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Developing Fava Beans as a Sustainable Source of High-Quality Protein for Food Supply Chains through Optimised Genetics, Farming and Processing

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Abstract

Consumer preferences for plant proteins as alternatives to animal sources have increased in recent years due to improved nutritional and environmental sustainability benefits. Pulses such as peas and fava beans are excellent sources of plant-based protein (PBP); however, supply inconsistencies and price volatilities deter the development of efficient PBP-based end-to-end supply networks that meet consumers' expectations. Imported soya is the principal source of PBP for food manufacturing but this is associated with various negative factors including deforestation, land-use change and increased carbon emissions, whereas other domestically produced protein-crops such as pea are limited in their application by functionality and off-tastes. Fava beans (*Vicia faba L.*), a widely grown grain legume crop, represents an excellent source of highly nutritious yet under-utilised PBPs that have potential as an alternative source to animal-derived proteins. "Favuleux" is a multi-disciplinary innovation project focussed on evaluating and optimising the cultivation, production and prototyping of high-quality fava bean protein extracts to deliver innovative solutions for the food industry through integrated PBP supply networks. The project will establish the major factors influencing fava beans-based supply chains enabling the food industry to: (i) respond to emerging market needs; (ii) interact with end-users to build consumer confidence; and (iii) deliver enhanced training to farmers and producers to promote environmental sustainability and improve crop husbandry via resource stewardship.

Keywords: Plant-based protein; Fava beans-based supply network; Sustainable food production

1. Introduction

Global protein consumption requirements are increasing due to the changing nutritional habits and the growing population, hence intensifying pressures over food security and sustainability (Fasolin et al., 2019). Indicatively, projections estimate that by 2050 global consumption for meat and dairy products will increase by around 173 % and 158 %, respectively (FAO, 2011). In this regard, expansion of agricultural activities and productivity improvements are required to ensure food security; however, food production growth associates to inevitable overexploitation of natural resources and contributes to climate change (FAO, 2017). For example, the increased needs for arable land to breed livestock could have fuelled the Amazon forest fires to provide land for cattle farming and support beef production; since 1960 about 15 % of the Amazon forest has been replaced and almost 80 % of the deforested areas (~900,000 km^2) are now covered by pastures (Veiga et al., 2002). Contemporarily, mass balance flows to convert vegetables to animal or dairy-based proteins are not efficient as for example the production of 1 kg of meat requires 7 kg of vegetables (Nadathur et al., 2017). To that end, the yet largely unexploited potential of plant-based protein (PBP) ingredients provides an opportunity to tackle nutritional needs while fostering the transition to more sustainable food production systems (Hoehnel et al., 2019).

Pulses, such as peas, lentils, common beans, lupins and fava beans, are amenable alternative sources of protein with associated nutritional, health and sustainability benefits (FAO, 2019); however, pulses are largely under-utilised as staples and food ingredients in Western-style diets. PBP extracts are proven to deliver nutritional value and support healthy diets through their rich content in vitamins, antioxidants, fibres, anti-inflammatory agents and minerals (Kojima et al., 2018). In addition, the production of the same quantity of PBPs requires about 100 times less water compared to the equivalent protein content of animal origin (Bessada et al., 2019).

Except for the associated environmental benefits, the increasing awareness of consumers over the health benefits of plant-based diets fosters the utilisation of such isolates in food products. For example, animal-based protein intake elevates the risk of Type 2 Diabetes while the consumption of food incorporating high-quality PBP extracts facilitates the prevention of the disease (Adeva-Andany et al., 2019). Whilst there is a burgeoning market for PBP, the majority of first- and second-generation products have relied on soy or pea protein sources. Despite this being a step towards decreasing animal protein consumption, current solutions containing soy protein are reliant on South American exports that contribute to deforestation, land-use change, and transport-associated carbon emissions. Therefore, research and practise initiatives are investigating the commercial potential of crops, like pulses, as alternative and sustainable sources to animal proteins in order to ensure food security, biodiversity and sustainability (Fasolin et al., 2019).

In particular, pulses (i.e. dried edible seeds of the legume family), like peas and fava beans, comprise excellent sources of PBP that represents about 30 % of their dried weight (Bessada et al., 2019). Furthermore, pulses have the ability to 'fix' atmospheric nitrogen and improve soil fertility, thus reducing farmer's demand for fertilizers (Venkidasamy et al., 2019). Despite the sustainability benefits of pulses, their development has been hindered due to a range of challenges, including: (i) the 'lock-in' of agricultural and food systems to major crops like wheat due to greater gross margins and ease of production (Magrini et al., 2018); (ii) lower functional performance as opposed to particular animal-based proteins; (iii) limited consumer acceptability due to sensory bottlenecks like taste and lack of knowledge on pulses' preparation (Chardigny and Walrand, 2016); and (iv) lower profitability against inexpensive imported soybean (Iannetta et al., 2016).

Domestically produced pea proteins demonstrate much improved environmental credentials over soya; however, pea proteins' palatability and functionality can limit the range of applications hence leaving scope for alternative PBPs to potentially address this niche. Fava beans, as a widely grown pulse crop, represents an excellent source of highly nutritious, yet under-utilised, PBP source that is characterised by improved performance compared to current plant-derived solutions like pea and soya in human diets. Therefore, in order to establish fava beans as a protein source in the food industry, transformations and alignment between the upstream and the downstream of the respective crop supply chains are required to engage the involved stakeholders, and address yield variability and price volatility challenges (Magrini et al., 2018). To that end, the European Union, through the European Institute of Innovation & Technology (EIT) Food initiative, supports research and business efforts aiming at the commercial development of sustainably grown PBP sources to partially replace meat and dairy intake in consumers' diet. In this context, "Favuleux" is a multi-disciplinary innovation project supported by EIT Food that focuses on the development and assessment of integrated fava beans (*Vicia faba L.*) based supply networks for the delivery of locally produced high-quality protein extracts for the food industry.

The aim of this research is to present the multi-disciplinary research activities within "Favuleux", from an integrated supply network perspective, which are undertaken to evaluate and optimise the cultivation, production and prototyping of high-quality fava beans-based protein extracts to deliver innovative solutions for the food manufacturing industry. The rest of the paper is organised as follows. In Section 2, the research background with regards to fava beans-based proteins is summarised and the "Favuleux" project is presented. In Section 3, the "Favuleux" research efforts to establish fava beans-based value chains are described, along each echelon of operations. Key transformations for the establishment of fava beans-based supply systems are discussed in Section 4. Conclusions and suggested areas for future research are discoursed in Section 5.

2. Fava beans-based protein: Research background

2.1. Fava beans

Fava beans, also known as field, broad or horse beans, is a leguminous crop widely cultivated across temperate regions of Europe, Africa, Asia and Australia (Millar et al., 2019); fava beans are characterised by high protein (~250 g/1 kg of seed; predominantly comprising of legumin and vicillin) and energy (~320 kcal/100 g of dry weight) content. In 2017, an area of approximately 165,000 ha were cultivated in the UK, yielding approximately 650,000 t of produce worth more than £140 M/ha. This accounts for approximately 37 % of the European production. In France fava beans production accounts to 26 % of the European production with a crop area of 86,000 ha and a yield of 240,000 t (Statista, 2016). Although utilised extensively as feed, consumption of fava beans as a source of protein for human nutrition is thus far limited by issues related to their economic feasibility due to inconsistent supplies, price and functionality as food ingredients (Day, 2013). From a supply perspective, fava beans provide a range of key benefits (Multari et al., 2015), including the ability to: (i) grow in diverse climatic zones, (ii) be harvested, stored and transported using the same technology as to other agricultural commodities (e.g., wheat); (iii) easily isolate proteins from starch and fibre fractions thus generating additional value and secondary market opportunities. Unfortunately, fava beans can contain specific molecules (e.g., tannins, glycosides, lectins, phytic acids, saponins) that could exert anti-nutritional functions (e.g., favism, amino acid deficiency) and undesirable sensory properties; nonetheless, such unfavourable characteristics can be mitigated and often eliminated by establishing an integrated processing pipeline to further enable production scalability in respective food manufacturing systems or through selective breeding during cultivar development.

2.2. *The "Favuleux" project*

"Favuleux" (Full title – "Favuleux: Developing Fava bean as a sustainable source of high quality protein for food, through optimized genetics, farming and processing") aims to investigate supply chains required to develop fava beans as an environmentally sustainable source of protein for superior healthy dietary purposes (EIT Food, 2019). To that end, "Favuleux" will align multi-disciplinary expertise in crop genetics, agronomy, processing, quality optimization, food production and supply chain evaluation. The activity programme of the project will create an integrated supply chain to deliver nutritious, healthy and sustainable vegetable protein for food production. Innovation activities will contribute directly to stabilising the fava beans supply chain for stimulating economic growth in the food and farming sectors in an environmentally sustainable manner.

3. Fava beans value networks

3.1. *Selection and cultivation of raw material*

Fava beans have been cultivated widely in Europe since the 1970s as a break-crop in cereal rotations to alleviate pressure from pests and diseases, control weeds and provide sources of nectar for important pollinating species and residual nitrogen for subsequent crops. Fava is grown as an annual broad-acre crop, with winter and spring sown varieties harvested from late summer in the UK and Europe using conventional combining techniques. Seeds for certified elite varieties can be purchased from a range of plant breeders across Europe and are readily available to growers. Spring fava beans are sown at a rate of 35-40 seeds/m^2 and return an average yield of 5.24 t/ha (~500 g/m^2) (PGRO, 2019). Current elite fava bean varieties have broadly been selected on performance characters including establishment, disease resistance, standing ability and yield, whereas protein content has only recently received interest as a priority trait. Crude protein content ranges from 26 % to 29 % in current elite varieties of fava bean. Despite being produced over wide areas in many EU Member States (Figure 1), and demonstrating clear nutritional benefits, 2/3 of fava bean produced (in the UK) are currently used in agriculture and aquaculture, with the final 1/3 featuring as premium food product exported to North Africa (e.g., Egypt).
Greater differences in protein content have been observed in more genetically diverse landrace and experimental germplasm with levels ranging from 24 % to 36 %, demonstrating potential for further increasing levels in elite material. "Favuleux" will test a range of 10 diverse fava bean cultivars varying in protein content, composition and yield potential in order to identify optimally performing varieties that are suitable for use as food ingredients. This will facilitate selection and multiplication of germplasm for upscaling efforts to continue to develop fava bean as a viable alternative to animal and current PBPs.
The presence of anti-nutritionals such as tannins and vicine/convicine (VC) has historically posed a challenge to the wider uptake and utilisation of fava beans. However, progress has been made with reduced VC varieties through using chemical analysis (Purves et al., 2018) and the availability of white-flowered, low-tannin beans. The majority of tannins can be negated easily through removal of the fibrous testa (seed-coat) and only sections of the population deficient for glucose-6-phosphate dehydrogenase (G6PD) are susceptible to the effects of favism caused by VC.

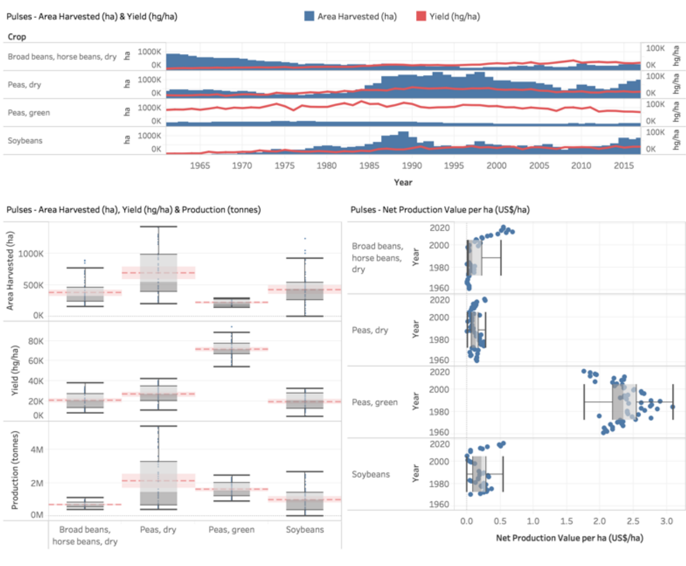

Figure 1. Broad beans as plant-based protein sources in the European Union.

Similar to many pulse crops, fava beans' performance is observed to be variable every year due to variation in the environment and biotic stress, thus leading to inconsistencies in supply and in volatile prices that often deter feed and food manufacturers. This situation has resulted in fragmented supply chains and lack of accurate reporting on market prices, production, supply and demand, along with limited engagement with consumers that hampers uptake and wider utilisation of fava bean and fava protein extracts. Legumes as a whole have received far less investment than major arable crops. However, supporting basic and translational research and development, and enhanced plant breeding efforts, could have a large and positive effect on reducing uncertainty in the food production pipeline. Ensuring growers' access to updated information and cultivation techniques is another strategy to increase crop productivity; an online training course providing information on fava beans' agronomy will be devised within "Favuleux" to support growers in sustainably intensifying production.

3.2. Processing and production

Fava beans are usually harvested at approximately 9 % moisture and then are stored or dried. Thereafter, lots are transported by road to merchants where they are visually assessed for damage, pests and diseases. The product is air cleaned to remove stones and other contaminants before further processing. Subsequently, fava seeds are de-corticated to remove the fibrous testa, before fine milling into flour and air fractionating into protein and starch. A tonne of raw fava bean will yield approximately 240 kg protein, 520 kg starch and 200 kg fibre, and a small quantity of oil. Purifying pulses into their constituent components generates additional value compared to the raw product in a similar manner to pea. Fava beans-based protein extracts (similar to pea isolates) are expected to be valued at about £5,000 per t whereas starch can be utilised effectively for brewing and feed thus generating additional income streams. However, inconsistencies in supply and price will need to be addressed.

The value chain potential of fava beans isolates depends on their quality, composition and range of functional properties. In sequence, the characteristics of fava beans extracts depend on the methods and conditions of isolation which, in turn, can efficiently accommodate beans of particular intrinsic factors like botanical variety, size, shape, amino acid content, and conformation of proteins (Multari et al., 2015). Due to under-utilisation as a food- ingredient, these characteristics have not received a great attention from industry and much progress could be made through optimising or improving these specific attributes by screening for natural or induced diversity. Currently the range of fava containing products is extremely limited and protein extracts have only recently become widely available to consumers through the specialist health-food market. PBP is a rapidly expanding sector nonetheless and further testing and validation of fava proteins in key food products to demonstrate their benefits compared to current plant-based solutions and drive wider applications and uses of the food products.

3.3. Supply chain and value network

In general, the establishment of pulses as sources of protein for food products requires the development of novel supply chains and involves the adoption of innovative business operations and technologies both upstream and downstream the respective networks. The "current state" of conventional protein sources includes meat and other animal products (like milk, eggs) and entails a linear network configuration from feed, to breeding, to processing, to final consumption. On the other end, the "future state" of PBP sources allows the configuration of circular supply networks with multiple benefits to a wider ecosystem of stakeholders. In particular, a fava beans-based protein supply chain typically should consist of six major echelons of operations, namely: (i) seeds cultivation; (ii) primary production (farming); (iii) secondary manufacturing (processing, protein extraction); (iv) food and feed product manufacturing; (v) distribution; and (vi) retailing. In the emerging ecosystem, fava beans pods can be an inexpensive source for feed while the starch remaining from the processing of the beans can be used as biofertilizer. From a supply network design perspective, crops' seasonality, farming and processing capacity constraints, transportation requirements and demand signals are key parameters that need to be captured (Apaiah and Hendrix, 2005). "Favuleux" will explore, model, simulate and optimise alternative supply chain configuration scenarios to inform the decision-making process of industrial and institutional stakeholders. Economic and environmental sustainability within the fava beans production pipeline will be evaluated using multi-layer supply chain mapping and modelling, capturing: (i) actor level supply system interdependencies; (ii) supply chain mapping and modelling (multi-tier network of firms within the supply network structure); and (iii) operations flow model, showing primary input/output material/resources and information flows from farm through to potential intermediates and end-use markets. Models will be developed in conjunction with sustainability and resources' appropriation analyses to provide an integrated evaluation of the economic and environmental viability of the fava beans-based protein pipeline. The commercial value and viability of fava beans-based protein networks requires the procurement of beans from diverse sources while the maturity of the protein extraction and food processing technology can ensure favourable functional, sensory and price properties for the consumers. Figure 2 depicts the value chain mapping of fava beans-based protein system. The highlighted in green colour actors and operations capture the "future state" transformations that occur in a fava beans-based protein value chain system, additional to the "current state" (highlighted in white colour).

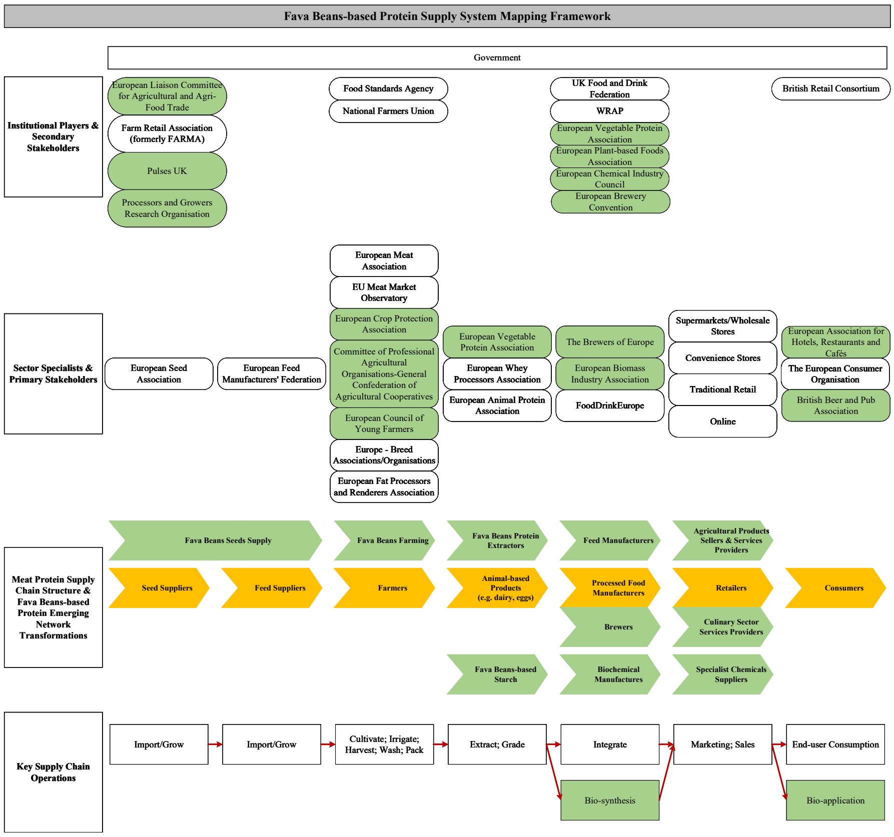

Figure 2. Value chain mapping of fava beans-based protein system.

4. Future perspectives for enhancing fava beans-based protein supply chains/commodities

Establishing novel and integrated supply chains that leverage fava beans-based protein requires that a plethora of variables are captured to ‘un-lock’ the system. In particular, a systems view is initially required to understand the prevalent factors that can dictate the causal behaviour and viability of the fava beans-based protein supply network system over time (see Figure 3). Upstream the supply chain, continuous engagement with breeders, cooperatives and farmers is paramount to facilitate their knowledge over pulses and link them to markets in order to help the breakout of the techno-economic ‘lock-in’. From the breeders’ perspective, despite the gamut of genomic tools and genetic resource collections, the small scale and number of related research programs hinders progress in developing improved bean cultivars; in 2015 less than 150 beans varieties were registered in the European Union (the respective number for wheat was about 2,250) (Magrini et al., 2016). A strategic decision refers to establishing agricultural cooperatives for the provision of selected fava beans varieties for PBP applications, exclusively cultivated or intercropped. At the farming stage, due to the nitrogen fixation of pulses, farmers need support to switch from the traditional and facile standard agro-chemical input-based model to a more biological-regulated model while information technologies are also needed to demonstrate the economic impact of the new farming practise on a multi-year basis. Operations-wise, seasonality of fava beans production along with crop variety specifications and weather conditions specify the yield and the availability of beans. Considering that the shelf life of dried beans is over a year (under normal conditions – room temperature, dry place), inventory planning and control is necessary to ensure responsiveness to demand signals. At the processing stage, advanced protein extraction processes are required to ensure high milling and protein extraction efficiency, while ensuring economic feasibility and environmental sustainability. Downstream the supply chain, culinary education of consumers over the nutritional benefits of fava beans-based isolates is required to increase the respective demand and raise awareness towards the benefits of partially substituting animal-based protein in food.

5. Conclusions

Fava beans-based protein offers a healthy, nutritious alternative to animal-based proteins and a more sustainable alternative to imported soya. In addition, fava beans-based protein is characterised by improved palatability to domestically produced pea, but yet it is largely under-utilised as a food ingredient. This situation has arisen due to various confounding factors that have resulted in fragmented supply chains and variable costs in raw materials that prohibit production of fava bean-based proteins at a scale required for the development of food products.

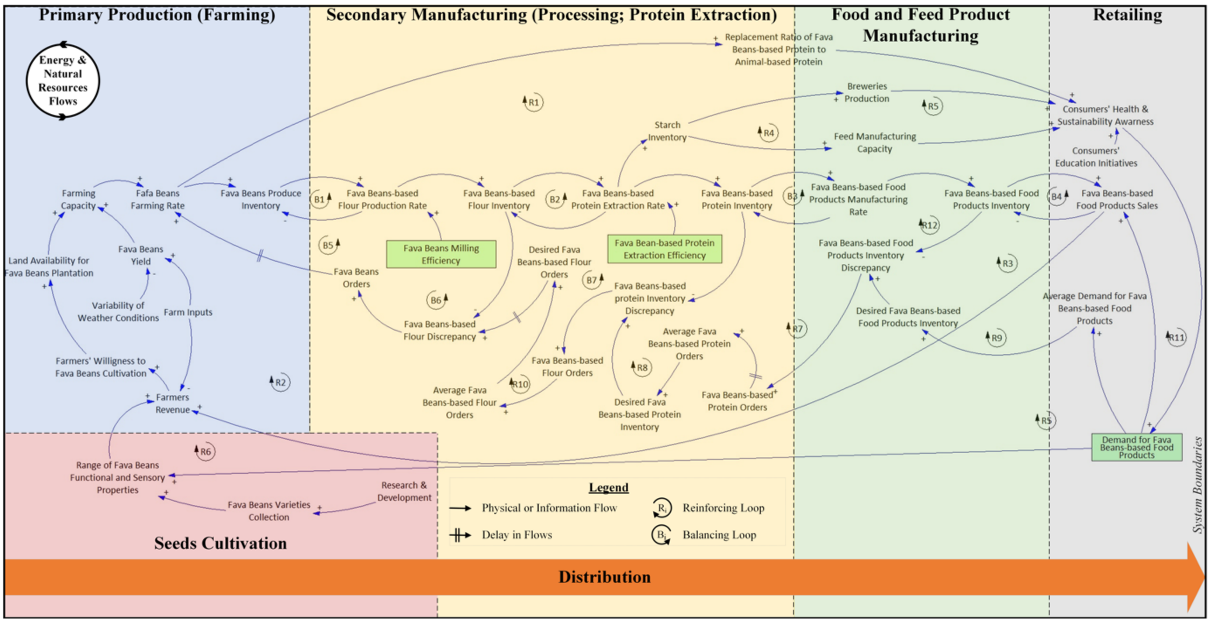

Figure 3. Causal loop diagram of the fava beans-based protein supply network system.

As a response to this, "Favuleux" will undertake a comprehensive evaluation of the factors influencing the fava beans supply chain, conducting both systems and network level analyses to identify bottlenecks in order to provide a framework for delivering sustainable sources of high-quality protein. This will actively support the concurrent project activities comprising beans' variety selection, development of efficient processing techniques and prototyping in key food products to demonstrate efficacy, build consumer confidence, and contribute to promote sustainable agricultural practices whilst effectively stimulate growth across the whole food production pipeline. Multiple areas across the supply network will require optimisation in order to ensure fava beans-based proteins can be delivered as an effective alternative to animal and current vegetable derived solutions; whilst this presents a major challenge, it also highlights many opportunities.

One of the primary steps in establishing and developing the supply chain will be demonstrating efficacy and performance of the new fava beans-based proteins to food manufacturers and consumers to encourage adoption. Greater utilisation would promote increased cultivation, potentially generating higher revenues on farm and increasing seed sales for plant breeders to meet this demand. Profits would feedback into developing new, improved fava beans varieties to better meet the requirement of industry and consumers and in-turn would aid to reduce supply inconsistencies by: (i) mitigating yield loss and environmental effects; and (ii) limiting price fluctuations thus rendering fava beans-based protein as a more economically viable alternative for food ingredients producers. Creating additional value in the supply chain will help incentivise uptake, joining currently fragmented parts of the chain to establish fava beans and its protein extract as a valued commodity. Optimising the fava beans-based protein supply networks could have a strong and positive influence on stimulating growth in across the food production pipeline, whilst contributing to support sustainable farming practices promoting legumes in the rotation and reduce reliance on environmentally unfavourable imported soya. This will require focused effort and investment to develop the necessary technologies and techniques to deliver but could contribute to enhance productivity and promote growth in agricultural and food production sectors, whilst improving consumer health and well-being.

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