the majority of the opportunities identified they are replacing fossil fuel-based based products.

Recommendations

- The Zero Waste Scotland bioarisings data needs to be updated to finesse the validity and extent of the opportunities identified.
- The routes to valorisation have identified several common technologies. This suggests that establishing a biorefining hub and spokes, with the technologies distributed across the producer regions, could allow new entrants into the area without significant capital investment.
- A hub and spokes-based biorefining initiative, possibly via a cooperative governance, could have the more technically complex equipment at the hub and the simpler technologies (mills, drier etc) at the producer spokes. Indeed, the latter may already be there in another guise (grain driers etc).
- A support mechanism to kick start the shift to valorising bioarisings is needed to highlight the value and utility of this process.
- Engagement of primary producers is vital and the need to ensure value capture at that level is key to establishing biorefining as a viable and additional addition to the farming business portfolio.

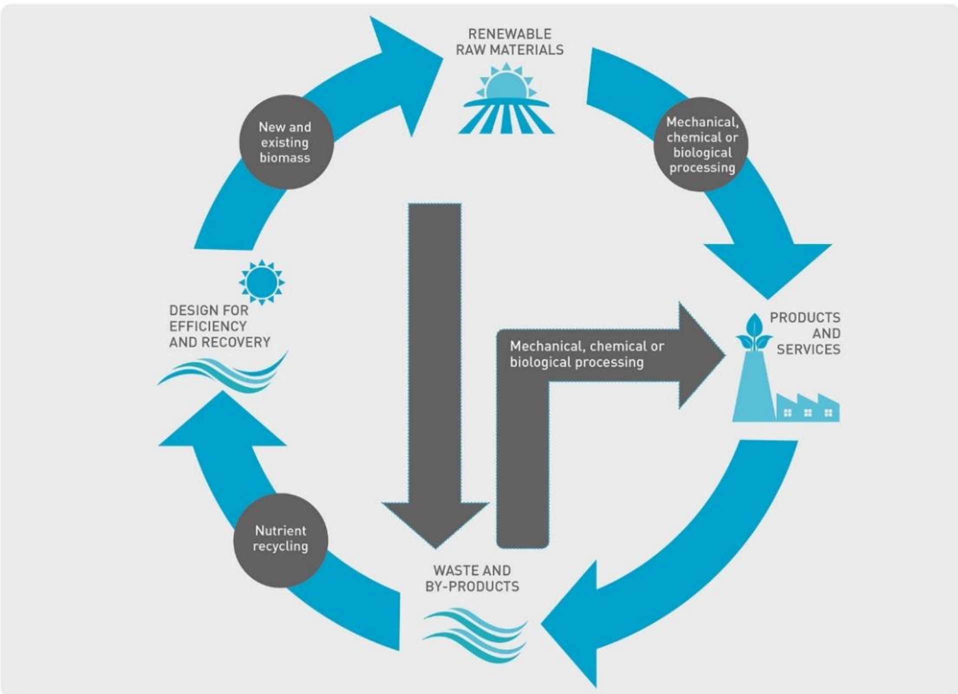
Introduction

The need to optimise resource use has many drivers. The relationship between fossil fuel use and climate change is generally well accepted and underpinned by a significant body of evidence. The fossil fuel economy is a linear one based upon mine-manufacture-use-dispose. It is abundantly clear from national and international bodies such as the Intergovernmental Panel on Climate Change[1] and Scottish Government (2021) that we need both adaptive and mitigative actions to address the impacts of climate change. This report considers one of these actions, the adoption of resource use optimisation and more specifically the adoption of a circular economy approach with a focus on materials in the North East of Scotland.

The support for this approach is growing apace internationally and Scotland has been viewed as a leader in the area. At its simplest level, a circular economy means keeping materials flowing in the economy at as high a value as possible for as long as possible. One of the global thought leaders in the area, the Ellen McArthur Foundation, defines the circular economy as being "based on the principles of designing out waste and pollution, keeping products and materials in use, and regenerating natural systems."[2]

Within this broad definition, there are subsectors and here we deal with agricultural bioarisings and, hence the circular bioeconomy, which we will define as **"a model of production and consumption, which involves sharing, leasing, reusing, repairing, refurbishing and recycling existing biomaterials and products as long as possible"**. This is best represented by the Zero Waste Scotland graphic (Figure 3).

Figure 3. Agricultural bioarisings and the circular bioeconomy[3]



1 https://www.ipcc.ch/
2 www.ellenmacarthurfoundation.org
3 https://www.zerowastescotland.org.uk/circular-economy/bioeconomy

Activity in this area has been significant and examples of this include the large EU Horizon 2020 initiative, the Bio-Based Industries Joint Undertaking, a €3.7 billion Public-Private Partnership between the European Union and the Bio-based Industries Consortium (BIC), now rebranded the Circular Bio-based Europe Joint Undertaking (CBE JU)[2] under Horizon Europe. This continues with the aim of contributing to a more resource-efficient and sustainable low-carbon economy, as well as increasing economic growth and employment, in particular in rural and coastal areas. A key objective is the development of a competitive bio-based industries sector based on advanced biorefineries[3] that source their biomass sustainably in Europe.

At the Scottish national level, aspects of waste valorisation have been delivered on by Zero Waste Scotland. Their Sector Study on Beer, Whisky and Fish (Zero Waste Scotland, 2014) estimated waste/co-product volumes (tonnes) and valorisation options such as protein extraction and conversion into feed for aquaculture and livestock, biofuel production and other more niche end uses. Following this, a broader ranging report, Biorefining Potential for Scotland, was developed looking at the wider Scottish bioarisings landscape and the potential for valorisation (Zero Waste Scotland, 2017). However, detail on the potential for valorisation was identified in a general sense and no attempt was made to rank these opportunities. The report identified the significant potential that the bioarisings represented, based on data for the year 2014, and highlighted that the available ~27MT were diverse in type, location and gross composition. With this in mind, a Scottish Environment, Food and Agriculture Research Institute (SEFARI) fellowship was established to consider the available data further for specific valorisation opportunities relating to agriculture and explore these in terms of viability, timeliness, durability and impacts beyond simple economic development.

Methodology

The Fellowship, supported by the partners below, was developed to explore new opportunities for the bioeconomy within the agricultural sector. More specifically, the report by Zero Waste Scotland (2018) identified the bioeconomy as being a major opportunity for Scotland's North East region but the granularity of this potential had yet to be defined and forms the basis of this project.

- Zero Waste Scotland - exists to lead Scotland to use products and resources responsibly, focusing on where they can have the greatest impact on climate change. Their goal is to inform policy, and motivate individuals and businesses to embrace the environmental, economic, and social benefits of a circular economy. They are a not-for-profit environmental organisation, funded by the Scottish Government and European Regional Development Fund.
- Circular North East is the local engagement partner for Zero Waste Scotland in the North East of Scotland. Circular North East works to inspire businesses in the North East of Scotland to adopt circular strategies by connecting companies, helping them realise the benefits the circular economy presents to diversify, reduce costs, gain, value and exploit new business opportunities. A key element of this programme is working with the agriculture and food and drinks sector to exploit the opportunities afforded by the bioeconomy.
- SEFARI is a consortium of six globally renowned research institutes including Biomathematics and Statistics Scotland, The James Hutton Institute, The Moredun Research Institute, The Rowett Institute, The Royal Botanic Garden Edinburgh, and Scotland's Rural College. As SEFARI, these institutes deliver the Scottish Government funded Strategic Research Programme (SRP), which addresses key mid to longer-term challenges for Scotland's environment, agriculture, land use, food and rural communities.

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[2] https://www.bbi.europa.eu/news/commission-gives-green-light-successor-bbi-ju

[3] Biorefinery – A processing facilitiy that convert biomass into value-added products such as biofuels, biochemicals, bioenergy/biopower, and other biomaterials.

The identification of the bioeconomy opportunities in the North East utilises the data from the aforementioned Zero Waste Scotland biorefining report (Zero Waste Scotland, 2017) and used to build the Scottish Bioresource Mapping Tool[4]. This interactive tool allows for guided mining of Scottish local authority-based bioarising data in terms of type, location and gross composition. However, this has been taken further here in terms of discussion within the waste/co-product generating industries, literature analysis on the specific wastes/co-products and application of over 30 years of experience in the chemistry and valorisation of biobased materials, in the form of Prof Derek Stewart, the author. From this, the wastes have been assessed for commercial potential bearing in mind the moving landscape in terms of the evolving policy and strategy landscapes for a green recovery and Net Zero emissions[5], industrial decarbonisation[6], the circular economy[7], energy[8] and economic recovery[9].

The assessment of these opportunities was developed through the lens of sustainability with the need to obtain the maximum value, including economic, from our (Scottish) resources and in a manner that does not damage the environment and ideally benefits it through the substitution of fossil fuel-based resources.

[4] https://www.ibioic.com/innovation-support

[5] https://www.gov.scot/publications/securing-green-recovery-path-net-zero-update-climate-change-plan-20182032/

[6] https://www.gov.uk/government/publications/industrial-decarbonisation-strategy#:~:text=The%20Industrial%20decarbonisation%20strategy%20is,and%20without%20pushing%20emissions%20abroad.&text=sets%20out%20the%20government's%20vision,UK%20industrial%20sector%20in%202050

[7] https://www.gov.scot/publications/making-things-last-circular-economy-strategy-scotland/

[8] https://www.gov.scot/publications/scotlands-energy-strategy-position-statement/

[9] https://www.gov.scot/binaries/content/documents/govscot/publications/strategy-plan/2020/06/towards-robust-resilient-wellbeing-economy-scotland-report-advisory-group-economic-recovery/documents/towards-robust-resilient-wellbeing-economy-scotland/towards-robust-resilient-wellbeing-economy-scotland/govscot%3Adocument/towards-robust-resilient-wellbeing-economy-scotland.pdf?forceDownload=true

Findings

The initial analysis of the mapping data was undertaken to first eliminate waste/co-products beyond the agricultural scope of this project and where significant activity had already been undertaken: rubber (Arabiourrutia et al, 2020; Fazli et al, 2020), aquaculture/fisheries (Zero Waste Scotland, 2014; Wu and Song, 2021), brewery (e.g. dried distillers grains with solubles (DDGS) (Chatzifragkou et al, 2015; Li et al, 2019; Skendi et al, 2020) and whey (Banaszewska et al, 2014; Rebouillat and Ortega-Requena, S., 2015; Pires et al, 2021). However, the full scope of the bioarisings available, in 2014 at least, is shown in Appendix 1 in the form of a graphic representation. Even from this the complexity of the bioarising landscape is immediately evident with, for example, the local authorities (LAs) active in primary production (farming). Unsurprisingly the sources of significant levels of bioarisings. for example, slurry and farmyard manure (FYM), are major components of the bioarisings complement and the major ones for the Local Authorities (LA) of Aberdeenshire, Dumfries and Galloway, the Borders etc.

This data was then further analysed to yield further distribution profiles which were grouped into three areas

- waste/co-products derived from primary production (Appendix 1, Fig. 4);
- manure and slurry (Appendix 1, Fig. 5);
- crops (Appendix 1, Fig. 6).

In the first of these, there is a significant geographic spread in terms of the aforementioned bioarisings whose cumulative total is 16.7MT, approximately 62% of the total bioarisings identified in the Biorefining Potential for Scotland Report by Zero Waste Scotland (Zero Waste Scotland, 2017). The remaining 38% comprise wastes, such as paper and cardboard, rubber, household mixed food and garden waste, brewing and distilling by-products etc that are either compositionally diverse or are already being dealt with in terms of valorisation. For example, the brewing and distilling waste has a valid ongoing use as livestock feed and is the focus of protein extraction activities for further value upscaling, into feed ingredients (ECO-FCE[10] and BIOWASTE4SP[11]), bioethanol (Li et al, 2019) and as a feedstock for yeast protein production (Anon, 2012).

The cities and less agriculture focussed LAs are unsurprisingly at the lower end of the scale with the major agricultural LAs represented in arguably two groupings with Aberdeenshire-Highlands one group (3.5-1MT) and Perth and Kinross-Stirling (0.75-0.4 MT respectively). In all of these areas, slurries and manure are the dominant bioarisings.

Further mining or segregation of the data reveals more insights (Table 2). Slurry and manure in isolation comprise 53% of the 27MT bioarisings total. Unsurprisingly, the dairy slurries and manures are concentrated in the Scottish South West, the Scottish dairy region whilst the beef industry-based slurries and manure are highest in Aberdeenshire (Appendix 1, Fig. 5).

Removal of the slurry/manure data from the bioarisings survey leaves the crop-based data and highlights several interesting points. Firstly, the distribution in terms of local authorities generating the bioarisings was essentially limited to ~9 out of the 32 local authorities with levels >50kT (Appendix 1, Fig. 3). Secondly, the dominant bioarisings are the straws (Table 1) comprising 1.66Mt (72%) of the total crop bioarisings for 2014 (2.31Mt) and 6% of the total bioarisings (27MT). The next more abundant bioarisings are from horticulture. This latter group’s bioarisings are well below the levels of the straws but hold significant potential.

[10] http://www.eco-fce.eu/
[11] https://cordis.europa.eu/project/id/312111/reporting

Across the bioarisings there are significant and/or minor, but important, compositional variations that determine the range of opportunities that these potential feedstocks can be used for (valorised). In the following section, we will explore all of the factors on a bioarising-by-bioarising basis.

Table 2. Major agricultural-related bioarisings based on the 2014 Scottish bioarisings data assessment Zero Waste Scotland, 2017)

Bioarisings	Value in 2014 (Tonnes)
Slurry	6000000
Manure	8400000
Straw (barley)	957000
Straw (wheat)	460000
Straw (oilseed rape)	153000
Straw (oat)	90000
Potato (haulms)	203000
Carrot, brassica etc	137000
Potato (tuber)	132000
Soft fruit	967

Cereal Straw

As identified earlier cereal straws comprise a significant proportion (72%: 1.66Mt) of the crop-based bioarisings. Overall, the cereal straws have roughly the same basal composition (Table 2). However, this gross composition does mask specific compositional variation and potential applications/opportunities which will be discussed below.

Table 3: General straw composition (Sin, 2012)

Component	Concentration (% w/w)
Cellulose	30-45
Hemicellulose	20-35
Lignin	6-16
Ash	2-4
Wax	0.4-1.0

In terms of opportunities, the most obvious route for valorisation rests with the fact that straws are predominantly polysaccharide-based bioarisings and this underpins its easiest use as a feedstock for energy production. Indeed, this approach of using perceived “biomass residuals” has the essential advantages of not requiring “additional acreage” and of not competing with the food industry (Weiß and Glasner, 2018). Also, the science behind straw pelletisation and use as a fuel in combined heat and power systems are now well established (Whittaker and Shield, 2017). In Scotland (and the UK) the main use for the straw is as bedding material for livestock and/or incorporation into the soil to return nutrients and organic matter, increase/maintain soil health and possibly reduce the risk of compaction. Estimates of incorporation back into the soil have proved difficult to gauge but the study of Bell et al (2018) did identify this as a route still routinely used for the aforementioned reasons.

Regardless of the use, there is a strong market already with the prices per tonne ranging from £30-100 (AHDB, 2021). Nevertheless, there are opportunities that could generate greater returns within an environment of economic growth and the decarbonisation of processes and products.

Cereal Waxes

Markets

Although wax is a specific and small (%) component of straw, the markets and demands for natural waxes make this a high-value valorisation route for the large Scottish straw bioarisings and worthy of specific attention (Pham et al 2018). The global wax market was valued at $9.3 Bn in 2016, and it is anticipated to increase to $11.8 Bn by 2023. While the shift from conventional petroleum wax-based products to synthetic and crop waxes is increasing, the wax landscape is also changing regarding end-user profile. Demand for conventional mainstream wax applications, such as lighting candles, has slowed down although the scented candle market is projected to reach ~$4Bn by 2024 and a CAGR of ~6% (Market Research Future, 2021). Relatively newer rheology and surface applications are some of the fastest-growing applications for these new waxes. The ability of new and growing applications to adapt to non-petroleum wax types will set the stage for future wax supply and demand balance.

The demand for vegetable waxes- or those derived from plants - is seeing substantial growth in applications that are under greater influence of societal norms, culture, beliefs, and lifestyles. With their beneficial green label, these waxes are making steadier strides into the market space for low-melt, soft waxes, making high volume advances into more commodity-like applications such as candles. Crop wax jellies are also replacing speciality petroleum jellies in cosmetics applications. These waxes not only play an important role for consumers, but soft vegetable waxes are also difficult to substitute across these applications with other high-melt and harder synthetic waxes at a lower price point. Encouraged by such applications, the supplies of crop waxes are forecast to experience annual growth of 2.0% to 2.5% in the next five years (Kline, 2021).

As alluded to above, wax is used in high value cosmetics, e.g., lipstick, and targeted at middle east countries due to the waxes elevated melting temperatures. Extraction technologies are evolving with the use of pressurised liquid CO_2 an ideal and benign solvent. Alternatively, purely mechanical and thermal treatments are being used (Vinther and Lawther, 2015) [see below]. Regardless of this the technology to process the straw-to-wax is now established and reasonably inexpensive and this would be offset against products entering a clean label and high unit value sector: cosmetics. Notably, the establishment of these extraction technologies allows alternative feedstock to be processed to a range of products including fruit, carrots, brassicas and coloured compounds, various wastes for volatile components.

Technology

There are two routes to this:

1. A mechanical dry/wet milling process such as that patented (Vinther and Lawther, 2015) and commercialised by Jena Trading (Denmark). This cracks the wax coated surface from plant materials and then this significantly enriched fraction is extracted with a solvent to remove the wax from the residual plant material. Investment for this process is ~ £0.5M. The bulk of investment is into the milling and fractionation equipment with the extraction of the enriched fraction done

at a smaller scale compared to option 2 and therefore the investment in extraction equipment would be significantly smaller

2. Immediate solvent extractions: this uses milled straw and immersion in a solvent, thereby solubilising the wax. Notably for this, the solvents can be chloroform, hexane etc through to water and CO_2 mixtures (Deswarte et al., 2006). The latter is preferred for clean label applications. Pursuing a clean label route requires a commercial supercritical fluid extraction system which was rated at €1.4M in 2015 (Attard, 2015; Attard et al 2015) and with technological advances could be £1M today. Notable this system can be used for a wide range of other feedstock (and would need to be to justify the investment). However, Johner et al (2016) described a lower scale system built with a cost at that time of £11,800[12]. This is one that could reasonably operate via a farming cooperative and create a portfolio of clean label extracts (at the 100g scale) for multiple markets. This could be seen as an entry option to the market and allow revenue to be generated and the market scale tested in action. Alternatively, this could be the model adopted for a primary producer cooperative to operate and exploit (see Recommendations).

Regardless of the technology to process the straw-to-wax is now established and comes at a range of scales and investment levels, and the latter would be offset against products entering a clean label and high unit value sector: cosmetics. Notably, following the establishment of the extraction technologies other wastes for alternative products can be similarly processed: fruit, carrots, brassicas and coloured compounds, various wastes for volatile components etc.

It is worth considering the utility of the straw following the extraction of the components such as wax etc. There is potential value (economic and/or environmental) to be accrued if the post-extraction residues can be used for a variety of uses including livestock bedding, incorporated into the soil for enhancement of carbon content and soil structure (Siedt et al., 2021), and energy generation via anaerobic digestion (AD) or used for the production of heat and power by combustion (Raud et al., 2021).

Alternative valorisation routes

One of the most obvious uses of straw is based on its deconstruction back to monomeric sugars and their subsequent fermentation. Glithero et al (2013) and Ghaffar (2019) both reviewed this process, the latter specifically for England, and concluded that this is indeed feasible with all steps in the conversion to sugar (and then ethanol) all well-established but with many issues around cost, investment, feedstock collection etc. However, this route of straw-to-sugar (known as C6 biorefining; Cherubini et al, 2009) is gaining more credence as the focus on the national/global Net Zero emissions/decarbonised processes agenda increase. Along with this, there is an increasing need for sugar(s) as basal feedstocks for high value industrial biotechnology production processes and the sustainable production of high value and volume chemicals currently generated from fossil fuel sources (Sun, 2010). This shift to sustainable chemicals and materials is highlighted in the recent statements by Unilever to eliminate fossil fuels in cleaning products by 2030 (Unilever, 2020)

Others have looked at alternative valorisation routes to energy via biogas from anaerobic co-digestion, synthetic fuels from thermal gasification, and combustion for heat and power generation and found similar feedstock collection, process costs and investment challenges (Venturinion et al, 2019).

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[12] Converted from the literature stated value of $16000 and an average £:$ exchange rate for 2016 of £1:$1.3552. https://www.exchangerates.org.uk/GBP-USD-spot-exchange-rates-history-2016.html#:~:text=This%20is%20the%20British%20Pound,rate%20in%202016%3A%201.3552%20USD

More niche routes to straw valorisation include the production of nanocellulose for composites structure fortification (Fortunati et al 2016), structural composites (Walker et al, 2020), fibreboards (Halvarsson et al, 2009) and xylitol, a sweetener, (Moraes et al, 2020).

Oilseed Rape (OSR) Straw

OSR straw is different from the cereals straws in having a distinct composition (Table 3.) with a high sulphur content (0.54%) compared to cereal straws (~0.1%). It is this higher sulphur content along with the relatively high cellulose content that has seen some utility and uptake in sectors such as feed for livestock (Abreu and Bruno-Soares, 1998; Griffith et al, 2017) and extraction processes for bio-based products (Svärd et al, 2018; Wood et al, 2014) and biofuels (Glithero et al, 2013; Matthew et al, 2014). However, uptake remains low key and piecemeal. The alternative market of animal bedding appears to be problematic too due to the use of certain herbicides during OSR production (NFU, 2018)

Table 4. Oilseed rape straw composition. (Ji et al 2014, Nie et al, 2020)

Component	Concentration (% w/w)
Cellulose	40-50
Hemicellulose	15-30
Lignin	15-20
Ash	3-5
Wax	0.4-1.0

The resistance/recalcitrance of the OSR straw to processing and application compared to other straws offers an alternative avenue for valorisation: horticultural substrates, the media plants are grown in. The global demand for horticultural substrate is increasing and growers are increasingly interested in locally sourced and eco-friendly products. The European market is peat-based, with substrates made mostly of sphagnum peat moss with a maximum replacement of 20-30% by wood fibres, coir or rice husks at present. Notably in China, rice husks are widely available as are perlite, coconut husks and green waste. There is however a significant level of fossil peat still in use in horticulture and with peat, moss and coconut coir deemed environmentally unsustainable as substrates the opportunity for replacements, as part of a valorisation pathway, is significant. Oilseed rape stem is strong and fibrous and would form the basis of a viable, low input feedstock for conversion to horticultural substrate.

Given the shoot-to-seed biomass ratio in oilseed rape of 2.9:1 (Zhu et al, 2020) and that Scottish OSR harvest was 122kT, this equates to ~353.6kT of straw (AHDB, 2020). Marks-Bielska et al (2019) state that "*oilseed rape straw should be ploughed in because it is practically useless in animal rearing or for other purposes on a farm*". This plant material could have value as a sustainable horticultural substrate. The incumbents, Rockwool and peat, are not sustainable (Gruda 2019) and peatlands are the largest natural terrestrial carbon store. The current alternative is coir but although useful has the highest impact on "ecosystem quality", which is often due to land occupation during the coconut harvesting stage (Quantis, 2012). This means the industry is actively seeking alternatives and these need to be low cost. Recent reports by Litterick et al (2020) and Bek et al (2020) have highlighted this with the former highlighting that the UK Government's 25 Year Environment Plan (2018) is likely to further focus on the search for peat-free and reduced-peat media. Indeed, Wallace et al (2010) reviewed the global situation regarding peat alternatives and identified materials such as bark, coir, wood fibre and waste, rice husk, leaf mould, compost and mineral sources (e.g., Rockwool, perlite, vermiculite etc) but these all suffer from problems in terms of sustainability and utility.

With the quantity of OSR bioarisings identified earlier as significant (153kT in 2014), this can be valorised into horticultural substrate readily by use of decortication equipment (~£10-15k)[13] and subsequent sterilisation (closed pits/containers and steam). The investment to do this is modest compared to the potential returns and the void that the horticultural sector is approaching in terms of sustainable replacements for peat and coir mean that such a sustainable alternative should be welcomed.

In the UK the standard for substrates is governed by the British Standards institute with several standards (see https://standardsdevelopment.bsigroup.com/). At the EU level EN/TC 223 – Soil Improvers and Growing Media (European Committee for Standardisation, Technical Committee 223), has developed a number of standards for soil improvers and growing media but these have only been incorporated into some national regulatory frameworks. This all means there is significant potential to explore the potential of oilseed rape straw as a substrate with the preliminary work required on the conversion of the straw to a fibrous support, likely via decorticator and scutching systems to expose the fibres, then trialling with various horticultural crops.

Potatoes - Harvested

The Scottish production and supply chain for potato, seed and ware, is well established. The advance of climate change and weather extremes mean that there is a consistent level of waste in the industry. For Scotland in 2014, this was 66Kt from a total production output of 1.2MT (AHDB, 2021). The current waste level is likely to be similar given a 2020 production that is the same (1.2MT).

The potato tuber is a storage organ that is, on average, 80% water and 20% dry matter. Of the dry matter, ~80% is carbohydrate, predominantly starch. Starch is a common feedstock for fermentation to ethanol and, via cereal starch, is the basis of the brewing and distilling sector. However, ethanol is also a key target for the biofuels sector. In current UK unleaded fuel, there is 5% ethanol whilst this year (2021) will see that increase to 10% ethanol (E10: UK Department of Transport, 2021). Notably, the vast majority of this bioethanol is imported from France (Hopwood et al., 2019) and this offers home production/import substitution opportunities.

The markets for bioethanol are set to increase. UK Gasoline and Diesel Sales for 2019 (Petrol Retailers Association, 2019) were 46.5bn litres (Total Road fuels). This is comprised of Petrol - 16.2bn litres (Retail), Diesel - 20.8bn litres (Retail), Diesel - 9.5bn litres (Commercial). The petrol is already E5 (5% bioethanol) and so the shift to E10 requires a further 0.81Bn litres bioethanol. Although the UK is committed to phasing out new petrol and diesel cars and vans by 2030, an issue at the heart of the Prime Minister's recent 'Ten Point Plan for a Green Industrial Revolution', progress is very slow and unlike to deliver the aim (Birkett and Nicolle, 2021) meaning in the UK alone the market for transportation-targeted bioethanol will still be substantial.

The Acetone-Butanol-Ethanol (ABE) process (Amiri, 2020; Karsten et al., 2021), an established microbial fermentation/distillation process is already up and running at Celtic Renewables[14]. The ABE process takes carbohydrates such as potato starch and converts these into acetone, butanol and ethanol at a ratio of 3:6:1. This yields a comparatively lower output of bioethanol from waste potatoes than traditional yeast-based starch fermentation, but the aforementioned increasing bioethanol demand along with significant demand for sustainable solvents, specifically acetone and butanol, makes this process worthy of support. The butanol market is predicted to grow from $4.18 Bn in 2017 to $5.58 Bn by 2022, registering a CAGR of 5.9% from 2017 to 2022. The demand for n-Butanol is growing due to the increased use of butyl acrylate, a common component of enamels, textiles, paper

[13] It is worth noting that the availability of decortication equipment would also have use in the emergence of hemp as a Scottish crop since decortication is a process fundamental to accruing multiproduct value in hemp (Musio et al., 2018)

[14] https://www.celtic-renewables.com/

finishes, and others. Similarly, the acetone market size has the potential to grow by 1,375.25 k tons during 2020-2024: the global acetone market size was estimated at USD 4.04 billion in 2018 and is projected to register a 5.4% CAGR in terms of revenue over the forecast period. Investment to date for the plant is ~£30M for a facility at Grangemouth.[15]

This process of potato to-biofuel/sustainable chemicals is an established and growing activity, and replication would seem unlikely in Scotland at least for the ABE process. However, as the plant grows the need for feedstock will increase. Consequently, this can be considered market ready and discussions for off-take of potato (and possible cereal grain) bioarisings can progress further and should be progressed.

Potato - Haulm

Potato haulms are the above ground biomass that would commonly be burned off (traditionally using sulphuric acid then latterly diquat treatment) to prepare the plant ready for harvest and storage. To date, the residues/bioarisings have never really been considered as a by-product. However, research into the haulms phytochemical constituents has demonstrated the potential to valorise this material.

Potato haulms have two key chemical components that have established and potential markets:

1. Solanesol, a complex, non-cyclic terpene alcohol that has a ready use as an ingredient in high value cosmetics. Solanesol is a precursor to Coenzyme Q10, a component incorporated into cosmetics to deliver healthy skin. On its own, solanesol is reported to possess antioxidant, anti-inflammatory, neuroprotective and antimicrobial activities. Furthermore, derivatives can form micelles (fatty droplets), that can be used to deliver ingredients/bioactives into the body or protect components from degradation in foods, supplements etc. Solanesol presence in potato tissues is well reported (Taylor and Fraser, 2011: Campbell et al, 2016).
2. Glycoalkaloids. These compounds, common in green potato tissues and greened potatoes, are toxic compounds and relatively easy to extract. They could form the basis for a ready and simple route to disease control as part of a programme of integrated pest and disease management (IPM) in non-solanaceous plants, i.e., not for use with potato, tomato, peppers etc. However, use in cereal crops to control bacterial and fungal disease (Fewell et al, 1994; Fewell and Roddick, 1997: Chowański et al, 2016) is a viable exploitation route in an area where the existing disease control strategies and solutions are being removed due to environmental concerns and increasing pathogen resistance (DEFRA, 2020a).

Markets

With respect to solanesol, the cosmetics market for natural ingredients is one based on clean labelling: using simple, natural and sustainable ingredients. Furthermore, demand for natural ingredients for cosmetics is on the rise in Europe. Environmental issues are growing in importance, making sustainability, ethical sourcing and their related labelling schemes more prominent (Bom et al, 2019, 2020). Changes in consumer behaviour and lifestyles are also creating openings and driving demand for natural ingredients. Although these trends are creating opportunities for natural ingredients, regulations and political uncertainty pose major risks/challenges for companies seeking access to the European market and these include the following:

- Validated sustainability and ethical sourcing: there is a need to ensure sustainability via compliance with the environmental regulatory systems using tools such as Environmental Risk Assessment and Management System (Bom et al, 2019);
- Highly regulated market;

[15] https://www.insider.co.uk/news/innovative-biotech-company-launch-crowdfunding-22905640

- COVID-19 impacts the European personal care sector;
- Brexit and trade uncertainty.

Although the above risks/challenges may seem significant what is suggested here, biorefining of agricultural produce, generate products that sit well with the evolving environmental and regulatory frameworks. Also, greater assurance can come from the increasing popularity of plant and food-based ingredients (colourants, oils etc) in personal care products (Amber and Fogarassay, 2019). Furthermore, the market appears to be buoyant and increasing. In 2015, Grand View Research announced that the global organic beauty market was likely to reach $15.98bn by 2020, as demand for organic skincare, haircare and colour cosmetics drives consumers to look for natural and organic labels. Then in 2016, market analysis released by Persistence Market Research showed that with the year-on-year growth in organic beauty, the global market should be worth just under $22bn by 2024. Those figures suggest approximate growth of 8-10% per year.

As identified above glycoalkaloids are also present in potato haulms and their exploitation via the proposed approach is timely. The review by Deloitte (2019) identified that the agrochemical market is experiencing "*declining revenues and margin*", "*increasing spending on research and development (R&D) of new active ingredients*" and "*increasing stringency of regulatory requirements*". However, they also identified that sustainable and low(er) input agricultural practices including Integrated Pest Management and the use of biologicals and natural solutions, e.g. glycoalkaloids, is viewed as impacting the sector most in the short term.

Indeed, the agrochemicals market is in flux with a range of new active ingredients entering development and subsequently in decline leaving the sector more reliant on older, off-patent chemistry, although the availability of older products has been affected by re-registration requirements, particularly in the EU. Allied to this is the direction of travel for agricultural support in the UK [16] which is outlined in the Pathway to Sustainable Farming - An Agricultural Transition Plan 2021 to 2024 (DEFAR, 2020b) and identifies the forthcoming outcomes of the consultation on the draft National Action Plan for the Sustainable Use of Pesticides from which an action plan will be finalised and the approach to support the uptake of Integrated Pest Management and the safe and sustainable use of pesticides identified.

This all means that there is an agrochemical market ready for sustainable solutions to pest and disease control and as part of this there is a place for potato haulm derived glycoalkaloids. At a global level, Research and Markets (2020) reported that the agrochemical market size is estimated to grow from $208.6 Bn in 2020 and is projected to reach $246.1 Bn by 2025, at a CAGR of 3.4%, during the forecast period. With respect to the integrated pest and disease management market into which the glycoalkaloid exploitation would fall, Research and Markets (2017) also identified that the global demand for IPM solutions and applications was valued at $91.8 Bn in 2016 and was anticipated to grow to $151 billion by 2025.

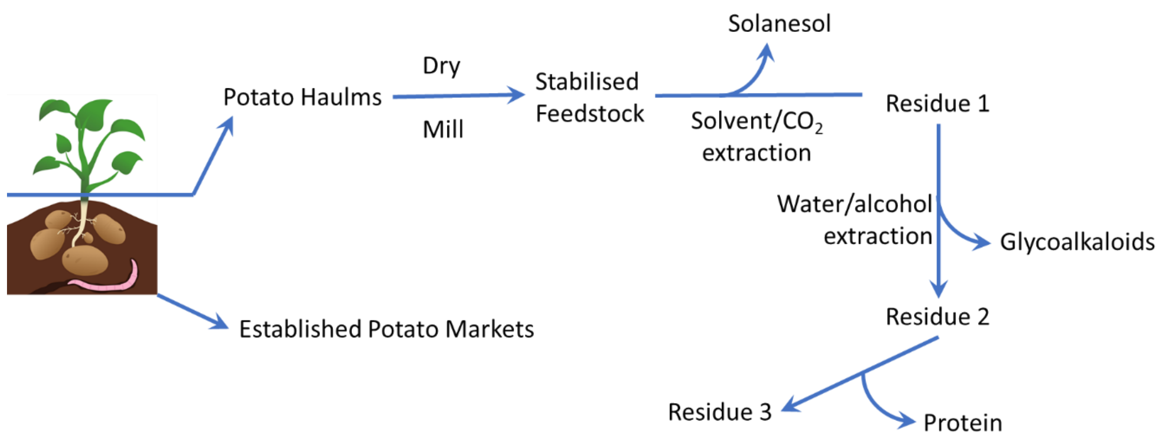
Technology

To realise the full valorisation of potato haulms investment needs to be in the equipment to harvest green potato haulms (already available) and the biorefinery equipment associated with compound purification: mills, dryers and chemical extraction systems including supercritical fluid (SFC) extraction

[16] Note that here the plans for agriculture outlined in DEFRA, 2020b are applicable to England and Wales but that analogues approaches are planned in Scotland.

(liquid and pressurised CO_2 as a solvent). Possibly the most economical route to valorisation of the potato haulm waste is adopting a sequential, rather than targeted, extraction route to the biomass (Figure 4). The technology here is well established, and based on drying, milling and extraction equipment that is commercially available and not necessarily high costs. If the SFC approach is used, then this would attract a larger technological cost (£50k-100ks) but provide a much cleaner solanesol extract.

Figure 4. An economical route to valorisation of potato haulm waste



The solanesol-extracted residue could then be re-extracted using more polar solvents (e.g., ethanol) to create a glycoalkaloid-enriched product that can be tested as is, or further purified (possibly by chromatography or membrane systems) thereby adding to the production costs but also the final product unit price. This approach could be further extended as potato haulms are reported to have appreciable protein contents (8-16% w/w dry matter) depending on the variety and time of harvest (Carruthers and Pirie, 1975; Kaplan et al, 2018). These proteins are likely to be contaminated with glycoalkaloids and not suitable for animal feed, but the protein has alternative uses such as sustainable wood adhesives (Norqvist et al, 2013) and as a feedstock for industrial biotechnology-driven production of fuels and chemicals (Li et al., 2018)

Investment in the sequential extraction technologies is not potato haulm specific and opens up opportunities for other organic wastes, e.g., carrot, fruit etc, as well as crops specifically grown for natural and sustainable extracts. This would, with appropriate feedstock/bioarising storage, allow the investment to be utilised all year and not only on a seasonal basis.

Scale of Opportunity

For potato haulms, the scale of the opportunity can be calculated as follows. Typically, a potato crop produces 4 tonnes per hectare dry weight of foliage. The area of potatoes planted in Scotland in 2020 was 28400 ha which equates to 113.6KT dry foliage. The levels of solanesol found in potato foliage ranges from 0.04-1.5% dry weight and this equates to 45-1704T of solanesol. If we assume that the waste processing activity would centre in the potato growing regions, a conservative figure of 50% of the waste and a nominal solanesol yield value of 0.25% would generate 285 tonnes solanesol. **In recent years, demand for high purity solanesol has grown from 4KT in the early 2000s, to an estimated international demand exceeding 66KT by 2022.** In 2008, the price of the high purity solanesol in the international market was generally around $ 300 per kg while the average export price of China's high purity solanesol is about $ 250 per kg. Given the earlier estimation of Scottish solanesol production of 285T, and likely at high quality, this then equates to £85.5M at 2008 prices. This is of course only accounting for solanesol. Sequential extraction to also generate glycoalkaloids adds further value.

Indeed, using the same calculation, the reported levels for glycoalkaloids in potato tissues above/below ground biomass (Friedman and Dao, 1992; Cao and Tibbetts, 1994; Kim and Lee, 2019) and Scottish potato production data for 2020 (as above) this means the Scottish potato haulm glycoalkaloid total content is approximately 603 tonnes. To give a representative feel for this as an agrochemical, Carmona et al (2020) identified in their review of fungicide applications on the integrated management of wheat stripe rust that application rates ranged from 40-500 grams of active ingredient/hectare. To give a representative feel for this as an agrochemical, Carmona et al (2020) identified in their review of fungicide applications on the integrated management of wheat stripe rust that application rates ranged from 40-500 grams of active ingredient/hectare. Applying these rates to the putative 603 tonnes of glycoalkaloid that could be harvested from the Scottish potato harvest represents a theoretical treatment area of 15.2-1.2 million hectares, respectively. For scale it is worth noting that in 2018 the total area of agricultural holdings in Scotland was 5.6 million hectares (Scottish Government, 2019).

Soft fruit

The bioarisings from the soft fruit sector can be considered niche in terms of volumes (Harvested waste: strawberries – 4.1 KT and raspberries - 557T) and chemical composition (McDougall and Stewart, 2012; Foito et al., 2018) but the localisation of production and the innate chemistries offer up opportunities in high value valorisation. These would best be targeted at the food ingredient, here antioxidant, and colourant markets.

Technology

The processing of soft fruit into antioxidant extracts for food is a relatively straightforward process and both for clean labelling in products.

1. Ethanol extraction - The key antioxidants in soft fruit (and indeed other fruit and vegetables) are ethanol soluble. This is crucial as ethanol is a food grade solvent permissible without labelling but its use as an extractant may require a licence. This extraction route creates a soluble antioxidant extract that can then be concentrated (ethanol removed) relatively easily. Indeed, both activities (extraction and concentration) can be done on farm with minimal investment (£100s - low £1000s) and sold into the food ingredient supply chain
2. Supercritical fluid extraction (SFC) employing CO_2 – This is similar to the process described above for cereal wax and potato haulm valorisation and would be a faster and more specific (cleaner extract) route to antioxidant preparation but would come with a larger investment for this specific extract. Investment in SFC technology for this purpose alone is unwarranted but could also be used for a range of biomass extraction applications and associated added value products which would create a positive business case. The Scottish SFC capacity is low and thought to be exclusively at the academic level and therefore could be a target for establishment, in combination with other technologies, such as decortication, milling etc, as part of developing a modular/adaptive processing hub (See Recommendations).

Extraction of the coloured components in the soft fruit bioarisings for colourants could follow much the same route as the antioxidants route: ethanol or CO_2 (SFC) extraction. Here the target would be the coloured compounds (anthocyanins: also antioxidants) and any process developed would/should keep the extracts confined to these to maximise value, i.e. a high percentage anthocyanin in the extract. Notably, this market is one that values products that can deliver clean label[17] branding and sustainability (see Unilever's shift to a fully sustainable supply chain; Unilever, 2020). Also, although inorganic pigments occur in nature as complex minerals, their use in natural cosmetics relies on low production costs but production is becoming associated with ethical issues such as child labour use in mineral mining.

Food Use - The use of raspberry extracts as colourants in food will have to follow distinct approval routes. This is well established and varies depending on the country. Notable in the area of ingredients 3,000 food additives and colourants can be found in the EAFUS list (Everything Added to Food in the United States) of FDA, over 2,000 food additives and colourants are designated under the Chinese Number System (CNS) and National Food Safety Standard for Uses of Food Additives, and only 402 substances are assigned to the catalogue of European Union inventory number ("E"-number) as approved by the European Food Safety Authority (EFSA). This highlights some distinct differences in market opportunities and for the moment the UK follows the EFSA E-number system. Nevertheless, the soft fruit bioarisings can be processed to a colourant, E 163 (anthocyanins), which is commonplace in many products already (EU, 2021) such as those below:

- Yoghurt;
- Dairy products;
- Glacé cherries;
- Ice cream;
- Jellies;
- Soft drinks;
- Tomato, carrot or vegetable soups;
- Confectionery.

Regardless of approval routes, the market for global natural food colourants is significant with Mordor Intelligence Inc (2021) estimating market value at $1.6 Bn in 2020, registering a CAGR of 8.47% during the forecast period (2021-2026).

For use as a food antioxidant, soft fruit extracts may avoid the approval routes by being added as a raspberry extract rather than fractionation down to a defined chemistry thereby allowing addition out with the specified use as a functional additive with the associated requirements to be labelled following the route identified above. This is unlikely to limit the market as the soft fruit extracts are largely regarded as antioxidants anyway (Hildago et al, 2017). Like food colourants, the global food antioxidants market is buoyant, and its size is estimated to be valued at $ 1.3 Bn in 2020 and expected to grow to $1.8 Bn by 2025 (Markets and Markets, 2020).

Non-Food use - For non-food colourant uses there are different regulations at national levels, and these depend on what the specific use of the colourant is; lipstick, near-eye use, shampoo etc. Regardless of the end use the extract may need a degree of chemical stabilisation to ensure that the colour does not fade too fast. Botanic/crop colourants can suffer from poor colour fastness/stability. However, this has been a previous focus of research and solutions have been delivered (Chung et al, 2016; Trouillas et al., 2016; Rose et al, 2018). As an example of use in non-food sectors, soft fruit anthocyanins have been explored for use as sustainable (fossil fuel free) hair dyes (Rose et al, 2018) identifying these as stable to multiple washes and that this stability could be extended using other components of the natural extract (Chung et al, 2016; Trouillas et al., 2016).

[17] Clean labelling is a widely accepted term used by the food and cosmetic industries, consumers and academics to describe a more consumer friendly label and trustworthy natural products.

These non-food markets are not trivial with the global "Hair Colour Market" value projected to reach $27.2Bn by 2026, from $18.1Bn in 2017, at a CAGR of 4.8% (Trend Market Research, 2021). Allied to this Grand View Research (2020) identified that the natural hair product market was valued at $8.74 Bn in 2019 and is expected to grow at a compound annual growth rate (CAGR) of 4.7% from 2020 to 2027. Additionally, Statistica (2020) identified significant increases across 2015-19 in the use of "Colouring matter of vegetable and animal origin" and "Plants and parts of plants" (~19 and 22 % increase in volume and 18% and 53% increase in value, respectively) all in an EU cosmetic market valued at €14Bn in 2019.

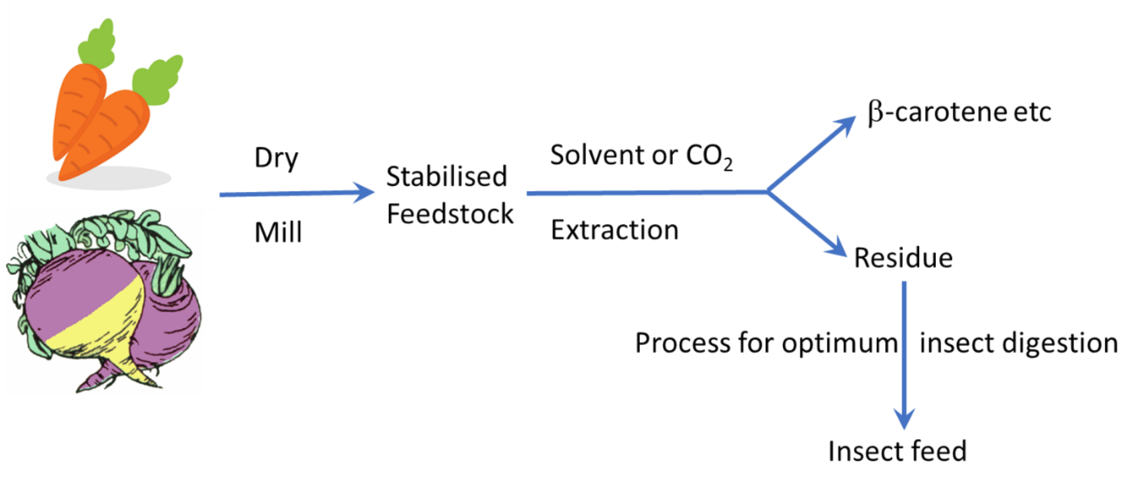
Fresh vegetables and salad crop bioarisings

The data from the 2014 mapping report identified ~230KT of bioarisings comprising brassica and other vegetables (carrot, etc) from primary production and processing biomass. Unlike the straw, potato and soft fruit bioarisings these vegetable sources have broadly similar compositions in that they tend to be ~80-90 water and the dry matter is predominantly carbohydrate based (6-8%) and ~1-2% protein depending on the tissues and crop (Sharma et al, 2012). Also, some of the vegetables have distinct species-specific phytochemicals that opens up unique valorisation possibilities. In carrot, this would be β-carotene, a Vitamin A precursor but, perhaps more important for valorisation purposes, an EFSA approved (Anon 2021c) orange colourant (E 160a) commonly used in diverse foods (EU, 2011). As mentioned earlier for soft fruit bioarisings, the food colourant market (Intelligence, 2021) was valued at $1.6Bn in 2020, registering a CAGR of 8.47% during the forecast period (2021-2026) and this growth is reflected in the smaller UK market value at ~£50M in 2016 and expected to grow to £73M in 2025 (Hexa Research, 2018).

To realise the colourant potential of β-carotene from carrot, the extraction protocols need to be food safety compliant, and this means alcohol- or CO_2-based extraction systems as earlier. The capital investment required to deliver such extractions is not substantial, £10k-100k depending on the extraction route (see Potato Haulms above) and would form the basis of a multi-feedstock extraction system generating many diverse extracts. Indeed, the same system could be used for the brassica (e.g. broccoli, turnip etc) bioarisings to extract glucosinolates, sulphur-containing natural compounds that deliver health benefits in terms of disease therapy and prevention but here, via simple extraction systems and protocols, could form the basis of sustainable beneficial products for plant health (e.g. defence chemicals, biofumigants/biocides) (Maina et al, 2020) in an IPM a global market (see Potato Haulms).

Interestingly, the removal of specific potentially valuable chemicals opens up additional interesting opportunities for valorisation. As stated earlier the vegetable dry matter is predominantly comprised of polysaccharides and a lesser amount of protein. This lends itself to use as a feedstock for insect production with Wang et al (2017) identifying such feedstock as ideal for the production of black soldier fly (*Hermetia illucens* L.) larvae. This sequential biorefining process is illustrated below (Figure 5).

Figure 5. A schematic sequential biorefining process for agricultural waste generating several products



This sector, insect biomass (and component) development, is increasing. In theory, the infrastructure for insect production should be relatively straight forward requiring:

- Biomass processing equipment to create a food medium suitable for the black soldier flies;
- Hatchery: A dry and humid area for the female to lay her eggs using materials such as cardboard and an attractant to direct the flies where to lay their eggs;
- Lavarium: An area for the hatched young larvae to feed on the supplied organic waste and grow to maturity;
- Puparium: A dry area for the harvested pre-pupae to undergo pupation;
- Insectarium: An area for pupae to hatch into adult flies, mate and lay eggs. Should have water points to prolong the lifespan of the flies.

Allied with this is processing technology. Investment here needs detail as to how much of the supply chain an investor wishes to maintain. Arguably vegetable producers (and, to a degree, processers) will have "pre-processing" technology already. The Black Soldier Fly (BSF) production facility would, at scale require £0.5-2M investment. In addition to this "steel" would be needed to process the BSF larvae to protein and oil with the Frass (larva excrement and casing (chitin)). The Zero Waste Scotland-supported study of Riera and Lenaghan (2019) identified that, based on the market value of key process outputs, and assuming a gate fee comparable to AD, BSF treatment of pre-consumer food waste (here waste vegetable) could generate £113 per tonne input: Gate Fee - £29; Fat/Oil - £26; Protein - £56; Frass - £1; Total - £113.

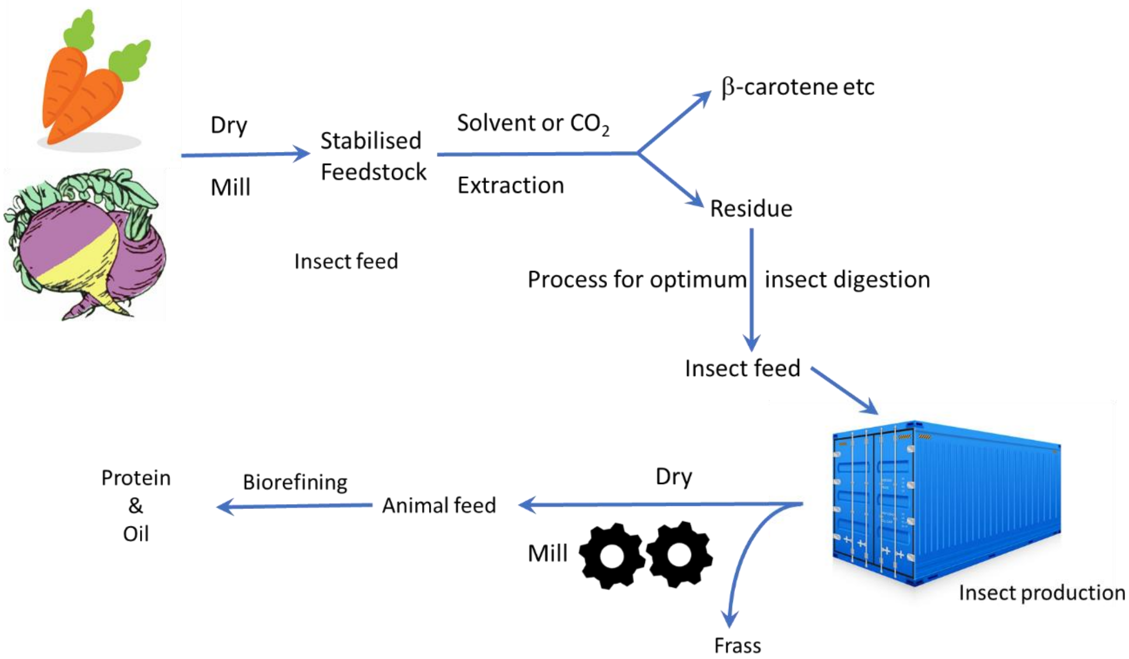
Investment for this area is still not particularly clear as few facilities of any scale have been established. Protix, in the Netherlands, has established a 14,000 square meter facility, making it the largest processing plant for insects worldwide (Byrne, 2019). Up until that point the investment in Protix had been €45M. Following this, it was announced that InnovaFeed has plans to build "the world's largest insect protein production site" with ADM (2020) in the US. This is to be a 60KT (protein) capacity facility and co-located with ADMs corn processing facility. The aim here is that when both are complete, the plant would have a target annual production capacity of 60KT of animal feed protein derived from black soldier fly larvae. The plant will also have the capability to annually produce 20KT of insect oils and 400KT of fertilizer (the frass valorisation route).

At the UK level, there has been a lot of focus on insect protein with the major project being the Innovate UK funded one led by Entocycle[18]. This £10M project, *Creating the world's first turnkey modular black soldier fly (BSF) breeding system for insect producers worldwide*, aims to build the UK's first large-scale farm breeding insects for animal feed and pet food (Guardian, 2020) and includes Scottish partners University of Stirling Institute of Aquaculture, Cooke Aquaculture Scotland, the Scottish Aquaculture Innovation Centre (SAIC), Beta Bugs Ltd, and Zero Waste Scotland.

At the Scottish level Roslin Technologies[19], an AgTech company working to improve sustainable protein production across the livestock and aquaculture sectors, recently invested in Protenga, an insect farm based in Singapore. Furthermore, there are plans submitted for a commercial protein-from-insects production facility in Aberdeenshire by Prospects Ltd (Prospects Ltd, 2021). Products based on insect protein are also already being generated such as Bug Bakes dog food (https://bugbakes.co.uk/).

From all of this, an entry level investment analogous to the above to establish a BSF facility at a viable scale (waste to protein [and co-products]) would appear to be approximately £0.5M. However, it is also worth considering a distributed cooperative model to deliver this, utilising containerised systems (cost ~£20k) for the BSF production thereby allowing for reductions in waste at the site of production. This allows for an extension of the schematic above (Figure 5) to encompass the cooperative model approach to valorisation (Figure 6).

Figure 6. Extension of Figure 5 to include a cooperative model



Notably, approval for larval protein into the supply chain was previously reserved for fishmeal but approval for pigfeed was greenlighted on 17/08/21 in an amendment to Annex IV to Regulation (EC) No 999/2001 (EU, 2021). Extension of this to other farmed animals is expected to follow.

It is reasonable to predict that this (insect) route to protein production (and associated co-product oil and frass) will see greater investment as the push to deliver on both economic sustainable growth and

[18] https://www.entocycle.com/
[19] https://roslintech.com/

resilience all within a Net Zero emissions/decarbonised production agenda. The investment route to this is currently vibrant and it is expected that globally this sector is set to expand significantly, particularly under a circular economy business model (Madau et al 2020).

Furthermore, rather than starting the whole process from scratch, there is also the alternative route that these (vegetable) bioarisings, as is or pre-processed, can find a home with these emergent and increasing insect growing initiatives and businesses. This would be a significantly reduced investment route.

Slurries and Farmyard Manures

These are ubiquitous bioarisings and, as identified earlier, slurry (6.0 MT) and manure (8.4 MT) in isolation comprise 53% of the Scottish bioarisings total. Notably, a recent study by Ricardo Energy & Environment (2018) identified that in 2018 the slurry levels were moderately increased to 6.35 MT highlighting this relatively stable feedstock to be used.

The chemistries and microbiological issues around these bioarisings limit their valorisation beyond the normal one of land fertilisation (Thiessen Martens and Entz, 2011) although some have argued that long-term use of manures will not necessarily enhance soil quality (Edmeades, 2003). In the ADAS-led (2013) joint government and industry slurry management and storage project slurries were identified as both beneficial in terms of being a valuable source of nutrients for crop growth but also that "*Manure management was estimated to account for c.20% of diffuse phosphorus and diffuse nitrate water pollution from agricultural land*." The pros and cons here rested on management and use.

That being said there are other uses for these bioarisings. Energy is the key valorisation route and has been progressed well in terms of anaerobic digestion (Anukam et al, 2019) with specific Scottish examples of this identified in Farmers Weekly (2017) highlighting smaller, simpler, slurry-only units, designed mainly to meet a farm's heat and electricity needs based around dairy farms.

Originally established as a viable route to on farm energy generation this attracted subsidies that have since changed/diminished. Recently Natwest (2020) identified that "*return on investment in smaller anaerobic digestion plants has diminished with changes to the Feed-in Tariff and Renewable Heat Incentive and that farmers are advised to weigh up the costs as these projects can still produce gains including direct income from energy sales and/or incentives, energy savings, and an increased amount of available fertiliser. A lower-cost small-scale solution is to burn the biogas in a boiler for on-site use*".

In 2016 Local United published "*Energy farms – anaerobic digestion*" which stated that "*to be viable AD plants have to be quite large and thus require significant capital investments of between £1-5million.*" Furthermore, the EU project Generating Renewable Energy Business Enterprise[20] identified that the levelized cost of electricity (LCOE) is lower for large-scale plants due to the use of more efficient conversion devices and their lower capital cost per unit of electricity produced. One of their studies found that LCOE was estimated to be 4.3 p/kWhe for AD plants processing the waste of 125 dairy cow sized herds compared to 1.9 p/kWhe for AD plants processing waste of 1000 dairy cow sized herds. Regarding the capital costs, it was identified that:

- A small digester of 10kWe capacity, using residues from 100 cattle, requiring a digester capacity of around 150m3, is likely to cost in the region of £50,000 to £70,000.
- A large AD plant's costs are substantially higher. A plant of 1MWe capacity, requiring a digester of around 10,000m3, is likely to cost between £3 million and £7 million.

[20] https://grebe.interreg-npa.eu/generating-renewable-energy-business-enterprises-grebe/

CAPEX - The capital costs for AD plants vary from £3,000 to £7,000 per MWh of electricity generating capacity (N.B.: 2017 figures but likely to still be close/valid). Variation in construction costs was reported to be driven by three factors including feedstock type, process configuration and economies of scale. Project development costs, including consultant's fees and planning costs form another significant component of the costs (4-5% of the overall capital investment costs).

OPEX - Operating costs for an on-site AD project will vary depending on the size of the plant. Annual operation and maintenance costs for a plant are likely to be in the region of 78% of the total capital cost. Issues to consider include the following

- Staff and labour costs - site, employee, and liability insurance;
- Pollution control measures and annual waste management licence fees;
- Training in health, safety, and environmental matters;
- Transport of materials/products to and from the facility is an extremely important factor to consider. It was estimated that the net cost of the digestate from a particular AD plant was £12 per tonne; thus, delivery should be carefully considered. Despite the fact that digestate is a valuable soil conditioner and fertiliser, its low dry matter content makes it expensive to move. When estimating the costs of imported feedstock, it is sensible to consider the delivery to site cost.

Regeneron (2021) have an online Biogas plant costs calculator to allow new entrants to get ballpark figures for the investment needed.

In terms of Net Zero aspirations, this should in theory make a significant climate change impact. According to Cecchi and Cavinato (2015), the environmental benefits of biogas technology are proven to be a sustainable alternative to fossil fuels. It needs to be noted that several greenhouse gases such as carbon dioxide, nitrous oxide and methane emissions are associated with biogas production. Paolini et al (2018) concluded that biogas can significantly contribute to abating greenhouse gas emissions. However, attention must be paid to undesired emissions of methane and nitrous oxide (N_2O). The emission budgets of the two compounds are scarcely related to direct release from biogas/biomethane combustion, whilst biomass storage and digestate management are the critical steps. Similar considerations apply to ammonia: to reduce its impact on secondary aerosol formation, efficient biomass and digestate storage should always be recommended. Among all the gaseous pollutants considered in direct emission from biogas combustion, nitrogen oxides (NOx) levels are of some concern in several case studies. On the other hand, volatile organic compounds do not seem to constitute a critical issue.

Another benefit from slurries/manure as an AD feedstock is that the digestate from the AD plants acts as viable fertiliser. The European Biogass Association (2015) calculated that >110MTCO_2eq. could be mitigated yearly if all EU biodegradable waste (agri and food wastes) that is still landfilled (over 78MT in the EU) would not be landfilled anymore.

Digesting these 78MT of biodegradable waste would additionally generate:

- 150 Petajoules[21] of renewable energy in form of biogas or biomethane with 11MT CO_2 eq. savings by replacing fossil fuel (oil).
- Organic fertiliser with approximately: 400kT nitrogen, 120kT phosphorus (P2O5), 450kT potassium (K2O) and 300kT carbon.

If we adopt this calculation for the Scottish slurry total of 6 MT and assume an equivalent conversion for slurry as was used for biodegradable waste then this equates:

[21] The petajoule (PJ) is equal to one quadrillion (10^{15}) joules. The 150PJ stated here, if used over a year, equates to approximately 4.7GW.

- 11 Petajoules of renewable energy in form of biogas or biomethane with 0.85MT CO_2 eq. savings by replacing fossil fuel.
- Organic fertiliser with approximately: 30kT nitrogen, 9kT phosphorus (P2O5), 353kT potassium (K2O) and 23kT carbon.

Alternative routes to extract energy from slurries and manure have been forwarded by others such as Akyürek (2019) who proposed a pyrolysis route for common by-products (or wastes). By co-blending livestock manure and recycled polyester Akyürek found that pyrolysis demonstrated a significant level of harvestable energy and that this was greater as a co-blended feedstock than from the manure alone. Su et al (2022) reviewed manure pyrolysis advances and came to similar conclusions. They identified that the co-blended plastics brought a higher hydrogen:carbon ratio to the mixture and this increased the harvestable energy with the benefit of increasing the quality of the biogas via an increase proportion of methane and ethane in the pyrolysis gas.

One of the alternative valorisation routes for slurry and manure is the adoption of advances in insect bioprocessing. Parodi et al (2022) reported that manure could be a feedstock for BSF larvae and that the larvae readily incorporated a significant proportion of the manure-derived ammonia into their tissues making this a productive route for both larval protein and reducing ammonia pollution from manure. Liu et al (2022) explored the use of BSF larvae as a tool for resource recovery from organic wastes, including manure, and identified that this created significantly less greenhouse gas emissions than conventional methods, partially by impeding anaerobic processes. Of course, this treatment route does come with challenges such as effective waste production, collection, and separation, the potential for the transmission of manure-derived pathogenic organisms to the BSF larve and the regulatory environment for BSF larval protein from this feedstock.

Changes in Bioarisings as Agriculture evolves

As our needs for food and sustainable materials evolve the requirements for agriculture will also change. There are several examples of how this may occur and here we will deal with three of these:

- Sugar Beet – The recent report by The National Non-Food Crops Centre (NNFCC) on the reestablishment of sugar beet (Hopwood et al., 2019) identified that the increasing shift to sustainable resources as part of the national policies to deliver Net Zero (2045 in Scotland, 2050 in the UK) and industrial decarbonisation (UK Government, 2021) offers opportunities to generate bioethanol for transportation fuel and industrial chemicals. Furthermore, the report stated that "*A domestic sugar beet refinery could produce sufficient bioethanol to meet the current 4% and future 10% blend requirement in the petrol fleet, which amounts to 57 million litres in total. Up to 20,000ha of land could be utilised, delivering over 170 million litres of bioethanol per annum from over 1.6 million tonnes of beet.*" Notably, the land available for arable production in Scotland is ~625800 hectares and there is, therefore, the potential to see sugar beet become a crop within normal Scottish agricultural rotations. The processing of sugar beet to extract the sugar leaves give sugar beet pulp that is ~25% (dry weight) of the sugar beet feedstock (Van Zeist et al, 2012). This pulp can be used as a livestock feed or processed further to generate pectin suitable as a gelling agent in processed foods (Kühnel et al., 2011; Adiletta et al., 2020). More recently a Scottish SME, Cellucomp, have established sugar beet pulp as a feedstock for processing into products such as composites with performance characteristics comparable to those based on conventional carbon fibre technology and rheology modifiers of industrial non-food liquids.
- Protein Crops – As with sugar beet, the Net Zero (2045 in Scotland, 2050 in the UK) and industrial decarbonisation (UK Government, 2021) agenda are having a significant influence

on food products and consumer behaviour with sales of plant-based foods increasing 50% in 2020 (Wells, 2021). This protein will be derived at scale from crops such as faba bean which has up to 35% protein (per dry weight bean) (Karkanis et al., 2018). The exploitation of these and other legumes means that processing will generate, besides the protein, bioarisings such as the bean hulls which can be valorised as a diluent to wheat to add greater fibre to bread (Ni et al, 2020), starch for fibre and fermentation to ethanol and oligosaccharides (small chain polysaccharides) with prebiotic activity (Singh et al 2017). The annual global demand for protein is increasing as populations increase. Some reports estimate world demand for animal-derived protein to double by 2050 and this raises concerns around sustainability and Green House Gas (GHG) emissions related to meat-based protein (Henchion et al., 2017). In addition, and arguably allied to this, the market for plant-based protein is projected to grow from $10.3 Bn in 2020 to $15.6 billion by 2026, recording a CAGR of 7.2% (Markets and Markets, 2021). The area of legumes (peas and beans) produced in Scotland in 2019 was 12262 ha but has the potential to expand as part of efforts on intercropping and better crop management (Wiltshire et al, 2021).

- Insects for Proteins: As described earlier the development of bioarisings as feedstocks for insects, commonly black soldier fly larvae, production is developing. This process itself also produces products besides protein with oil a common product at 20-40% w/w (Wang et al., 2017). Also, frass (insect excreta and discarded carcass casings), are common by products/bioarisings with, for example, the yellow meal worm able to convert 220g of corn and carrot-based feedstock into 4g of biomass and 180g of frass (Wang et al, 2017: Poveda, 2021). Notably, frass has a ready market as a sustainable fertiliser.

Conclusions and Recommendations

Conclusions

The recent report by the Intergovernmental Panel for Climate Change (IPCC, 2021) identified some stark consequences for the planet. It is clear that human-induced climate change is already affecting many weather and climate extremes in every region across the globe and that global surface temperature will continue to increase until at least the mid-century under all. The consequences of this are likely to be "increases in the frequency and intensity of hot extremes, marine heatwaves, and heavy precipitation, agricultural and ecological droughts in some regions".

To mitigate against these consequences, behaviours at personal to national levels need to change and shift towards low Green House Gas emission, decarbonised processes (UK Government, 2021). This will involve the development of strategies to practically apply these behaviour changes and include the development of renewable energy, increasing the efficiency of industrial processes, and accelerating the innovation of low carbon technologies.

Here we discuss one such route to climate change mitigation all whilst allowing for economic development and growth: the valorisation of agricultural bioarisings. Work undertaken in 2017 by Zero Waste Scotland (Zero Waste Scotland, 2017) identified that Scotland has, based on the 2014 data, significant levels of bioarisings from agricultural sources that currently have nil or low value uses. The cumulative total of agricultural-related bioarisings is 16.7Mt.

The bioarisings are diverse in their nature (semi-liquids, solids), source and composition and consequently further analysis has revealed that they can be used as feedstocks for a broad range of products across multiple sectors including, energy, food, cosmetics, pest and disease control, etc. Allied with this there are significant opportunities for the valorisation of agricultural bioarisings into feedstocks, ingredients and products into global markets looking to deliver both economic returns ***and*** Net Zero emissions. Notably, for the majority of the opportunities identified they are replacing fossil fuel-based based products.

It should be noted that this approach, one of resource use efficiency and sustainable/renewable feedstocks, does not impinge on agricultural practices and the current and future primary outputs. Consequently, this approach represents an opportunity for the primary producer to diversify the farm business portfolio.

Recommendations

The report identifies several opportunities for the various agricultural bioarisings and the approach of valorisation per se. From this several recommendations are immediately apparent and worthy of further investigation and support:

1. Data on bioarisings across Scotland needs to be updated to finesse the validity and extent of the opportunities identified: The opportunities presented here are based on the available data for 2014 and to truly establish these opportunities as worthy of pursuing, the sustainability of the agricultural bioarisings feedstock needs to be established. This means that the analysis needs to be refreshed and ideally run regularly.

2. The routes to valorisation have identified several common technologies. This suggests that establishing a biorefining hub and spokes, with the technologies distributed across the producer regions, could allow new entrants into the area without significant capital investment. This approach introduces a significant level of derisking into valorisation through exposure to the technologies, albeit at a limited scale, allowing interested parties and

investors to ground truth the process and generate “product”, allowing the commercial development aspect to be developed.

3. A hub and spokes-based biorefining initiative, possibly via a cooperative governance model, could have the more technically complex equipment at the hub and the simpler technologies (mills, drier etc) at the producer spokes. Indeed, the latter may already be there in another guise (grain driers etc). This approach is one commonly followed where innovation is being developed and scaled up through the technology readiness levels[22]. Furthermore, exploitation of the cooperative approach further generates several benefits to members including, lower individual capital investment and financial derisking, creation of agricultural bioarising feedstock critical mass, and farm business diversification into Net Zero enterprises.

4. A support mechanism to kick start the shift to valorising bioarisings is needed to highlight the value and utility of this process: The recent initiative by UKRI to establish a programme on circular economy research to deliver environmental and economic benefits saw them establish a coordinating hub and five national research centres[23]. However, the circular bioeconomy is notably absent in any of these activities. This is somewhat surprising given the identified levels of agricultural bioarisings in Scotland alone (16.7 tonnes), and that UK agriculture, a major component of the circular bioeconomy, was responsible for GHG emissions of 45.6 million tonnes of CO_2 in 2017: 10% of UK total GHG emissions. This omission, therefore, leaves an opportunity for Scotland to lead the way and create a focused and supported initiative on the circular bioeconomy and the valorisation of agricultural bioarisings.

5. Engagement of primary producers is vital and the need to ensure value capture at that level is key to establishing biorefining as a viable and additional addition to the farming business portfolio. The report has identified that there are opportunities, particularly for the primary producers, to add value to their bioarisings. However, it is clear that the journey from bioarisings to new business opportunities requires a diversity of skills, inputs and expertise and this highlights the need for engagement across the established and nascent supply chains.

6. Ensure that valorisation is a component of agricultural evolution. The need to significantly reduce GHG emissions has brought agricultural production processes into sharp focus. More specifically the sustainable production of dietary protein has been to focus of much attention and research with many countries developing production strategies that are encompassing a greater level of crop-based sources (Zero Waste Scotland, 2020). Processing the protein crops generates several bioarisings with unique chemistries and these offer valorisation routes to either sustainable replacements for existing products or new products per se.

[22] Technology Readiness Levels (TRL) are a type of measurement system used to assess the maturity level of a particular technology. Each technology project is evaluated against the parameters for each technology level and is then assigned a TRL rating based on the projects progress.
[23] https://www.ukri.org/news/national-circular-economy-research-programme-launches/

References

- Abreu, J.M.F. and Bruno-Soares, A.M., 1998. Characterization and utilization of rice, legume and rape straw. Options Mediterraneennes–Serie B, Etudes et Recherches, 17, pp.39-51.
- ADAS. 2013. Appendix to the Report of the Joint Government and Industry Slurry Management and Storage Project: WT1508 Slurry Storage and Management.
- ADM. 2020 ADM, InnovaFeed announce construction of world's largest insect protein facility in Decatur, Illinois. https://www.adm.com/news/news-releases/adm-innovafeed-announce-construction-of-worlds-largest-insect-protein-facility-in-decatur-illinois. Accessed 01/01/2021.
- ADAS. 2013. Report of the Joint Government and Industry Slurry Management and Storage Project.
- Adiletta, G., Brachi, P., Riianova, E., Crescitelli, A., Miccio, M. and Kostryukova, N., 2020. A simplified biorefinery concept for the valorization of sugar beet pulp: Ecofriendly isolation of pectin as a step preceding torrefaction. Waste and Biomass Valorization, 11(6), pp.2721-2733.
- AHDB. 2020. Cereal and oilseed rape harvest: final estimates – 2020. https://www.gov.scot/publications/cereal-oilseed-rape-harvest-2020-final-estimates/ . (Accessed 01/01/2021).
- AHDB. 2021. GB Potato Production. https://ahdb.org.uk/potato/production (accessed 01/07/2021).
- Akyürek, Z., 2019. Sustainable valorisation of animal manure and recycled polyester: co-pyrolysis synergy. Sustainability, 11, p.2280.
- Amberg, N. and Fogarassy, C., 2019. Green consumer behaviour in the cosmetics market. Resources, 8(3), p.137.
- Amiri, H., 2020. Recent innovations for reviving the ABE fermentation for production of butanol as a drop-in liquid biofuel. Biofuel Research Journal, 7(4), pp.1256-1266.
- Anon. 2011. COMMISSION REGULATION (EU) No 1129/2011 of 11 November 2011 amending Annex II to Regulation (EC) No 1333/2008 of the European Parliament and of the Council by establishing a Union list of food additives. Official Journal of the European Union, L 295/1.
- Anon. 2012. High value protein concentrates from wheat-bioethanol through recovery of yeast protein, and reducing fibre content of distillers dried grains. Innovate UK project No. 101070.
- Anon 2021. Plant-based Protein Market by Source (Soy, Wheat, and Pea), Type (Isolates, Concentrates, and Textured), Form, Application (Food (Dairy Alternatives, Meat Alternatives, and Performance Nutrition) and Feed), and Region - Global Forecast to 2026. Research and Markets.
- Anon. 2020. Straw prices supported by poorer yields. AHDB, https://ahdb.org.uk/news/straw-prices-supported-by-poorer-yields. Accessed on 15/06/2021.
- Anukam, A., Mohammadi, A., Naqvi, M. and Granström, K., 2019. A review of the chemistry of anaerobic digestion: Methods of accelerating and optimizing process efficiency. Processes, 7(8), p.504.
- Arabiourrutia, M., Lopez, G., Artetxe, M., Alvarez, J., Bilbao, J. and Olazar, M., 2020. Waste tyre valorization by catalytic pyrolysis–A review. Renewable and Sustainable Energy Reviews, 129, p.109932.

- Arrard, T.M. 2015. Supercritical CO2 extraction of waxes as part of a holistic biorefinery. PhD Thesis University of York. https://core.ac.uk/download/pdf/30268356.pdf. (Accessed 15/06/2021).
- Attard, T., McElroy, C., Hunt, A., 2015. Economic Assessment of Supercritical CO_2 Extraction of Waxes as Part of a Maize Stover Biorefinery. Int. J. Mol. Sci. 16, 17546-17564.
- Banaszewska, A., Cruijssen, F.C.A.M., Claassen, G.D.H. and Van der Vorst, J.G.A.J., 2014. Effect and key factors of byproducts valorization: The case of dairy industry. Journal of dairy science, 97(4), pp.1893-1908.
- Bachmair J, Effenberger M and Gronauer A. Greenhouse gas balance and resource demand of biogas plants in agriculture. Eng Life Sci 2010; 10: 1291–1300.
- Bek, D., Lennartsson Turner, M., Lanari, N., Conroy, J., & Evans, A. (2020). Transitioning to peat free horticulture in the UK: an assessment of policy, progress, opportunities and barriers. https://hta.org.uk/uploads/assets/219d3ce6-e9a2-4659-b0a52d7a1bd6dd1e/FINALCOVNTRYUNIREPORT-HTAGMAFinalCoversauthors29Sept20-1.pdf (Accessed 01/07/2021).
- Bell, J., Inman, G., McDowell, 2018. Straw and Forage Study. A Review commissioned under the Scottish Government RESAS Policy Underpinning: Special Economic Studies - 2017/18. SAC Consulting, Edinburgh.
- Birkett, E., Nicolle, W. 2021 Charging Up: Policies to deliver a comprehensive network of public EV chargepoints. Policy Exchange.
- Bom, S., Jorge, J., Ribeiro, H.M. and Marto, J., 2019. A step forward on sustainability in the cosmetics industry: A review. Journal of Cleaner Production, 225, pp.270-290.
- Bom, S., Fitas, M., Martins, A.M., Pinto, P., Ribeiro, H.M. and Marto, J., 2020. Replacing synthetic ingredients by sustainable natural alternatives: a case study using topical O/W emulsions. Molecules, 25(21), p.4887.
- Byrne, J. 2021. Insect meal producer Protix attracts over $18 M in investment. Feed Navigator (04/02/2021). https://www.feednavigator.com/Article/2021/02/04/Insect-meal-producer-Protix-attracts-over-US-18m-in-investment. (Accessed 01/03/2021).
- Campbell, R., Freitag, S., Bryan, G.J., Stewart, D. and Taylor, M.A., 2016. Environmental and genetic factors associated with solanesol accumulation in potato leaves. Frontiers in plant science, 7, p.1263.
- Cao, W. and Tibbitts, T.W., 1994. Phasic temperature change patterns affect growth and tuberization in potatoes. Journal of the American Society for Horticultural Science, 119(4), pp.775-778.
- Carmona, M., Sautua, F., Pérez-Hérnandez, O. and Reis, E.M., 2020. Role of fungicide applications on the integrated management of wheat stripe rust. Frontiers in Plant Science, 11, p.733.
- Carruthers, I.B. and Pirie, N.W., 1975. The yields of extracted protein and of residual fiber from potato haulm taken as a by-product. Biotechnology and bioengineering, 17(12), pp.1775-1782.
- Cecchi, F. and Cavinato, C., 2015. Anaerobic digestion of bio-waste: A mini-review focusing on territorial and environmental aspects. Waste Management & Research, 33(5), pp.429-438.
- Chatzifragkou, A., Kosik, O., Prabhakumari, P.C., Lovegrove, A., Frazier, R.A., Shewry, P.R. and Charalampopoulos, D., 2015. Biorefinery strategies for upgrading distillers' dried grains with solubles (DDGS). *Process biochemistry*, *50*(12), pp.2194-2207.

- Cherubini, F., Jungmeier, G., Wellisch, M., Willke, T., Skiadas, I., Van Ree, R. and de Jong, E., 2009. Toward a common classification approach for biorefinery systems. Biofuels, Bioproducts and Biorefining, 3(5), pp.534-546.
- Chowański, S., Adamski, Z., Marciniak, P., Rosiński, G., Büyükgüzel, E., Büyükgüzel, K., Falabella, P., Scrano, L., Ventrella, E., Lelario, F. and Bufo, S.A., 2016. A review of bioinsecticidal activity of Solanaceae alkaloids. Toxins, 8(3), p.60.
- Chung, C., Rojanasasithara, T., Mutilangi, W. and McClements, D.J., 2016. Stabilization of natural colors and nutraceuticals: Inhibition of anthocyanin degradation in model beverages using polyphenols. Food Chemistry, 212, pp.596-603.
- DEFRA. 2018. A Green Future: Our 25 Year Plan to Improve the Environment. DEFRA.
- DEFRA. 2020a. Review of Evidence on Integrated Pest Management: Final Report. DEFRA, Project 27269.
- DEFRA. 2020b. The Path to Sustainable Farming: An Agricultural Transition Plan 2021 to 2024
- Deloitte. 2019. The Future of agrochemicals. Deloitte, https://www2.deloitte.com/content/dam/Deloitte/us/Documents/energy-resources/us-eri-future-of-agrochemicals.pdf (Accessed 19/08/2021)
- Deswarte, F.E., Clark, J.H., Hardy, J.J. and Rose, P.M., 2006. The fractionation of valuable wax products from wheat straw using CO 2. Green Chemistry, 8(1), pp.39-42.
- Edmeades, D.C., 2003. The long-term effects of manures and fertilisers on soil productivity and quality: a review. Nutrient cycling in Agroecosystems, 66(2), pp.165-180.
- EU. 2021. Amending Annex IV to Regulation (EC) No 999/2001 of the European Parliament and of the Council as regards the prohibition to feed non-ruminant farmed animals, other than fur animals, with protein derived from animals. Official Journal of the European Union, L 295/1
- EU. 2021. EU Food Additives Database. https://webgate.ec.europa.eu/foods_system/main/index.cfm?event=substance.view&identifier=38. (Accessed 17/06/2021).
- European Biogas Association. 2015. Contribution of anaerobic digestion to the European Circular Economy. https://www.europeanbiogas.eu/wp-content/uploads/2019/05/2015-11-13_EBA-position-on-Circular-economy.pdf. (Accessed 01/04/2021).
- Farmers Weekly. 2017. What can slurry-only AD plants offer dairy farmers? Issue 03/01/2017. https://www.fwi.co.uk/livestock/can-slurry-ad-plants-offer-dairy-farmers.Accessed 17/06/2021.
- Fazli, A. and Rodrigue, D., 2020. Waste rubber recycling: A review on the evolution and properties of thermoplastic elastomers. Materials, 13(3), p.782.
- Fewell, A.M., Roddick, J.G. and Weissenberg, M., 1994. Interactions between the glycoalkaloids solasonine and solamargine in relation to inhibition of fungal growth. Phytochemistry, 37(4), pp.1007-1011.
- Fewell, A.M. and Roddick, J.G., 1997. Potato glycoalkaloid impairment of fungal development. Mycological research, 101(5), pp.597-603.
- Foito, A., McDougall, G.J. and Stewart, D., 2018. Evidence for health benefits of berries. Annual Plant Reviews online, pp.105-148.

- Foito, A. and Stewart, D., 2018. Metabolomics: A high-throughput screen for biochemical and bioactivity diversity in plants and crops. Current pharmaceutical design, 24(19), pp.2043-2054.
- Fortunati, E., Benincasa, P., Balestra, G.M., Luzi, F., Mazzaglia, A., Del Buono, D., Puglia, D. and Torre, L., 2016. Revalorization of barley straw and husk as precursors for cellulose nanocrystals extraction and their effect on PVA_CH nanocomposites. Industrial Crops and Products, 92, pp.201-217.
- Friedman, M. and Dao, L., 1992. Distribution of glycoalkaloids in potato plants and commercial potato products. Journal of Agricultural and Food Chemistry, 40(3), pp.419-423.
- Guardian. 2020. UK insect farm project for sustainable animal feed awarded £10m. The Guardian. https://www.theguardian.com/environment/2020/oct/06/insect-farm-supply-sustainable-animal-feed-wins-10m-london. Accessed 10/01/2021.
- Ghaffar, S.H., 2019. Wheat straw biorefinery for agricultural waste valorisation. Green Materials, 8(2), pp.60-67.
- Glithero, N.J., Wilson, P. and Ramsden, S.J., 2013. Straw use and availability for second generation biofuels in England. Biomass and Bioenergy, 55, pp.311-321.
- Grand View Research. 2020. Natural Hair Care Product Market Size, Share & Trends Analysis Report. Grand View Research. https://www.grandviewresearch.com/industry-analysis/natural-hair-care-products-market. (Accessed 17/06/2021).
- Griffith, C., Ribeiro Jr, G.O., Oba, M., McAllister, T.A. and Beauchemin, K.A., 2017. Potential for improving fiber digestion in the rumen of cattle (Bos taurus) through microbial inoculation from bison (Bison bison): In situ fiber degradation. Journal of animal science, 95(5), pp.2156-2167.
- Gruda, N.S., 2019. Increasing sustainability of growing media constituents and stand-alone substrates in soilless culture systems. Agronomy, 9(6), p.298.
- Halvarsson, S., Edlund, H. and Norgren, M., 2009. Manufacture of non-resin wheat straw fibreboards. Industrial crops and products, 29(2-3), pp.437-445.
- Henchion, M., Hayes, M., Mullen, A.M., Fenelon, M. and Tiwari, B., 2017. Future protein supply and demand: strategies and factors influencing a sustainable equilibrium. Foods, 6(7), p.53.
- Hexa Research. 2018 U.K. Natural Food Colors Market Size and Forecast By product (Carotenoids, Curcumin, Anthocyanin, Carmine, Copper Chlorophyllin), By application, And Trend Analysis, 2014-2025.
- Hidalgo, G.I. and Almajano, M.P., 2017. Red fruits: extraction of antioxidants, phenolic content, and radical scavenging determination: a review. Antioxidants, 6(1), p.7.
- Hopwood, L., Turley, D., Mitchell, E., Litterick, A., 2019. Opportunities for re-establishing sugar beet production and processing in Scotland: A Report for Scottish Enterprise. https://www.nnfcc.co.uk/publications/report-sugar-beet-scotland. (Accessed 01/01/2021).
- IPCC, 2021: Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press.
- Ito, S.I., Ihara, T., Tamura, H., Tanaka, S., Ikeda, T., Kajihara, H., Dissanayake, C., Abdel-Motaal, F.F. and El-Sayed, M.A., 2007. α-Tomatine, the major saponin in tomato, induces programmed

cell death mediated by reactive oxygen species in the fungal pathogen Fusarium oxysporum. FEBS letters, 581(17), pp.3217-3222.

- Ji, W., Shen, Z. and Wen, Y., 2014. A continuous hydrothermal saccharification approach of rape straw using dilute sulfuric acid. *BioEnergy Research*, *7*(4), pp.1392-1401.
- Johner, J.C.F. and Meireles, M.A.D.A., 2016. Construction of a supercritical fluid extraction (SFE) equipment: validation using annatto and fennel and extract analysis by thin layer chromatography coupled to image. Food Science and Technology, 36(2), pp.210-247.
- Kaplan, M., Ulger, S., Kokten, K., Uzun, S., Oral, E.V., Ozaktan, H., Temizgul, R. and Kale, H., 2018. Nutritional composition of potato (Solanum tuberosum L.) Haulms. Progress in Nutrition, 20(Supplement 1), pp.90-95.
- Karkanis, A., Ntatsi, G., Lepse, L., Fernández, J.A., Vågen, I.M., Rewald, B., Alsiņa, I., Kronberga, A., Balliu, A., Olle, M. and Bodner, G., 2018. Faba bean cultivation–revealing novel managing practices for more sustainable and competitive European cropping systems. Frontiers in plant science, 9, p.1115.
- Karstens, K., Trippel, S. and Götz, P., 2021. Process Engineering of the Acetone-Ethanol-Butanol (ABE) Fermentation in a Linear and Feedback Loop Cascade of Continuous Stirred Tank Reactors: Experiments, Modelling and Optimization. Fuels, 2(2), pp.108-129.
- Kim, Y.U. and Lee, B.W., 2019. Differential mechanisms of potato yield loss induced by high day and night temperatures during tuber initiation and bulking: Photosynthesis and tuber growth. Frontiers in plant science, 10, p.300.
- Kline. 2021. Global Wax Industry: Market Analysis and Opportunities. Report #y635G. Kline Europe, London.
- Kühnel, S., Schols, H.A., Gruppen, H.: Aiming for the complete utilization of sugar-beet pulp: Examination of the effects of mild acid and hydrothermal pretreatment followed by enzymatic digestion. Biotechnol. Biofuels 4, 1–14 (2011).
- Li, S.Y., Ng, I.S., Chen, P.T., Chiang, C.J. and Chao, Y.P., 2018. Biorefining of protein waste for production of sustainable fuels and chemicals. Biotechnology for biofuels, 11(1), pp.1-15.
- Li, X., Chen, S., Yu, Y., Wang, S., Xu, Z., Huang, H. and Jin, M., 2019. Ethanol production from mixtures of Distiller's Dried Grains with Solubles (DDGS) and corn. Industrial Crops and Products, 129, pp.59-66.
- Litterick, A., Bell, J., Sellars, A. and Carfrae, J., 2020. Rapid Evidence Assessment of the Alternatives to Horticultural Peat in Scotland. ClimateXChange.
- Liu, T., Klammsteiner, T., Dregulo, A.M., Kumar, V., Zhou, Y., Zhang, Z. and Awasthi, M.K., 2022. Black soldier fly larvae for organic manure recycling and its potential for a circular bioeconomy: A review. Science of The Total Environment, p.155122.
- Local United. 2016. Energy Farms—Anaerobic Digestion; National Energy Foundation: Milton Keynes, UK.
- Madau, F.A., Arru, B., Furesi, R. and Pulina, P., 2020. Insect farming for feed and food production from a circular business model perspective. Sustainability, 12(13), p.5418.
- Maina, S., Misinzo, G., Bakari, G. and Kim, H.Y., 2020. Human, Animal and Plant Health Benefits of Glucosinolates and Strategies for Enhanced Bioactivity: A Systematic Review. Molecules, 25(16), p.3682.
- Market Research Future, 2021. Global Scented Candles Market Research Report: Information by Product Type (Synthetic Wax, Paraffin Wax, Vegetable Wax, and Animal Wax), by Category

(Mass and Premium), by Distribution Channel (Store-Based and Non-Store-Based), and Region—Forecast till 2027. Market Research Future.

- Markets and Markets. 2020. Food Antioxidants Market by Source (Fruits & Vegetables, Oils, Spices & Herbs, Botanical Extracts, Gallic Acid, & Petroleum), Application (Prepared Meat & Poultry, Fats & Oils, Bakery & Confectionery, & Others), Type, Form, Region - Global Forecast to 2025. Markets and Markets.
- Markets and Markets. 2021. https://www.marketsandmarkets.com/Market-Reports/plant-based-protein-market-14715651.html. (Accessed 28/06/2021).
- Marks-Bielska, R., Bielski, S., Novikova, A. and Romaneckas, K., 2019. Straw stocks as a source of renewable energy. A case study of a district in Poland. Sustainability, 11(17), p.4714.
- Mathew, A.K., Crook, M., Chaney, K. and Humphries, A.C., 2014. Continuous bioethanol production from oilseed rape straw hydrosylate using immobilised Saccharomyces cerevisiae cells. Bioresource technology, 154, pp.248-253.
- McDougall, G.J., Stewart, D. (2012) Berries and Health: A review of the evidence. Food Health and Innovation Service. https://www.hutton.ac.uk/webfm_send/741. (Accessed 17/06/2021).
- Moraes, E.D.J.C., Silva, D.D.V., Dussán, K.J., Tesche, L.Z., de Almeida Silva, J.B., Rai, M. and de Almeida Felipe, M.D.G., 2020. Xylitol-sweetener production from barley straw: optimization of acid hydrolysis condition with the energy consumption simulation. Waste and Biomass Valorization, 11(5), pp.1837-1849.
- Mordor Intelligence Inc. 2021. Natural Food Colorants Market - Growth, Trend, COVID-19 Impact, and Forecast (2021-2026). Mordor Intelligence, US.
- Musio, S., Müssig, J. and Amaducci, S., 2018. Optimizing hemp fiber production for high performance composite applications. Frontiers in plant science, 9, p.1702.
- Natwest. 2020. Does AD pay off on smaller farms? https://natwestbusinesshub.com/articles/does-anaerobic-digestion-pay-off-on-smaller-farms. (Accessed 17/06/2021).
- NFU. 2018. Rape straw CANNOT be used for animal bedding if it has been treated with AstroKerb. https://www.nfuonline.com/cross-sector/science-and-technology/crop-protection/crop-protection/rape-straw-cannot-be-used-for-animal-bedding-if-it-has-been-treated-with-astrokerb/. (Accessed 15/06/2021).
- Ni, Q., Ranawana, V., Hayes, H.E., Hayward, N.J., Stead, D. and Raikos, V., 2020. Addition of broad bean hull to wheat flour for the development of high-fiber bread: Effects on physical and nutritional properties. Foods, 9(9), p.1192.
- Nie, H., Wang, Z., You, J., Zhu, G., Wang, H. and Wang, F., 2020. Comparison of in vitro digestibility and chemical composition among four crop straws treated by Pleurotus ostreatus. Asian-Australasian journal of animal sciences, 33(1), p.24.
- Nordqvist, P., Nordgren, N., Khabbaz, F. and Malmström, E., 2013. Plant proteins as wood adhesives: Bonding performance at the macro-and nanoscale. Industrial crops and products, 44, pp.246-252.
- Paolini, V., Petracchini, F., Segreto, M., Tomassetti, L., Naja, N. and Cecinato, A., 2018. Environmental impact of biogas: A short review of current knowledge. Journal of Environmental Science and Health, Part A, 53(10), pp.899-906.

- Parodi, A., Yao, Q., Gerrits, W.J., Mishyna, M., Lakemond, C.M., Oonincx, D.G. and Van Loon, J.J., 2022. Upgrading ammonia-nitrogen from manure into body proteins in black soldier fly larvae. Resources, Conservation and Recycling, 182, p.106343.
- Petrol Retailers Association. 2019. The UK Retail Road Fuels Market 2020. Petrol Retailers Association. https://www.ukpra.co.uk/en/about/facts-and-figures. (Accessed 17/06/2021).
- Pham, T.C.T., Angers, P. and Ratti, C., 2018. Extraction of wax-like materials from cereals. The Canadian Journal of Chemical Engineering, 96(10), pp.2273-2281.
- Pires, A.F., Marnotes, N.G., Rubio, O.D., Garcia, A.C. and Pereira, C.D., 2021. Dairy By-Products: A Review on the Valorization of Whey and Second Cheese Whey. Foods, 10(5), p.1067.
- Poveda, J., 2021. Insect frass in the development of sustainable agriculture. A review. Agronomy for Sustainable Development, 41(1), pp.1-10.
- Prospects Ltd. 2021. Planning application for an Insect farm. https://planning.org.uk/docs/20210518/168/QS9GRLCAL2C00/1hlcldrij75mzyd1.pdf. (Accessed 19/06/2021).
- QUANTIS. 2012. Comparative life cycle assessment of horticultural growing media based on peat and other growing media constituents: A report prepared for the European Peat and Growing Media Association. https://www.warum-torf.info/download/comparative-life-cycle-assessment-of-horticultural-growing-media-based-on-peat-and-other-growing-media-constituents. (Accessed 01/01/2021).
- Raud, M., Rocha-Meneses, L., Lane, D.J., Sippula, O., Shurpali, N.J. and Kikas, T., 2021. Utilization of Barley Straw as Feedstock for the Production of Different Energy Vectors. Processes, 9(4), p.726.
- Ricardo Energy & Environmen. 2018. Slurry Storage on Scottish Farms - A Feasibility Study. A Report for ClimateXChange, ED 10661 Issue Number 3. https://www.climatexchange.org.uk/media/2971/slurry-storage-on-scottish-farms.pdf
- Riera, A., Lenaghan, M. 2019. Black Soldier Fly A Circular Economy Solution for Scotland. Zero Waste Scotland. Accessed 19/06/2021. https://zerowastescotland.org.uk/sites/default/files/ZWS1388%20ZWS%20Black%20Soldier%20Fly%20CE%20Report%20Brief%20v2.pdf
- Rose, P.M., Cantrill, V., Benohoud, M., Tidder, A., Rayner, C.M. and Blackburn, R.S., 2018. Application of anthocyanins from blackcurrant (Ribes nigrum L.) fruit waste as renewable hair dyes. Journal of agricultural and food chemistry, 66(26), pp.6790-6798.
- Rebouillat, S. and Ortega-Requena, S., 2015. Potential applications of milk fractions and valorization of dairy by-products: A review of the state-of-the-art available data, outlining the innovation potential from a bigger data standpoint. Journal of Biomaterials and Nanobiotechnology, 6(03), p.176.
- Regeneron. 2021. Costs for a biogas plant. https://www.renergon-biogas.com/en/investment-costs-of-a-biogas-plant/. (Accessed 01/07/2021).
- Research and Markets. 2020. Global Agrochemical Market (2020 to 2024) - Size & Forecast with Impact Analysis of COVID-19.
- Scottish Government. 2017. Scottish Agricultural Census: June 2017. The Scottish Government by APS Group Scotland, 21 Tennant Street, Edinburgh. PPDAS306666 (10/17).
- Scottish Government. Agriculture facts and figures: 2019. Scottish Government.

- Scottish Government. 2021. Climate Change Plan: Monitoring Reports May 2021. Scottish Government.
- Sharma, K.D., Karki, S., Thakur, N.S. and Attri, S., 2012. Chemical composition, functional properties and processing of carrot—a review. Journal of food science and technology, 49(1), pp.22-32.
- Siedt, M., Schäffer, A., Smith, K.E., Nabel, M., Roß-Nickoll, M. and van Dongen, J.T., 2021. Comparing straw, compost, and biochar regarding their suitability as agricultural soil amendments to affect soil structure, nutrient leaching, microbial communities, and the fate of pesticides. Science of the Total Environment, 751, p.141607.
- Sin, E.H.K. 2012. The extraction and fractionation of waxes from biomass. PhD Thesis University of York. https://core.ac.uk/download/pdf/9554768.pdf (accessed 15/10/2021).
- Singh, B., Singh, J.P., Shevkani, K., Singh, N. and Kaur, A., 2017. Bioactive constituents in pulses and their health benefits. Journal of food science and technology, 54(4), pp.858-870.
- Skendi, A., Zinoviadou, K.G., Papageorgiou, M. and Rocha, J.M., 2020. Advances on the valorisation and functionalization of by-products and wastes from cereal-based processing industry. *Foods*, *9*(9), p.1243.
- Statistica. 2020. What is the demand for natural ingredients for cosmetics on the European market?. https://www.cbi.eu/market-information/natural-ingredients-cosmetics/what-demand. Accessed 17/06/2021.
- Svärd, A., Moriana, R., Brännvall, E. and Edlund, U., 2018. Rapeseed straw biorefinery process. ACS Sustainable Chemistry & Engineering, 7(1), pp.790-801.
- Su, G., Ong, H.C., Zulkifli, N.W.M., Ibrahim, S., Chen, W.H., Chong, C.T. and Ok, Y.S., 2022. Valorization of animal manure via pyrolysis for bioenergy: A review. Journal of Cleaner Production, p.130965.
- Sun, R., 2010. Cereal straw as a resource for sustainable biomaterials and biofuels: chemistry, extractives, lignins, hemicelluloses and cellulose. Elsevier.
- Taylor, M.A. and Fraser, P.D., 2011. Solanesol: Added value from Solanaceous waste. Phytochemistry, 72(11-12), pp.1323-1327.
- Thiessen Martens, J. and Entz, M., 2011. Integrating green manure and grazing systems: A review. Canadian Journal of Plant Science, 91(5), pp.811-824.
- Trends Market Research. 2021. Global Hair Care Market https://www.trendsmarketresearch.com/report/analysis/MMR/global-hair-care-market. (accessed 15/10/2021).
- Trouillas, P., Sancho-García, J.C., De Freitas, V., Gierschner, J., Otyepka, M. and Dangles, O., 2016. Stabilizing and modulating color by copigmentation: Insights from theory and experiment. Chemical reviews, 116(9), pp.4937-4982.
- UK Department of Transport. 2021. E10 petrol explained. https://www.gov.uk/guidance/e10-petrol-explained. (Accesses 17/06/2021).
- UK Government. 2021. Industrial Decarbonisation Strategy. UK Government. CCS0221092964, 978-1-5286-2449-7.
- Unilever. 2020. Unilever to eliminate fossil fuels in cleaning products by 2030. https://www.unilever.com/news/press-releases/2020/unilever-to-invest-1-billion-to-eliminate-fossil-fuels-in-cleaning-products-by-2030.html. (Accessed 15/06/2021).

- Van Zeist, W.J., Marinussen, M., Broekema, R., Groen, E., Kool, A., Dolman, M., Blomk, H. (2012) LCI data for the calculation tool Feedprint for greenhouse gas emissions of feed production and utilization - Sugar Industry. Blonk Consultants.
- Venturini, G., Pizarro-Alonso, A. and Münster, M., 2019. How to maximise the value of residual biomass resources: The case of straw in Denmark. Applied Energy, 250, pp.369-388.
- Vinther, P. Lawther, J.M. 2015. Separation of wax and fibers from plants. EP3152284A1, European Patent Office.
- Walker, P., Thomson, A. and Maskell, D., 2020. Straw bale construction. In Nonconventional and vernacular construction materials (pp. 189-216). Woodhead Publishing.
- Wallace, P., Homes, S., Alexander, R., England, J., Gaze, R. 2010. Review of growing media use and dominant materials (peat and alternatives) for growing media in other countries (European and international). DEFRA Report SP1206.
- Wang, H., ur Rehman, K., Liu, X., Yang, Q., Zheng, L., Li, W., Cai, M., Li, Q., Zhang, J. and Yu, Z., 2017. Insect biorefinery: a green approach for conversion of crop residues into biodiesel and protein. Biotechnology for biofuels, 10(1), pp.1-13.
- Weichselbaum, E., 2010. An overview of the role of potatoes in the UK diet. Nutrition Bulletin, 35(3), pp.195-206.
- Weiß, B.D. and Glasner, C., 2018. Evaluation of the process steps of pretreatment, pellet production and combustion for an energetic utilization of wheat chaff. Frontiers in Environmental Science, 6, p.36.
- Wells, L. 2021. UK sees record sales of plant-based foods. Talking Retail. https://www.talkingretail.com/news/industry-news/uk-sees-record-sales-of-plant-based-foods-13-01-2021/. (Accessed 28/06/2021).
- Whittaker, C. and Shield, I., 2017. Factors affecting wood, energy grass and straw pellet durability–A review. Renewable and Sustainable Energy Reviews, 71, pp.1-11.
- Wiltshire, J., Freeman, D., Willcocks, J. and Wood, C., 2021. The potential for leguminous crops in Scotland. Ricardo Energy & Environment.
- Wood, I.P., Elliston, A., Collins, S.R., Wilson, D., Bancroft, I. and Waldron, K.W., 2014. Steam explosion of oilseed rape straw: establishing key determinants of saccharification efficiency. Bioresource technology, 162, pp.175-183.
- Wu, Y. and Song, K., 2021. Source, Treatment, and Disposal of Aquaculture Solid Waste: A Review. Journal of Environmental Engineering, 147(3), p.03120012.

- Wiltshire, J., Freeman, D., Willcocks, J. and Wood, C., 2021. The potential for leguminous crops in Scotland. Ricardo Energy & Environment.

- Zero Waste Scotland. 2014. Sector Study on Beer, Whisky and Fish, Project Ref AEA/010/41.
- Zero Waste Scotland. 2017. Biorefining Potential for Scotland; Mapping bioresource arisings across Scotland. https://www.zerowastescotland.org.uk/sites/default/files/Biorefining%20Potential%20for%20Scotland%20Final%20report.pdf. (Accesses 01/01/2021).
- Zero Waste Scotland. 2018. Circular Economy Opportunities - North East Scotland. https://www.zerowastescotland.org.uk/sites/default/files/Circular%20Economy%20Opportunities%20North%20East%202018.pdf (Accessed 01/01/2021).

- Zero Waste Scotland. 2020. The Future of Food: Sustainable protein strategies around the world. https://www.zerowastescotland.org.uk/content/future-food-sustainable-protein-strategies-around-world. (Accessed 01/01/2021).
- Zhu, J., Liang, W., Yang, S., Wang, H., Shi, C., Wang, S., Zhou, W., Lu, Q., Islam, F., Xu, W. and DiTommaso, A., 2020. Safety of oilseed rape straw mulch of different lengths to rice and its suppressive effects on weeds. Agronomy, 10(2), p.201.

Appendix 1

Figure 1. All Bioarisings in this report by Local Authority (Zero Waste Scotland. 2017).

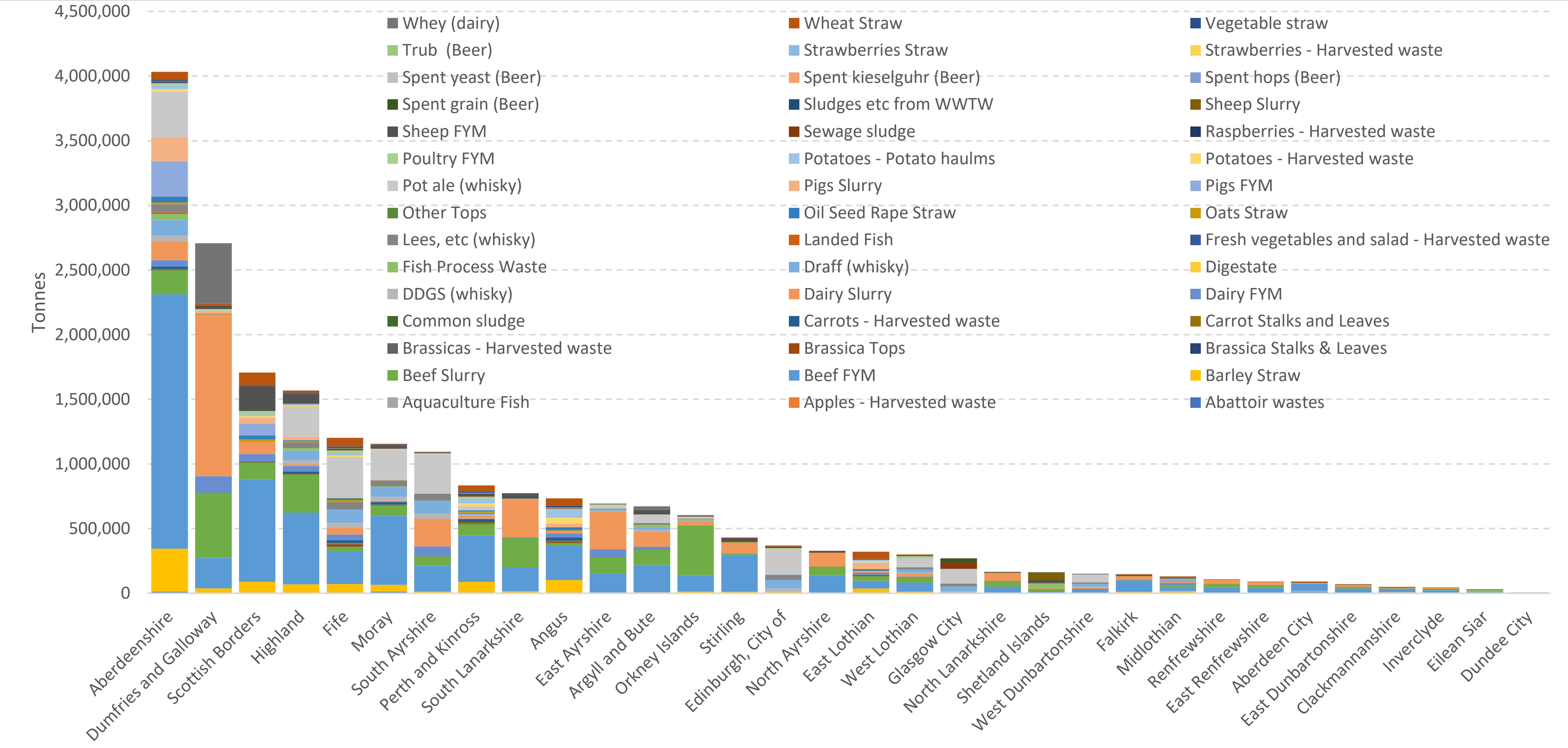


Figure 2. Bioarising by Local Authorities focussing on primary production bioarisings (Zero Waste Scotland. 2017).

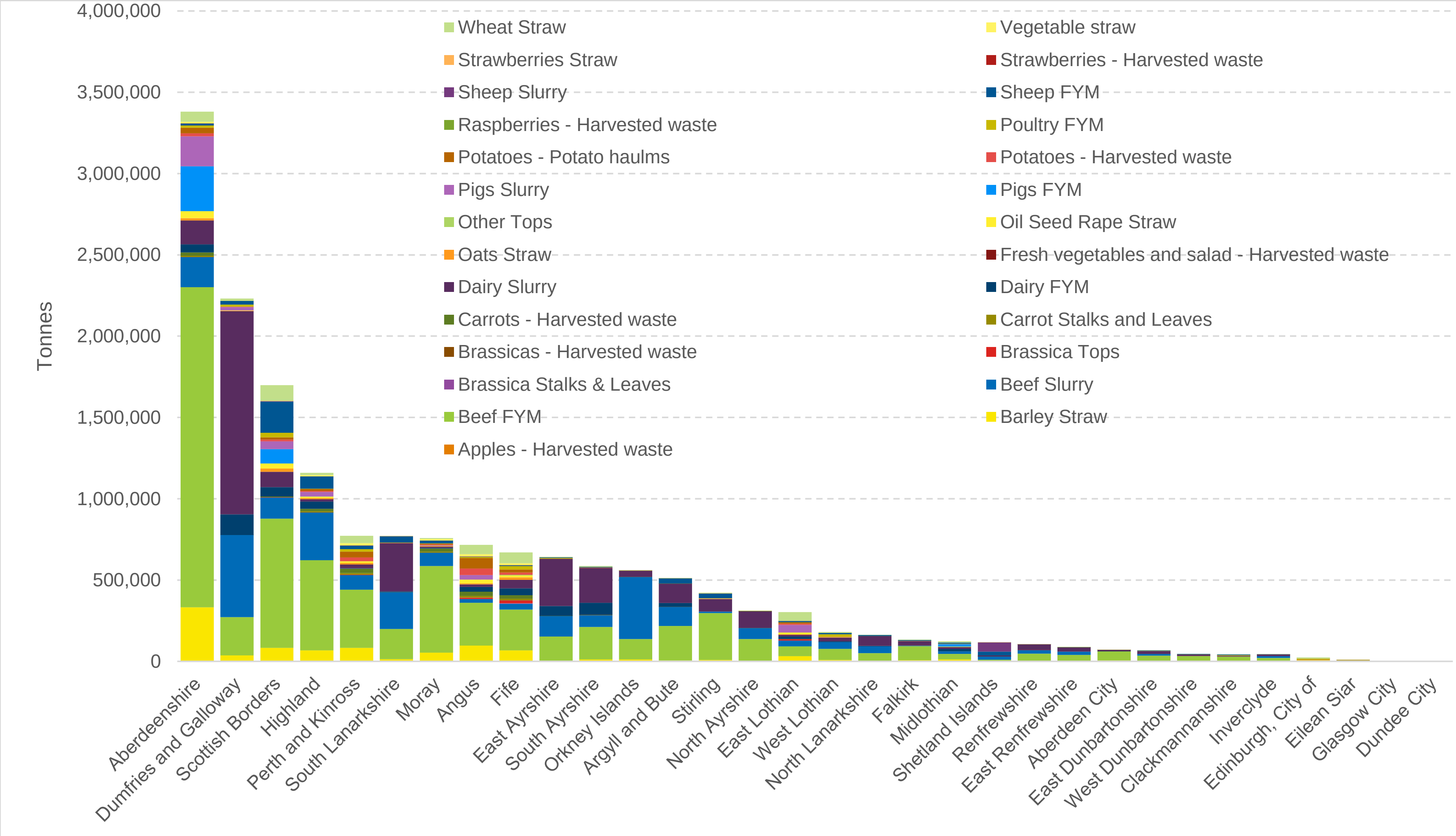


Figure 3. Manure and slurry based bioarisings available for valorisation (Zero Waste Scotland. 2017).

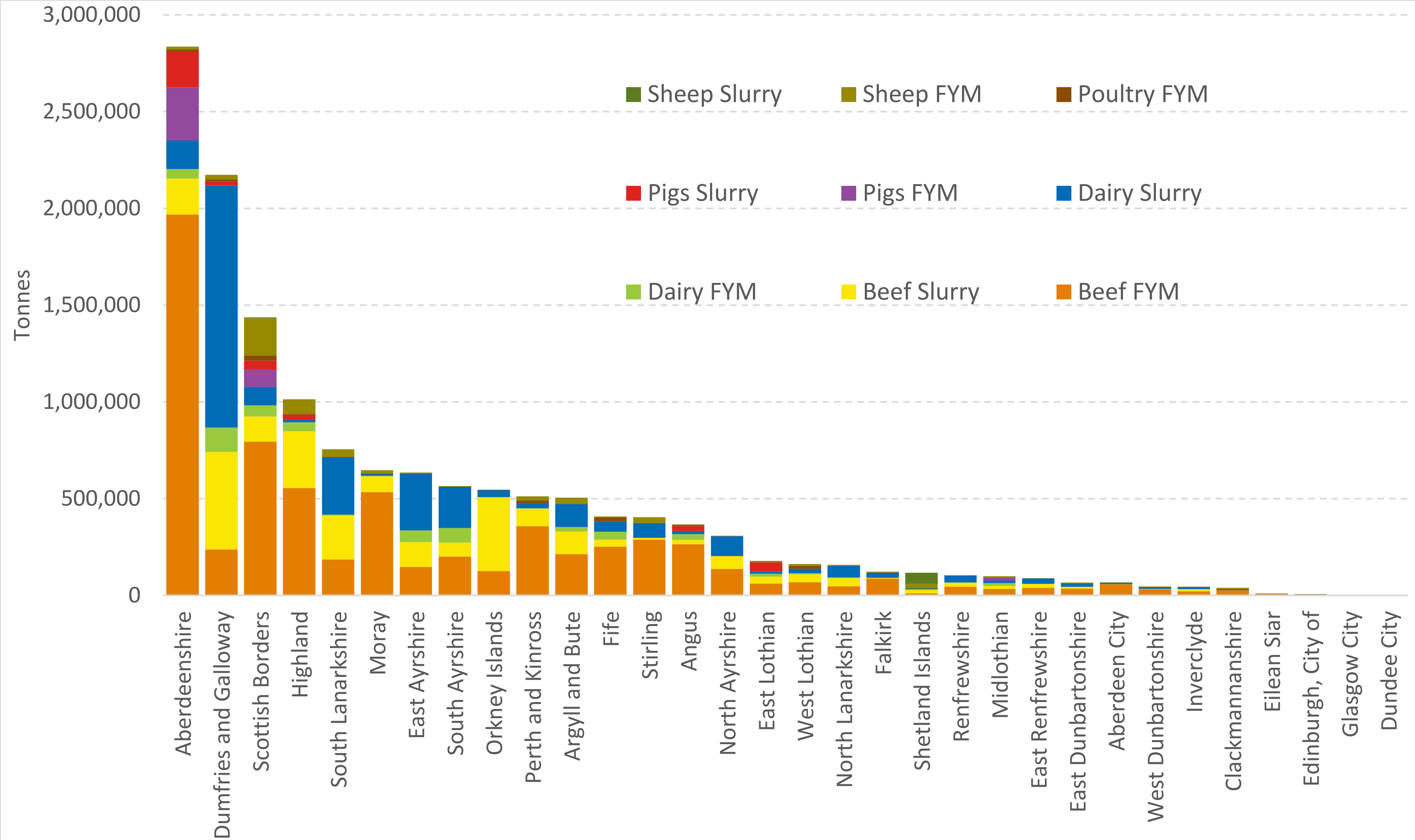


Figure 4. Crop based bioarisings available for valorisation (Zero Waste Scotland. 2017).