Future of animal feed: Genetically modified / engineered protein crops and alternative cultivation methods

Genetically modified/engineered (GM/GE) plant crops have been incorporated in livestock feed production commercially for more than 30 years. It is estimated that 70 to 90% of the GM/GE crop biomass, which includes GM soy, is consumed by livestock globally [van Eenennaam & Young, 2014]. The most common GM/GE crops that are used in livestock feeds either as protein or as energy sources are soy, maize, and potato. These feed ingredients make for up to 10%, 30%, and 5% respectively of the typical diets of different livestock species (e.g., pigs, poultry, cattle) [Flachowsky, Chesson & Aulrich, 2007]. Genetically modifying protein crops can reduce breeding times and enhance resistances to pests, weeds and plant diseases, which also translates into more cost-effective production and less expensive feed ingredients for livestock [Eriksson et al., 2018; Gocht et al., 2021].

Home-grown (i.e., locally grown) legumes such as fava beans, lupins, and peas, and cultivations of duckweed have presented an opportunity to replace conventional protein crops (e.g., soy) with protein sources that are less damaging to the environment considering significant environmental impacts such as land degradation, fossil fuel depletion, and global warming potential [Watson et al., 2017; Sherasia et al., 2018; So?ta et al., 2019]. In addition to legumes and duckweed, other promising alternative plant-based sources of high-quality proteins for feedstuffs are algae and seaweed (macroalgae), which can also provide livestock with a range of vitamins, minerals, and fatty-acids [Costa et al., 2021, Duarte, Bruhn & Krause-Jensen, 2021]. State-of-the-art hydroponics and aquaponics practices (e.g., hydroponics fodder from cereal grain) may unlock additional benefits for sustainability primarily by reducing the land footprint of protein and reliance on synthetic inputs (e.g., fertilisers) [Bartelme et al., 2018].

Environmental implications

Land degradation, land use change and land availability related impacts

Home-grown proteins could substitute sizeable amounts of imported protein that has been grown in high-risk regions like the Brazilian Cerrado, thereby relieving land-related pressures in those regions [Paiva et al., 2020]. Future climate change projections have indicated more than a twofold increase in soybean yields for areas of the North (i.e., East Canada), and so growing soybeans locally along with other local protein crops (e.g., lupins) could enhance the effectiveness of this practice to reduce land-use related impacts [Cordeiro et al., 2019]. GM/GE protein crops are more resilient to extreme climates and could help accelerate a shift of protein crop production to Northern areas [Alig & Ahearn, 2017]. Although not many studies have quantitatively investigated the direct effect of GM/GE crops on land-use change, evidence suggests that there is the possibility of unintended negative consequences due to the displacement of locally grown proteins and knock-on effects on land use [Eriksson et al., 2018]. Introducing more protein from soilless cultivations in livestock feed, such as freshwater algae and marine macroalgae (seaweed), present another opportunity in mitigating land-related impacts [Øverland, Mydland & Skrede, 2019; Koesling et al., 2021].

An issue that should be carefully considered when evaluating alternative protein sources, particularly soilless cultivations, is that of land degradation, which is largely caused by the abandonment of crop production-associated land [Winkler et al., 2021]. Steering away from protein grown in the South (e.g., Brazilian soy) without planned sustainable alternative land uses or conservation actions (e.g., reforestation) may result in vast areas of abandoned and mismanaged land. This, in combination with effects of climate change in the south such as increasing temperatures and frequencies of extreme droughts, could exert pressures on the land surface and especially the soil organic carbon [Olsson et al., 2019]. Moreover, the specific soil management practices (e.g., tillage, reduced tillage) should be considered when genetically modified/engineered and home-grown alternatives are implemented, because these can have a great impact on soil carbon sequestration and therefore soil quality [Johnson, 2018].

Greenhouse gas emissions, atmospheric pollution and fossil fuel depletion

GM/GE protein crops being resilient to plant diseases, poor soil conditions, and nutrient availability, could help reduce the production and use of chemical inputs, further mitigating such impacts. Reducing spray runs on the field and requirements for tillage (i.e., to prepare the soil for cultivation and for weed control) can help reduce fossil fuel usage by many billions of litres annually and significantly reduce associated GHGs [Brookes & Barfoot, 2020]. Hydroponics and aquaponics may present another alternative to help mitigate GHGs and fossil fuel depletion, since they are soilless cultivations and most of their energy-related impacts are associated with the use of electricity (i.e., for lighting, greenhouse and water heating), which can be generated through renewable sources. While such alternative cultivation methods could be implemented at large scales using energy sourced from fossil fuel and still reduce several environmental impacts (e.g., land-use, nutrient leaching from fertilisers), renewable energy sourcing would largely improve their pollution mitigation potential and economic viability. The use of fertilisers is also minimal with these cultivation methods and accounts for less than 2% of their abiotic depletion potential [Chen et al., 2020]. Another way to improve livestock sector carbon footprint and energy-efficiency is by obtaining protein for livestock feed from crops grown locally (i.e., home-grown protein), since using geographically shorter supply chains could help reduce emissions and energy requirements for transportation and packaging [Taelman et al., 2015].

Nitrogen and phosphorus related impacts

GM/GE crops have increased resistances to extreme weather conditions, water and nutrient scarcity among others. With these enhanced genotypes, they can supply the livestock sector with protein throughout the year with reduced synthetic fertiliser needs [Paul, Nuccio & Basu, 2018]. Further reductions can be achieved with the adoption of algae and seaweed cultivations for protein production. In addition to the fact that these alternatives do not make use of synthetic fertilisers, they absorb very large amounts of carbon, nitrogen, and phosphorus from freshwater and oceanic ecosystems that could otherwise lead to significant aquatic acidification and eutrophication impacts [Zheng et al., 2019; Gao et al., 2021]. Most of the alternatives discussed here have the potential to greatly reduce the need for such inputs and therefore, significantly mitigate relevant environmental impacts and reduce economic costs. Despite the many opportunities to mitigate nitrogen and phosphorus related impacts of livestock feed, there are some potential, relevant risks that need to be considered. Soy protein has been a very popular choice for animal production because it is very well balanced and easily digestible. Substituting soy with alternative protein feeds may result in changes in manure and urine compositions, through varied N and P amounts excreted, which in turn may lead to higher concentrations of nitrogen on fields with their application at crop production [Trabue et al., 2021].

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Impacts to water quality and depletion of water resources

GM/GE crops, due to their resistances can provide abundant, healthy protein crop yields throughout the year without overburdening the available water resources with synthetic and chemical inputs [Paul, Nuccio & Basu, 2018; Dinar, Tieu & Huynh, 2019]. Reducing the use of fertilisers, pesticides, and insecticides can help improve the ecological quality of waters and prevent losses of biodiversity from the potential leaching of such chemicals in freshwater bodies and coastal ecosystems [Kumar et al., 2020]. However, recent research has also highlighted a potential opposite effect and threat of transgene sequences to be transferred to weeds, creating herbicide-tolerant superweeds. This may lead to an overall increase in the use of herbicides, which needs to be considered particularly in relation to water safety [Tsatsakis et al., 2017].

Soilless cultivation alternatives such as hydroponics and aquaponics can also help improve water use efficiency when compared to traditional crop production, particularly when exploiting wastewater resources [124 et al., 2019]. The uptake of toxic metals and other contaminants by the plant however, is a major concern that needs to be considered when wastewater is used for growing purposes [Cifuentes?Torres et al., 2021]. Seaweed farming can improve life below water by facilitating the development of complex habitats, stimulating biodiversity, providing organic matter within and beyond the boundaries of their habitat, and converting large amounts of carbon to low carbon feed and energy [Duarte, Bruhn & Krause-Jensen, 2021].

However, it may also be the driver for negative environmental changes that need further investigation and careful consideration when planning for large-scale seaweed farming. For example, it creates competition for light and nutrients between cultivated and wild species (e.g., planktonic communities), pollution from artificial material as farming infrastructure, noise disturbances to animals due to increased vessel activity in the area and may significantly alter the geomorphology of coastal ecosystems. This is due to the absorption of kinetic energy from waves, creating microclimates that may even extend beyond the farming boundaries [Campbell et al., 2019].

The use of home-grown proteins may present an opportunity to further reduce the water footprint of livestock feed, especially if it substitutes imported protein grown in high-risk regions in terms of water scarcity (i.e., Brazilian soy from the Cerrado) [Santos & Naval, 2020].

Impacts to biodiversity

Using GM/GE crops may drive changes to agricultural biodiversity, for example reducing weed seeds diversity by up to 36% [Andow, 2003] through the mechanisms of gene and trait transfer to non-targeted, wild species, invasiveness, and weediness [Tsatsakis et al., 2017]. Furthermore, farmers tend to use more potent chemicals when herbicide and pesticide resistant GM/GE crops expand beyond domestication boundaries (i.e., weediness), leading to biodiversity losses of terrestrial and aquatic species in nearby fields and water bodies [Schütte et al., 2017]. Such effects can be disastrous to the point that close to complete mortality (96% – 100%) has been reported as the potential effect of specific chemical herbicides on North American freshwater biodiversity [Relyea, 2005].

Economic implications

Production and supply economics

GM/GE crops can help significantly reduce costs for fertilisers, water, pesticides, and herbicides, while supplying increased yields [Kumar et al., 2020]. Given their potential to be cultivated in a broader geographic range than conventional crops, they could help reduce transportation costs if produced closer to the receiving markets or to transportation hubs. Shifting to more home-grown protein alternatives like lupin, can also help reduce fuel for transportation and the associated costs, and are generally less costly to cultivate compared to traditional protein sources like soy [Lo, Kasapis & Farahnaky, 2021]. Even in scenarios where transportation fuel may rely on renewable sources (i.e., bioethanol), it is important to consider that demand may continue driving prices of biofuel feedstocks high, which include valuable conventional protein sources for the livestock sector like soy and rapeseed [Popp et al., 2016; O'Malley & Searle, 2021]. This further highlights the need to incorporate more alternative protein sources to maintain market stability and feed availability globally.

Literature is conflicted about the economic viability of seaweed farming as an alternative to sourcing protein for feed, suggesting that it is a good solution when implemented in poorer countries especially as post-harvest processing technologies become better and more affordable [Duarte, Bruhn & Krause-Jensen, 2021], but not a cost-effective industry when implemented in the Northern countries primarily due to the increased labour costs compared to the global South [van den Burg et al., 2016; Emblemsvåg et al., 2020].

The economics of alternative protein sources at large scales is a major concern for their adoption, since only a few alternative protein production and supply systems have been tested and exploited commercially to date (e.g., genetically modified/engineered protein crops). Hydroponics and aquaponics practices are mainly implemented in small scales, for example to provide single cattle farms with fodder or in urban systems for the provision of leafy vegetables, where they generate high profits [Girma & Gebremariam, 2018; Greenfeld et al., 2019]. While little research has been done to evaluate their economic performance at industry level, there may be economic benefits through integrated production systems and the co-production of protein crops and fish-meals, also relieving pressures from the demand of such ingredients both for livestock feed and human food [Goddek et al., 2015; Palm et al., 2018].

Robustness to economic uncertainties and extreme events

Among the alternatives discussed here, there are production methods that consume less energy than conventional protein crop systems and rely much more on electricity, which can be sourced from renewables, rather than fossil fuel for their needs. These include hydroponics cultivations, algae and seaweed farming, insect farming, sourcing proteins from microorganisms, and from industry waste streams and by-products. Electricity for these systems can be sourced from a variety of renewable sources, for example from biogas and solar, wind, and tidal energy, which rapidly becomes less expensive than energy from fossil fuel. Local solutions for energy sourcing can further enhance understanding and control by governmental authorities over relevant inputs and emissions associated with the agri-food sector. Therefore, considering the dependencies between fossil fuel and feed ingredient prices and the added benefits of local renewable energy, such alternative protein sources may offer resilient solutions for the future of livestock feed, particularly as policy makers continue to support the development and diversity of the renewable energy sector [Punzi, 2019].

Over the past two years, the Covid-19 pandemic has forced strict restrictions on global trading and caused a great shock to the economy of the livestock sector due to the inaccessibility of conventional feed ingredients and other necessary resources [Lioutas & Charatsari, 2021; Rzymski et al., 2021]. Local protein sources, for instance from the home-grown cultivation systems discussed here, could potentially help mitigate some of these economic impacts. Furthermore, the pandemic has raised awareness about the investment in developing automation technologies and has driven advancements in treatment practices that eliminate the risks of pathogen and disease dispersal [Henry, 2020]. As discussed above, many of the alternatives presented here could benefit greatly from such developments, which would potentially enable them to make the step to commercial, large-scale production. Aside from Covid-19 related impacts, uncertainties around global trading dynamics and future trading partners call for protein sources that are resilient to fluctuations in import / export policies and do not rely on imported resources, including imported energy [Taghizadeh-Hesary et al, 2019; Choi et al., 2021; Yao et al., 2021]. The conflict in Ukraine has already led to historical high prices for European wheat and corn, and a huge increase in the price of sunflower meals, a main protein ingredient in livestock diets [IFIP, 2022]. Furthermore, the availability of chemical fertilisers and pesticides is expected to become very limited since Ukraine and Russia are major exporters of such inputs, while their price has already almost doubled and is expected to continue to rise [Schiffling & Kanellos, 2022]. Increasing adoption of locally grown genetically modified/engineered crops, microalgae and seaweed farming, and protein from waste streams may help minimise dependency of the livestock feed production sector on such inputs, especially if these are accompanied by a shift from fossil fuel towards renewable locally sourced energy. A diversification of protein sources may help avoid cases where feed producers shift to other profitable crops (e.g., energy crops for biofuel) in times of such crises, therefore leading to a more robust livestock sector [USDA, 2022].

Social implications

Policy making in the agri-food sector often overlooks the social pillar of sustainability and considers it as a lower priority compared to environmental and economic considerations. However, as this section discusses for each alternative protein feed category, their production and use may have important social implications for animal health and welfare, food safety and public health, and social development.

Nutritional value and animal growth

GM/GE protein crops (e.g., Soybean Mon87701) can improve conventional ingredient nutrient profiles, therefore potentially improving animal growth without compromising animal and human health [Buzoianu et al., 2013; EFSA, 2020]. Studies have found that GM/GE soy can contain between 48% - 63% of crude protein, compared to the 20% - 55% average protein content that can be obtained by conventional soy crops [Edwards et al., 2000; Sauvant et al., 2004; Giraldo et al., 2019]. This shows an opportunity in that smaller quantities of GM/GE soy crops could substitute conventional soy and fulfil the relevant livestock requirements for protein. Research has also shown that the inclusion of seaweed (macro-algae) as a protein source in poultry diets can improve growth performance, laying rates and product quality [Coudert et al., 2020]. Seaweed protein contents can vary widely however, depending on the farmed species (e.g., Palmaria palmata, Porphyra sp.) between 3% - 47% [Morais et al., 2020]. Crude protein contents from homegrown legumes and duckweed can also be comparable to conventional protein feeds, ranging between 20% - 45% [So?ta et al., 2019; 2021].

Animal health and welfare

The resistant genotypes of GM/GE crops may help mitigate losses in nutritional value and more importantly potential fungal and bacterial contaminations caused by damages or decay under poor conditions of transportation and/or storage. Using local protein crops may offer another option to mitigate fungal and bacterial contaminations caused by the transportation and/or storage of feeds, particularly when these substitute ingredients that are imported from different countries and very long distances (e.g., soybeans). Transportation of contaminated feed stuffs over long distances (e.g., from China to the USA) greatly increases the risk for transmission of pathogens, including fungal toxins and viruses. Studies have shown that this has been the main pathway for transmission of animal diseases such as the African Swine Fever and Foot/Hoof and Mouth Disease across countries and even continents [Becton et al., 2022]. These diseases, although they are not contagious and harmful to humans, can cause severe impairments for animal growth thereby leading to a significantly less productive sector [Becton et al., 2022].

Social development

Home-grown protein crops could stimulate economic and social growth in local rural communities mitigating negative impacts of urbanisation [Swain & Teufel, 2017] and smallholders, local producers may acquire a more central role in the agricultural sector.

The introduction of novel technologies and practices required for the commercialisation of alternative protein sources may promote cross-sectoral knowledge sharing and collaborations, and opportunities for education as the demand for more specialised on-farm labour may increase [Marinoudi et al., 2019]. On-farm work safety could be improved significantly through production methods that minimise the use of hazardous agrochemicals (e.g., pesticides, herbicides, chemical fertilisers) and that rely on automated technologies [Elahi et al., 2019]. Through increased efficiency, reduced on-farm risks, and reduced demand for heavy physical labour, alternative protein production chains may contribute to an overall improvement of labourer welfare and gender representation in the livestock sector.

Furthermore, the alternative protein sources presented in this section have the potential to mitigate greatly negative impacts on terrestrial and aquatic ecosystems and biodiversity, and therefore preserve ecosystem services improving firstly human wellbeing and quality of life, but also global agricultural growth [Rukundo et al., 2018]. This is particularly important when considering the extent of damages to some of the planet’s most valuable and pressured ecosystems such as the Brazilian Cerrado and Amazon’s and Borneo’s rainforests, whose services are appreciated globally [Flach et al., 2021]. As previously discussed, shifting to local protein crops, growing genetically modified/engineered crops in the global North, or adopting more of the landless cultivation methods presented here, may help reduce pressures and contribute towards the conservation of such important ecosystems [Weindl et al., 2020].

Consumer perception and acceptance

Consumer perception has always been a big concern and a barrier to the adoption of alternative proteins both for human consumption and for livestock feed. Although meat consumers and livestock farmers seem to be positive about alternatives such as GM/GE crops, insects, algae, and lab-grown feeds used in livestock production there is still much to be explored regarding the tipping point in acceptance and the specific factors that affect it [Verbeke et al., 2015; Onwezen et al., 2019]. Providing sufficient and credible information with the products at the point of sale is critical to build trust with the consumers and facilitate their habituation and acceptance towards alternative feeds [Altmann et al., 2022; Khaemba et al., 2022]. Issues of mislabelling need to be controlled and avoided particularly as long as GM/GE protein ingredients are perceived as having safety issues by some consumers [Montgomery et al., 2020]. Feed and food fraud threaten customer trust and acceptance, but also food security since they often exclude vital information about potential sources of fungal, bacterial, or chemical contamination. Other studies however have shown that overly exposing the public to risk assessment protocols for relevant modern biotechnologies and procedures (e.g, transgenesis) may contribute to feelings of distrust and fear regarding the safe use of GM/GE feeds for livestock [Giraldo et al., 2019].

Food safety

The use of GM/GE protein crops as livestock feed can have unintended negative implications for human health. The safety of most transgenic protein feeds has been evaluated in the context of “direct use as human foods” because they can also be consumed by humans (e.g., soybeans, canola). However, more research is needed to understand, monitor and regulate the risks for toxicity and allergenicity of GM/GE livestock feeds to humans through indirect exposure by consumption of livestock products [Giraldo et al., 2019]. An unintended negative impact is horizontal transfers of genes from GM/GE protein foods, the presence of which has been reported in the digestive tract of humans; this does not exclude the possibility for a transfer to humans through livestock meat products. However, the quantities recorded have been relatively small (i.e., maximum ~4% of transgenic DNA) and studies suggest that the low pH in animals’ stomach can degrade most of it before large quantities reach humans [Netherwood et al., 2004; Dona & Arvanitoyannis, 2009; Korwin-Kossakowska et al., 2020]. Another potential threat to human health may arise indirectly through the overuse of glyphosate (herbicide) that many farmers do to combat weediness of herbicide resistant GM crops; accumulated glyphosate in plant tissues and root system promotes the growth and mycotoxin production of the fungi Fusarium which can reach humans through the pathways described above [Diaz-Llano & Smith, 2006].

Aside from the adoption of protein sources that are more resilient to biological contaminants, minimising mycotoxin outbreaks starts with good management practices such as thorough grain/seed cleaning, removal of damaged seeds and debris, and sanitation of handling and storage equipment [Ráduly et al., 2021]. However, considering that pressures of climate change and unavoidable transportation/storage issues (e.g., Ukraine-Russia conflict) can greatly affect the growth and distribution of contaminants and the risks they pose to feed and food safety, it is critical that we employ multiple controlling mechanisms including alternative protein sources that are grown more locally [Magnoli et al., 2019].

Finally, recent research has shown that there is no evidence to suggest that GM/GE protein crops expose humans to novel allergens or that they are more allergenic than the conventional counterparts [Dunn et al., 2017]. On the contrary, some studies propose that GM/GE feeds and foods may even reduce the expression of proteins that lead to allergic reactions, therefore being more suitable for human consumption from this perspective [Dubois et al., 2015]. Overall, more research is required to precisely evaluate the risk for severe allergic reactions caused by animal feeds; for example, how potent can protein meals from fava beans be as an allergen for individuals with G6PD deficiency? The inclusion of seaweed in feeds may also lead to allergic reactions, similar to those exhibited due to intolerances in seaweed-extract food additives (e.g., carrageenan from red seaweed) [Santo et al., 2020].

Regulatory implications

While the popularity of GM/GE protein feed ingredients has greatly increased over the past two decades, incorporating them at commercial scales in livestock feeds requires thorough safety assessment and labelling protocols. The US and Canadian regulatory authorities perform comparisons with conventional counterparts through scientific experimentation to evaluate the safety of GM/GE products, while legislation in EU focuses more on controlling and certifying the modification process. In all cases however, it is important that the regulatory system knows the actual genes that are being transferred to the feed crop and understands potential changes in its functionality (e.g., production of novel protein / enzyme with potential allergenic action) [Giraldo et al., 2019]. Besides GM/GE protein feeds, labelling and traceability protocols are important also for the use of homegrown legumes and seaweed, especially when considering potential risk of allergies and intolerances.