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Sustainable development in circular agriculture: An illustrative bee↺legume↺poultry example

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Abstract

Circular economic principals of production are based on material flows through the system with minimum external inputs, recycling of resources, generating minimum waste, emissions, or pollution. Agriculture presents a major opportunity for the utilization of wastes, by-products and co-products in the development of a circular economy via the design of circular agricultural production systems and the creation of new sustainable value chains. The present work outlines an illustrative example of a circular bee↺legume↺poultry agricultural production system, based on the premise that: (1) there is an urgent need to prioritize pollinator stewardship and pollinator ecosystem restoration to counteract pollinator decline, (2) the EU Plant Protein Plan fosters EU-grown plant proteins including local legumes, and (3) poultry production is the most important segment of the animal production industry, and the fastest growing agricultural sub-sector. For the successful implementation of circular agriculture, multidisciplinary research is needed regarding all sectors involved, as well as practical evaluations and the realization of proof of concept depending on the geographical location. For sustainable circular agricultural practices to be adopted by agriculturists and agricultural workers, a culture shift is needed, with close cooperation between all actors involved.

KEYWORDS
apiculture, biodiversity, European Green Deal, legumes, poultry production, sustainable agriculture

1 | CIRCULAR AGRICULTURE

In contrast to the linear economic principal of production which is based on "take, make, use, and dispose," a circular economic principal of production is based on "grow, make, use, and restore," that is, on material flows through the system based on minimum external inputs, recycling of resources, generating minimum waste, emissions, or pollution (Camilleri, 2020; Ward et al., 2016). In March 2020, the European Commission adopted the new Circular Economic Action Plan (CEAP) under the umbrella of the European Green Deal as a prerequisite to achieve the EU's 2050 climate neutrality target and to halt biodiversity loss (EU, 2022a). Specifically, "the EU needs to accelerate the transition towards a regenerative growth model that gives back to the planet more than it takes, advance towards keeping its resource consumption within planetary boundaries, and therefore strive to reduce its consumption footprint and double its circular material use rate". In 2018, the EU produced 2337 million tons of waste; the 0.9% of waste generated by agriculture, forestry, and fishing (Eurostat, 2022) represents a major opportunity for the utilization of agricultural wastes, by-products and co-products in the development of a circular economy via the design of circular agricultural production systems and the creation of new sustainable value chains (Toop et al., 2017).

Basic concepts of circular economy have historically been implemented in agricultural practices, including the use of animal manure as fertilizer for crops and on-farm feed production in mixed crop-livestock farming systems. However, yield-centric intensification and specialization of agricultural production systems have led to spatial segregation of animal and crop production (Garrett et al., 2020). In Europe, between 2016 and 2019, the EU27 and United Kingdom produced 1.4 billion tons of manure from cattle (~75%) and pigs and chickens (~12% each); in 2018, 4% of European highly intensive farms produced 80% of the total amounts of manure (Köninger et al., 2021). As a result, large surpluses of on-farm nitrogen (N) and phosphorus (P) are generated that may lead to pollution of freshwater bodies, limiting the N that may be applied from animal manure in these nitrate vulnerable zones (NVZs) through Nitrates Directive 91/676/EEC (Sigurnjak et al., 2019). Instead, animal manure surplus needs to be processed and/or exported to regions of relative shortage. Meanwhile, maximum crop production yields are reached with the use of mineral fertilizers, in particular chemically produced nitrogen fertilizers, to support plant growth and crop yields. Between 1961 and 2014, as global crop production more than tripled, the supply of nitrogen fertilizer increased 955% (Pellegrini & Fernández, 2018). But conventional fertilizers, and in particular chemically produced nitrogen fertilizers, are very energy-intensive to produce. For Western Europe, Kool et al. (2021) estimated an average carbon footprint of 5.62 CO_2 eq per kg production of nitrogen fertilizer, which is considerably higher than the estimate of 1.47 CO_2 eq per kg phosphorus fertilizer and 1.36 CO_2 eq per kg potassium fertilizer. Surplus of fertilizer nutrients applied to land may be lost to water courses leading to freshwater eutrophication (Basoli et al., 2014).

In Europe, spatial segregation of crop and livestock production is particularly pronounced regarding the production of high-quality protein feed crops. Whereas ruminants eat mostly roughage (grass, forages and crop residues), ~34% and 24% of protein-rich feed is fed to pigs and poultry, respectively (Hou et al., 2016). Because the area of farmland dedicated to legume production in the EU is only ~2% of total arable land, protein-rich feeds, and soya beans in particular, are imported into the EU, mostly from Brazil and Argentina where soybean production has expanded into natural ecosystems (De Visser et al., 2014; Roman et al., 2016). Between 2001 and 2016, direct soybean-driven deforestation reached a total of 3.4 Mha across South-America (Song et al., 2021). In response, one of the EU's action points under the European Green Deal as outlined in the EU Plant Protein Plan is to "examine the EU rules to reduce the dependency on critical feed materials (e.g., soya grown on deforested land) by fostering EU-grown plant proteins as well as alternative feed materials (…)" (EU, 2020).

Spatial segregation of crop and livestock production, decreasing landscape complexity and increasing land-use intensity (i.e., crop management intensity resulting in increased crop yields) are main drivers of biodiversity loss (Abdi et al., 2021). For example, livestock grazing results in the removal of biomass, trampling, and replacement of wild animals by livestock (Alkemade et al., 2013). The production of soybean in Brazil has resulted in biodiversity damage to mammals, birds, amphibians, reptiles and plants (Garcia Lucas et al., 2021). Nitrogen addition to N-limited grasslands improves productivity but decreases biodiversity that can last for decades despite decreases in soil nitrate after cessation of nitrogen addition (Isbell et al., 2013). Pesticide use, and in particular that of ecotoxic agrochemicals such as neonics is a key driver of terrestrial and aquatic insect decline, with cascading undesirable effects on insectivorous animals and key ecosystem services such as pollination, soil formation, soil nutrient cycling, water purification, and food web support (Van der Sluijs, 2020). In response, the "Biodiversity Strategy for 2030" initiative was set by the European Commission under the umbrella of the European Green Deal to restore degraded ecosystems and manage them sustainably, addressing the key drivers of biodiversity loss (EU, 2022b). Specifically, in 2018, the European Commission adopted the "EU Pollinators Initiative" that contributes to the EU Biodiversity strategy by addressing the reasons behind the dangerous decline in wild pollinators, and to urgently act to stop it (EU, 2022c). Insect pollinators, and different species of bees in particular, provide pollinating services for some 9.5% of the total worldwide agricultural production, producing 15%–35% of livestock feed and human food, and providing about 40% of the global human nutrient supply (Kline & Joshi, 2020; Van der Sluijs, 2020). Therefore, there is an urgent need to prioritize pollinator stewardship and pollinator ecosystem restoration to counteract the current crisis (Van der Sluijs, 2020). Poultry production is the most important segment of the animal production industry, and the fastest growing agricultural sub-sector, especially in developing countries (Yildiz, 2021). The present work outlines an illustrative example of a circular bee↻legume↻poultry agricultural production system.

2 | BEE–LEGUMES

A key element for the enhancement of legume crop yields is improvement of the crop-pollinator relationship, for example, through proper integration with beekeeping and pollination services. Many legume crops are considered predominantly self-pollinated, however, many crops also possess alternative pollination and reproduction mechanisms resulting in a variable amount of pollen transfer, supporting crop diversity and adaptation to the environment and climate change (Suso et al., 2016). Legumes are bee pollinated; bee species comprise honey bees, bumble bees, and semi-social and solitary bee species.

Pollinators increase seed set and self-pollination, and enhance cross-pollination (Palmer et al., 2009; Suso et al., 2016). During visitation, the mechanical stimulation of the flower induces pollen germination, enhancing the probability of fertilization, thus increasing crop yields (Marzinzig et al., 2018). For example, Nayak et al. (2015) showed that the total yield from faba beans from open-pollination increased by 185% compared to autonomous self-pollination. Furthermore, heterosis from out-crossing pollination improves yield performance of the offspring (Marzinzig et al., 2018). The challenge of integrating managed beekeeping to increase crop production is attracting honey bees to, and retaining them on target crops. This process may be difficult as it depends on a large number of factors, including the presence of plants flowering within flight range, stage of bloom and longevity of flowering of the target crop as well as plants in the same area, plant height and location, flower size, mass, inflorescences, movement, odors, and rewards, pollen and/or nectar accessibility, quantity, and quality, as well as the colony's current needs for pollen and nectar (Jay, 1986). *Vice versa*, sustainable legume cultivation offers ecosystem and environmental services by providing a rich pollinator foraging habitat and nesting sites for wild pollinator species. Pollinator protection is of particular importance in the context of dramatic pollinator decline resulting from agricultural intensification, such as the use of agricultural chemicals, monocultures, landscape fragmentation, habitat loss, and the effects of climate change (Suso et al., 2016). In particular, loss of legume-rich habitats is implicated in wild bee declines, such as that of bumblebees (Goulson et al., 2008). Isaacs et al. (2017) proposed the concept of Integrated Crop Pollination for integration of managed honey bees into farming practices that support complimentary wild pollinators to ensure stable and sustainable crop pollination. Farming practices need to support availability of floral resources before and after crop bloom, and natural or constructed nesting and overwintering sites and shelters. Legume species with different flower structure, phenology and flowering periods can complement each other in a mixture that will increase their value to pollinators; in addition, legume crops can be considered alongside habitats that are rich in early season resources and suitable nesting habitats (Cole et al., 2022).

One of the major challenges of legume crop production is that crops are regularly attacked by pests and pathogens at various stages of crop development which strongly affects crop yields worldwide, potentially causing up to 100% losses if untreated (Otiendo et al., 2020; Suso et al., 2016). Biotic stress factors include fungi, bacteria, viruses, nematodes, and herbivorous insects. Legume plants synthesize and accumulate antinutritional factors in defense, and produce pathogenesis-related proteins in response to physical or chemical stimuli resulting from a pathogen attack (Rodríguez-Sifuentes et al., 2020). Sustainable agroecological suppression methods include mitigation by biological pest control based on natural enemies. Natural enemies of insect pests in legume crops include spiders (Araneae), true bugs (Hemiptera), ground beetles (Carabidae; Coleoptera), rove beetles (Staphylinidae; Coleoptera), ladybird beetles (Coccinelidae; Coleoptera), praying mantis (Mantodea), lacewings (Neuroptera), earwigs (Dermaptera), and hoverfly larvae (Syrphidae; Diptera) (Otiendo et al., 2020). Legume crops can be considered alongside (semi-natural) habitats with improved resources for natural enemies, including nectar, pollen, alternative prey, shelter, and hibernation habitat. However, there is lack of information on ecological requirements for most natural enemies, such as information on necessary vegetation composition and structure, abundance and spatial arrangements; therefore, information on how to achieve the best impact and increase effectiveness is still needed (Holland et al., 2016). In addition, eco-friendly biological control agents referred to as biopesticides are a sustainable method for the suppression of pests and pathogens. Biopesticides can be classified as (1) biocontrol organisms including bacteria, fungi, viruses and protozoa, (2) plant-incorporated-protectants, that is, pest management compounds produced by transgenes in crops, and (3) naturally occurring, non-toxic biochemicals (Liu et al., 2019). For example, biocontrol organisms include *Trichoderma* spp., *Pseudomonas* spp., *Bacillus* spp., *Agrobacterium* radiobacter, nonpathogenic *Fusarium* spp., *Coniothyrium* spp. and *Aspergillus niger*, *Bacillus thuringiensis*, *Metarhizium* spp., *Beauveria bassiana*, and nuclear polyhedrosis virus (Mishra et al., 2018). Alternatively, Rodríguez-Sifuentes et al. (2020) proposed exploiting the great variety of legume crop protease inhibitors (a pathogenesis-related protein type produced in the presence of pathogens that prohibit pathogens from feeding on the crop's amino acids) as biopest alternatives to agrochemicals against insects, nematodes, phytopathogenic fungi, and bacteria. Because direct extraction of protease inhibitors from legume seeds is challenging and impractical, they can be implemented through the production of transgenic plants or through their production in recombinant microorganisms (Rodríguez-Sifuentes et al., 2020). The cocktail of agrochemical pesticides used on farmland to which pollinators are exposed throughout their development and adult life is one of the driving forces of honey bee colony losses and declines of wild pollinators (Goulson et al., 2015). Instead, pollinating insects like honey bees can be used to disseminate environmentally friendly microbiological control agents (MCA) to the crops in a highly targeted manner, with innovative pollinator-vectored biocontrol techniques, or "entomovector technology" (Hokkanen & Menzler-Hokkanen, 2007). Entomovector technology is based on loading a pollinating insect with an MCA powder-carrier formulation using specifically designed dispensers. The technique has been successfully applied against plant pathogens of, for example, apple, pear, strawberry, raspberry, blueberry, tomato, sweet pepper, and sunflowers, but its potential stretches to other crops and different diseases and pests (Smagghe et al., 2012). For example, the MCA *Clonostachys rosea* has been successfully vectored by honey bees, and can be used in a wide variety of crops, including legumes and grain crops, and may target a wide range of disease types (Jensen & Dubey, 2022). In addition, bees, through sampling of honey, pollen and wax, are excellent environmental monitors to health and environmental risks resulting from unsustainable pest management practices and airborne contamination (Loglio et al., 2019; Murcia-Morales et al., 2020). Therefore, honey bees can be used to certify the sustainable management of farming systems, for example, our illustrative bee↺legume↺poultry system and the surrounding environment.

3 | LEGUMES–POULTRY

Crop rotation and intercropping systems may benefit from incorporation of leguminous crops because of their ability to fix atmospheric N through symbiosis with rhizobia bacteria in their roots, returning N into the soil, which offers an environmentally friendly alternative to chemical N fertilization (Ditzler et al., 2021). As a consequence, according to Preissel et al. (2015), acceptable yields of crops subsequent to legumes can be maintained with a reduction of N fertilization by 60 kg N ha^{-1} on average. Whereas legume crops are generally perceived to be less competitive and less profitable than cereals, crop rotations with grain legumes are found to offer increased gross margins (Pelzer et al., 2017; Von Richthofen et al., 2006); for example, cereal yields following grain legumes are some 0.5–1.6 Mg/ha higher than after cereal pre-crops (Preissel et al., 2015). Furthermore, legume crop rotation improves land use efficiency and phosphorus uptake, reduces the risk of root diseases in the following crop, and helps control weeds thus reducing pesticide use (Pelzer et al., 2017; Tang et al., 2021).

Nearly all soy meal imported to and processed in the EU is used in animal compound feed, of which about 32% is fed to broilers and other types of meat poultry and about 10% to layer poultry (Van Gelder et al., 2008). Soybean meal is a major ingredient in poultry feeds because of its relatively low water content, high protein content (∼40%, up to 50%) with a suitable amino acid profile, minimal variation in nutrient content, and anti-nutritional factors that are easily reduced or eliminated, in addition to it comprising a crop that is readily available year-round (Dei, 2011). It has a well-balanced ratio of essential amino acids and is a major source of the amino acid lysine, which is the first limiting amino acid for poultry (De Visser et al., 2014). Traditional European protein crops include Leguminosae that could substitute soybean meal in poultry farming. For example, soybean meal in broiler and layer diets can be successfully substituted by field peas and faba beans (Proskina & Cerina, 2017; Różewicz et al., 2018), which are the most prominent grain legume crops grown in the EU, and by lupine (Lee et al., 2016; Różewicz et al., 2018), chickpea (Divéky-Ertsey et al., 2022), and common vetch (Nguyen et al., 2020). Acceptable inclusion levels of local legume crops and varieties, however, depend on their ratio of essential amino acids, as well as on the level and sort of anti-nutritional factors and to which extend these can be reduced or eliminated, such as canavanine, protease inhibitors, tannins and lectins that influence the taste and digestive system and are therefore detrimental to broiler and hen performance in high quantities. For example, anti-nutritional factors of common vetch include vicianine, vicine, convicine, and tannins in addition to the main toxin γ-glutamyl-β-cyano-alanine (GBCA), such that chickens may only tolerate feed with less than 20% common vetch (Nguyen et al., 2020).

In a circular agricultural production system, poultry litter and manure, when free from antibiotics or pathogenic bacteria- and antibiotic-resistant strains, can be used to recycle nutrients and improve soil properties such as cation exchange capacity, organic matter content, and water-holding capacity (Parente et al., 2021). With an approximate 3-3-2 nitrogen–phosphorus–potassium (N–P–K) fertilizer grade equivalent, poultry litter is a good substitute to the use of inorganic fertilizers (Lin et al., 2018). For example, Ngosong et al. (2020) observed an increased number of pods per plant but a lower nodule mass in common bean fertilized with poultry manure compared with single or split-dose 20:10:10 NPK fertilizer; in addition, poultry manure had a significantly positive effect on earthworm density. Slaton et al. (2013) concluded that poultry litter provided equivalent amounts of total P and K as a commercial fertilizer, producing similar seed yields and leaf nutrient concentrations of soybean. According to Kiss et al. (2021), the nutrient supply of a 100 ha field with 1.5 Mg/ha composted with stabilized pelletized poultry litter is a potential alternative for the complex fertilization of arable lands with a smaller environmental impact compared to several combinations of chemical fertilizers. Although poultry litter also contains some heavy metals, mainly copper and zinc (Luyckx et al., 2020), it may be possible to reduce their excretion in poultry manure by at least 20%–30% (up to 50%) by feeding lower levels of minerals (Leeson & Caston, 2008). Alternatively, although subject to the development of legislation on the use of waste materials, poultry litter ash fertilizer produced in a biomass power plant is free of pathogens and toxic organic substances such as pharmaceuticals; P, Zn, and Cu from poultry litter ash can hypothetically also be used in poultry feed (Luyckx et al., 2020). In addition, eggshells can be used as a fertilizer supplying calcium and as amendment for acidic soils (King'ori, 2011), and feather waste is a rich source of keratin proteins and amino acids that can potentially be converted in to valuable N-rich organic fertilizer (Joardar & Rahman, 2018).

4 | POULTRY–BEE

Kolayli and Keskin (2020) reviewed the apitherapeutic use of honey-bee-derived products to humanity, which have been used for thousands of years. Honey and propolis (bee glue) have antioxidant, antimicrobial, and anti-inflammatory properties. Propolis exhibits synergism with a number of antibiotics against various bacterial species. Pollen and bee bread is a balanced foodstuff with essential minerals, vitamins and co-enzymes, and primary- and secondary metabolites, that exhibits antioxidant, anti-inflammatory, anticarcinogenic, antibacterial, anti-fungicidal, hepato-protective, and anti-neurodegenerative activities. Royal jelly exhibits broad pharmacological activities in humans with antimicrobial, anti-neurodegenerative, and immunostimulatory and -modulatory effects with anti-aging properties. Bee venom is currently the most important apitherapeutic agent that positively influences the immune system, central- and peripheral nervous system, and cardiovascular system, exhibiting antibacterial, antifungicidal, antiviral, anti-inflammatory, anti-arthritis, antitumoral, and anti-neurodegenerative effects (Kolayli & Keskin, 2020). In addition, apilarnil is a drone larvae extract that contains small amounts of royal jelly, bee bread, honey, and propolis; it has antiviral and immunostimulatory properties, and it is an anabolic stimulator, increases appetite, vitality, and is rich in androgenic hormones stimulating sexual development (Altan et al., 2013). These nutritional and bioactive properties can also be successfully implemented in poultry feed. For example, honey reduced panting and heart rates, and improved bone weight and density in broiler chickens during heat stress (Abioja et al., 2012). Supplementation with propolis as a natural feed additive in poultry diets has positive effects on health and performance due to its antioxidant, antibacterial, and immunostimulatory properties (Mahmoud et al., 2016). Inclusion of bee pollen and royal jelly as a feed additive in poultry diets improved immunity, animal growth, intestinal functions, and meat quality (Haščík et al., 2017; Saeed et al., 2019). Dietary inclusion of bee venom increased growth performance, breast meat yield and quality, and can be considered as a natural alternative to in-feed antibiotics (Kim et al., 2018), and apilarnil administration suppressed blood glucose and cholesterol, reduced fearfulness, and stimulated male sexual maturation in broilers (Altan et al., 2013).

5 | GENETIC SELECTION AND MANAGEMENT METHODS FOR IMPROVED CIRCULARITY

Sustainability of our illustrative circular bee↺legume↺poultry agricultural production system can be improved by genetically selecting for enhanced associations between the bee, legume, and poultry sectors. Bee vectors may be selected for improved ecosystem functioning, for example by selecting for flight range, foraging behavior and communication, preferences for specific pollens or nectars, and loading capacity (Jay, 1986). For example, pollen-hording honey bee genotypes performed significantly more pollen-foraging trips and brought back more pollen loads than standard genotypes (Cane & Schiffhauer, 2001), and willingness to collect avocado nectar relative to competing blooms is heritable and can be genetically manipulated to breed for honey bees that are better fitted for the pollination of the target crop (Afik et al., 2010).

Although several local leguminous crops may produce acceptable to high yields, they may not be able to compete against highly genetically selected and commercialized crops. Phenotypic identification and quantification of nutrients, bioactive components, and anti-nutritional factors is necessary to establish the value of local varieties as feed crops, and to exploit genetic diversity in breeding programs for genetic improvement in these traits (De la Rosa et al., 2021). For example, the production costs of common vetch are much less than that of some of the competing legumes, but the anti-nutritional factor γ-glutamyl-β-cyano-alanine (GBCA) seed toxin has hindered common vetch's use in agriculture; the development of zero-toxin varieties would facilitate its inclusion in animal diets (Nguyen et al., 2020). Indeed, those local leguminous varieties that have been improved, primarily the pea but also faba beans, show significantly improved yields and quality of the grains (Voisin et al., 2014). Other targets for genetic selection are improved (climate change-)resilience to environmental stresses including drought, heat, cold, salinity, flood, submergence and pests, disease resistance, symbiotic efficiency of rhizobia, legume dinitrogen fixation capacity, and low-nutrient tolerance, but also enhanced environmental ecosystem function through selection of pollinator friendly varieties with better floral attractiveness and rewards for insects (Denison, 2021; Palmer et al., 2009).

Furthermore, because the quantity and quality of feed resources limits livestock productive output, feeding diets based on local crop ingredients with less favorable nutrient compositions may result in genotype-by-diet interaction, that is, feed efficiency and production levels of high-potential animal genotypes may come down strongly when dietary quality becomes unfavorable. Therefore, production systems based on local feed ingredients may require a different type of animal than those currently selected in intensive, high input–high output production systems, and those animals may not have the genetics with highest production potential under optimal conditions (Rauw et al., 2020). In this context, the exploration of the adaptability to local feed ingredients of local poultry breeds with lower production levels, or of more robust, slower growing broiler breeds that replace conventional fast-growing broilers (Saatkamp et al., 2019) may be of particular interest. Likewise, within genetic (local or commercial) line, variation in production efficiency when fed local feed ingredients opens the possibility to select for novel poultry lines that are better adapted to convert local ingredients to meat or eggs.

6 | CONCLUSION

There is an urgent need to address unsustainability of human practices (Bradshaw et al., 2021). Traditional agriculture has been largely replaced by modern large-scale, specialized agricultural farming systems, monoculture, and highly intensive practices aimed at gaining the greatest economic benefit (Helgason et al., 2021). Although this "Green Revolution" resulted in large increases in crop production and declines in food prices, thereby increasing calorie intake per capita, averting large-scale famines, and supporting population growth (Khush, 1999), agricultural practices are now a major driver of climate change through requirements for land, water, and energy, as well as increased anthropogenic emissions of greenhouse gasses and waste; vice versa, climate change has a major impact on agricultural production and food security. A series of policy initiatives were set by the European Commission under the umbrella of the European Green Deal, including the Circular Economy Action Plan, the Farm-to-Fork strategy, and the Biodiversity Strategy for 2030. These strategies are set to improve sustainable resource use, reduce pressure on natural resources, transition to a sustainable food system that has a neutral or positive environmental impact, foster EU-grown plant proteins and alternative feed materials, protect nature, reverse degradation of ecosystems, and halt biodiversity loss. The new CAP 2023–2027 supports transition toward more sustainable agriculture, reflecting higher green ambitions that contribute to the targets of the European Green Deal. Circular agriculture is based on closing nutrient loops in agricultural production systems, thereby reducing the dependency on external inputs such as chemical fertilizers and pesticides for crop production, and imported feedstuffs for livestock production; this

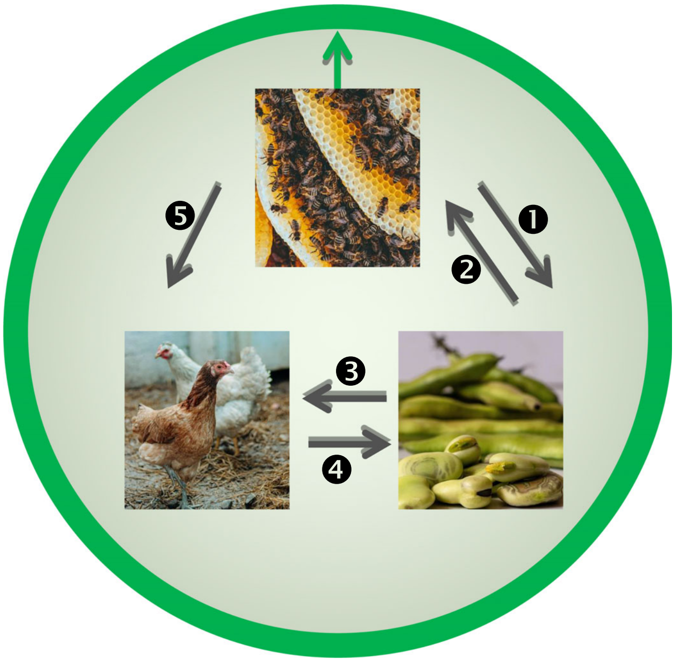

FIGURE 1 An illustrative circular bee↺legume↺poultry agricultural production system. This system differs from a linear production system that is based on modern large-scale, specialized agricultural farming systems, monoculture, highly intensive practices, and external inputs (chemically produced fertilizers for crops, and imported feedstuffs for poultry) [Colour figure can be viewed at wileyonlinelibrary.com]

makes it possible to reduce global CO_2 emissions, thereby minimizing the impact on the environment. For example, the Ministry of Agriculture, Nature and Food Quality in The Netherlands considers that "the only way to secure the future of our food supplies is to make the transition to circular agriculture as an ecologically and economically vital, prevalent production method" (LNV, 2018).

In the present work we presented an illustrative circular bee↺legume↺poultry agricultural production system (Figure 1). However, European legume protein crops have a long way to go before being competitive with imported soybean (EIP-AGRI, 2014). The production and implementation of unimproved varieties in animal feeds is hindered by lower protein content, the presence of anti-nutrients, the small production scale, lack of supplies of large and homogeneous batches of raw material, value chains that do not exist or are poorly organized, sociotechnical lock-ins and habits of specialization, a lack of awareness about the environmental impacts of existing production systems, and lack of information in general (Ditzler et al., 2021; Garrett et al., 2020; Pelzer et al., 2017; Różewicz et al., 2018). Local, unimproved feed resources may result in lower animal production, reduced production efficiency, and possibly increased costs to the consumer as a result of the reorganization of the feed supply chains, the need to supplement for unbalanced nutrient quality, or the pretreatment of feedstuffs to reduce anti-nutritional factors (Rauw et al., 2020). In addition, the implications for potential land use changes and competition (agricultural area needed as well as land allocation, and possible diversion of land used to grow food to land used to grow feed) need to be evaluated as local protein feed production may change land use nationally and may also induce other land use changes globally (Sasu-Boakye et al., 2014). Whereas improved crop yields and animal feed efficiency has decreased the land use per kg product over the last decades (Manceron et al., 2014), this trend may change by re-introduction of locally produced unimproved feed resources and possibly a concomitant reduction in animal production efficiency at least in the short-term. At the same time, land use depends on agronomic concepts that include the beneficial impacts of crop rotations on cropping systems (Schönhart et al., 2011). For example, based on pig and dairy cow production in Sweden, Sasu-Boakye et al. (2014) modeled that producing protein feeds locally instead of importing them would increase the land occupied for feed production with 11% for pigs and 25% for dairy cattle, however, local feed production reduced the estimated total yearly land use per kg pig carcass due to increased wheat yields achieved from crop rotation. Land use change is furthermore influenced by other focus areas that follow from an increasingly climate-conscious society. For example, the use of co-products, food waste, and biomass from marginal lands in livestock feed may improve sustainability of livestock production and avoid feed-food competition (Van Zanten et al., 2016). In addition, health benefits of a meat-free diet, the treatment of confined livestock, but also the negative implications of livestock production for our environment have resulted in a steady increase in the number of vegans, vegetarians or flexitarians (Rauw, 2015); reducing the amount of animal-based food shows large environmental benefits for GHG emissions, land use, and water use (Aleksandrowicz et al., 2016). The knowledge and knowledge-gaps, potential benefits, trade-offs and risks of circular agriculture should be further evaluated with multi-level and multi criteria assessment models and Life Cycle Assessment (Rufí-Salís et al., 2021; Therond et al., 2017).

For a circular agricultural system to be economically viable, all links in the circular chain need to be optimized, integrated, and adjusted to each other. We showed that genetic selection can play a prominent role, in addition to technical innovations in agronomy and the management of production animals and manure. Also, the "internet of things" (IoT) and precision farming systems can be incorporated in each sub-system for informed management, thereby increasing the efficiency of resource utilization and thus reducing the environmental footprint (Tagarakis et al., 2021). Furthermore, a necessary condition for economic sustainability and maintaining farm income on potentially reduced production yields and production efficiency is the development of business plans based on compensation through price premiums on the products; therefore, it is highly relevant to identify potential innovative market opportunities for differentiated products, based on superiority in sensory or nutritional properties and/or Green products that can be sold under a "locally and sustainably produced" label. For example, a traceability system can represent a tool able to interact with producers and consumers to foster transparency and trustworthiness (proof-of-validity and proof-of-location).

In this work we assigned a prominent role to bee vectors in circular agriculture. Management of bees is key to the provision of pollination for global food security, particularly for fruit and vegetable production, with an annual market value of additional crop production directly linked with pollination services estimated at $235 to $577 billion worldwide (IPBES, 2016). The use of bees as vectors that disseminate environmentally friendly biopesticides to reduce the dependency on chemical pesticides for crop production, and the use of bees as environmental monitors to environmental risks resulting from unsustainable pest management practices and airborne contamination is key to sustainable farming systems. Sustainability, competitiveness, resilience, and integration of the apiculture sector into circular agriculture can be guaranteed with the implementation of validated and effective good beekeeping practices (Rivera-Gomis et al., 2019).

For the successful implementation of circular agriculture, multidisciplinary research is needed regarding all sectors involved, as well as practical evaluations and the realization of proof of concept depending on the geographical location. For example, practical implementation requires knowledge on available bee vectors, legume crops and poultry breeds, their production potential, potential for improvement, water availability and use, ecosystem services, the economic benefits in rural communities where it could be implemented, and the environmental impact compared to that of traditional agricultural practices in the area. Because circularity increases the level of diversity in agricultural and environmental businesses and partnerships, this requires a diverse range of stakeholders, including primary producers, civil society, nature organizations, suppliers, the business community, processing and trade companies, and governments to get involved (LNV, 2018). Lioutas and Charatsari (2018) emphasize the importance of engagement and co-creation in the process of evaluating possible innovative solutions and taking action. Also Salem et al. (2018) clearly show that stakeholders' knowledge can only be utilized and result in improvements and actions when they are actively engaged. For sustainable circular agricultural practices to be adopted by agriculturists and agricultural workers, a culture shift is needed, with close cooperation between all actors involved.

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REFERENCES

Abdi, A. M., Carrié, R., Sidemo-Holm, W., Cai, Z., Boke-Olén, N., Smith, H. G., Eklundh, L., & Ekroos, J. (2021). Biodiversity decline with increasing crop productivity in agricultural fields revealed by satellite remote sensing. *Ecological Indicators*, *130*, 108098. https://doi.org/10.1016/j.ecolind.2021.108098

Abioja, M. O., Ogundimu, K. B., Akibo, T. E., Odukoya, K. E., Ajiboye, O. O., Abiona, J. A., Williams, T. J., Oke, O. E., & Osinowo, O. A. (2012). Growth, mineral deposition, and physiological responses of broiler chickens offered honey in drinking water during hot-dry season. *International Journal of Zoology*, 2012, 1–6. https://doi.org/10.1155/2012/403502

Afik, O., Dag, A., Yeselson, Y., Schaffer, A., & Shafir, S. (2010). Selection and breeding of honey bees for higher or lower collection of avocado nectar. *Journal of Economic Entomology*, *103*, 228–233. https://doi.org/10.1603/EC09235

Aleksandrowicz, L., Green, R., Joy, E. J. M., Smith, P., & Haines, A. (2016). The impacts of dietary change on greenhouse gas emissions, land use, water use, and health: A systematic review. *PLoS One*, *11*, e0165797. https://doi.org/10.1371/journal.pone.0165797

Alkemade, R., Reid, R. S., Van den Berg, M., De Leeuw, J., & Jeuken, M. (2013). Assessing the impacts of livestock production on biodiversity in rangeland ecosystems. *Proceedings of the National Academy of Sciences of the United States of America*, *110*, 20900–20905. https://doi.org/10.1073/pnas.10110131

Altan, Ö., Yücel, B., Açikgöz, Z., Şeremet, Ç., Kösoğlu, M., Turgan, N., & Özgönül, A. M. (2013). Apilarnil reduces fear and advances sexual development in male broilers but has no effect on growth. *British Poultry Science*, *54*, 355–361. https://doi.org/10.1080/00071668.2013.791382

Basoli, R., Spinelli, D., Fierro, A., & Jez, S. (2014). Mineral nitrogen fertilizers: Environmental impact of production and use. In F. López-Valdez & F. Fernández-Luqueño (Eds.), *Fertilizers, components, uses in agriculture and environmental impacts* (pp. 1–42). Nova Science Publishers.

Bradshaw, C. J. A., Ehrlich, P. R., Beattie, A., Ceballos, G., Crist, E., Diamond, J., Dirzo, R., Harte, J., Harte, M., Pyke, G., Ripple, W., Saltré, F., Turnbull, C., Wackernagel, M., & Blumstein, D. T. (2021). Underestimating the challenges of avoiding a ghastly future. *Frontiers in Conservation Science*, *1*, 615419. https://doi.org/10.3389/fcosc.2020.615419

Camilleri, M. A. (2020). European environment policy for the circular economy: Implications for business and industry stakeholders. *Sustainable Development*, *28*, 1804–1812. https://doi.org/10.1002/sd.2113

Cane, J. H., & Schiffhauer, D. (2001). Pollinator genetics and pollination: Do honey bee colonies selected for pollen-hoarding field better pollinators of cranberry *Vaccinium macrocarpon*? *Ecological Entomology*, *26*, 117–123. https://doi.org/10.1046/j.1365-2311.2001.00309.x

Cole, L. J., Baddeley, J. A., Robertson, D., Topp, C. F. E., Walker, R. L., & Watson, C. A. (2022). Supporting wild pollinators in agricultural landscapes through targeted legume mixtures. *Agriculture, Ecosystems & Environment*, *323*, 107648. https://doi.org/10.1016/j.agee.2021.107648

De la Rosa, L., López-Román, M. I., González, J. M., Zambrana, E., Marcos-Prado, T., & Ramírez-Parra, E. (2021). Common vetch, valuable germplasm for resilient agriculture: Genetic characterization and Spanish core collection development. Front. *Plant Science*, *12*, 617873. https://doi.org/10.3389/fpls.2021.617873

De Visser, C. L. M., Schreuder, R., & Stoddard, F. (2014). The EU's dependency on soya bean import for the animal feed industry and potential for EU produced alternatives. *OCL*, *21*, D407. https://doi.org/10.1051/ocl/2014021

Dei, H. K. (2011). Soybean as a feed ingredient for livestock and poultry. Retrieved from http://cdn.intechweb.org/pdfs/22604.pdf

Denison, R. F. (2021). Legume-imposed selection for more-efficient symbiotic rhizobia. *Proceedings of the National Academy of Sciences of the United States of America*, *118*, e2107033118. https://doi.org/10.1073/pnas.2107033118

Ditzler, L., Van Apeldoorn, D. F., Pellegrini, F., Antichi, D., Bàrberi, P., & Rossing, W. A. H. (2021). Current research on the ecosystem service potential of legume inclusive cropping systems in Europe. A review. *Agronomy for Sustainable Development*, *41*, 26. https://doi.org/10.1007/s13593-021-00678-z

Divéky-Ertsey, A., Gál, I., Madaras, K., Pusztai, P., & Csambalik, L. (2022). Contribution of pulses to agrobiodiversity in the view of EU protein strategy. *Stress*, *2*, 90–112. https://doi.org/10.3390/stresses2010008

EIP-AGRI. (2014). Final report, EIP-AGRI focus group protein crops. Retrieved from https://ec.europa.eu/eip/agriculture/sites/agri-eip/files/fg2_protein_crops_final_report_2014_en.pdf

EU. (2020). Farm to fork strategy. For a fair, healthy and environmentally-friendly food system. Retrieved from https://ec.europa.eu/food/system/files/2020-05/f2f_action-plan_2020_strategy-info_en.pdf.

EU. (2022a). European Commission, Circular economy action plan. Retrieved from https://ec.europa.eu/environment/strategy/circular-economy-action-plan_en

EU. (2022b). European Commission, Biodiversity strategy for 2030. Retrieved from https://ec.europa.eu/environment/strategy/biodiversity-strategy-2030_en

EU. (2022c). Biodiversity: Commission seeks views on strengthening actions to reverse the decline of pollinating insects. Retrieved from https://ec.europa.eu/environment/news/biodiversity-commission-seeks-views-strengthening-actions-reverse-decline-pollinating-insects-2022-03-17_en

Eurostat. (2022). Waste statistics. Retrieved from https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Waste_statistics#Total_waste_generation

Garcia Lucas, K. R., Antón, A., Ventura, M. U., Pereira Andrade, E., & Ralisch, R. (2021). Using the available indicators of potential biodiversity damage for life cycle assessment on soybean crop according to Brazilian ecoregions. *Ecological Indicators*, *127*, 107809. https://doi.org/10.1016/j.ecolind.2021.107809

Garrett, R. D., Ryschawy, J., Bell, L. W., Cortner, O., Ferreira, J., Garik, A. V. N., Gil, J. D. B., Klerkx, L., Moraine, M., Peterson, C. A., dos Reis, J. C., & Valentim, J. F. (2020). Drivers of decoupling and recoupling of crop and livestock systems at farm and territorial scales. *Ecology and Society*, *25*, 24. https://doi.org/10.5751/ES-11412-250124

Goulson, D., Lye, G. C., & Darvill, V. (2008). Decline and conservation of bumble bees. *Annual Reviews of Entomology*, *53*, 191–208. https://doi.org/10.1146/annurev.ento.53.103106.093454

Goulson, D., Nicholls, E., Botias, C., & Rotheray, E. L. (2015). Bee declines driven by combined stress from parasites, pesticides, and lack of flowers. *Science*, *347*, 1255957. https://doi.org/10.1126/science.1255957

Haščík, P., Papelková, A., Bobko, M., Trembecká, L., Elimam, I. O. E., & Capcarová, M. (2017). The effect of bee pollen in chicken diet. *World's Poultry Science Journal*, *73*, 643–649. https://doi.org/10.1017/S0043933917000435

Helgason, K. S., Iversen, K., & Julca, A. (2021). *Circular agriculture for sustainable rural development* (Policy Brief No. 105). United Nations Department of Economic and Social Affairs.

Hokkanen, H., & Menzler-Hokkanen, I. (2007). Use of honeybees in the biological control of plant diseases. *Entomological Research*, *37*, A11–A73. https://doi.org/10.1111/j.1748-5967.2007.00082.x

Holland, J. M., Bianchi, F. J. J. A., Entling, M. H., Moonen, A. C., Smith, B. M., & Jeanneret, P. (2016). Structure, function and management of semi-natural habitats for conservation biological control: A review of European studies. *Pest Management Science*, *72*, 1638–1651. https://doi.org/10.1002/ps.4318

Hou, Y., Bai, Z., Lensschen, J. P., Staritsky, I. G., Sikirica, N., Ma, L., Velthof, G. L., & Oenema, O. (2016). Feed use and nitrogen excretion of livestock in EU-27. *Agriculture, Ecosystems & Environment*, *218*, 232–244. https://doi.org/10.1016/j.agee.2015.11.025

IPBES (2016). The assessment report of the intergovernmental science-policy platform on biodiversity and ecosystem services on pollinators, pollination and food production. In S. G. Potts, V. L. Imperatriz-Fonseca, & H. T. Ngo (Eds.), *Secretariat of the intergovernmental science-policy platform on biodiversity and ecosystem services*. Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES).

Isaacs, R., Williams, N., Ellis, J., Pitts-Singer, T. L., Bommarco, R., & Vaughan, M. (2017). Integrated crop pollination: Combining strategies to ensure stable and sustainable yields of pollination-dependent crops. *Basic and Applied Ecology*, *22*, 44–60. https://doi.org/10.1016/j.baae.2017.07.003

Isbell, F., Tilman, D., Polasky, S., Binder, S., & Hawthorne, P. (2013). Low biodiversity state persists two decades after cessation of nutrient enrichment. *Ecology Letters*, *16*, 454–460. https://doi.org/10.1111/ele.12066

Jay, S. C. (1986). Spatial management of honey bees on crops. *Annual Review of Entomology*, *31*, 46–65. https://doi.org/10.1146/annurev.en.31.010186.000405

Jensen, D. F., & Dubey, M. (2022). *Clonostachys rosea* to control plant diseases. In *Burleigh Dodds series in agricultural science*. Burleigh Dodds Science Publishing.

Joardar, J. C., & Rahman, M. M. (2018). Poultry feather waste management and effects on plant growth. *International Journal of Recycling of Organic Waste in Agriculture*, *7*, 183–188. https://doi.org/10.1007/S40093-018-0204-Z

Khush, G. S. (1999). Green revolution: Preparing for the 21st century. *Genome*, *42*, 646–655. https://doi.org/10.1139/g99-044

Kim, D. H., Han, S. M., Keum, M. C., Lee, S., An, B. K., & Lee, S.-R. (2018). Evaluation of bee venom as a novel feed additive in fast-growing broilers. *British Poultry Science*, *59*, 435–442. https://doi.org/10.1080/00071668.2018.1476675

King'ori, A. M. (2011). A review of the uses of poultry eggshells and shell membranes. *International Journal of Poultry Science*, *10*, 908–912. https://doi.org/10.3923/ijps.2011.908.912

Kiss, N. É., Tamás, J., Szőllősi, N., Gorliczay, E., & Nagy, A. (2021). Assessment of composted pelletized poultry litter as an alternative to chemical fertilizers based on the environmental impact of their production. *Agriculture*, *11*, 1130. https://doi.org/10.3390/agriculture11111130

Kline, O., & Joshi, N. K. (2020). Mitigating the effects of habitat loss on solitary bees in agricultural ecosystems. *Agriculture*, *10*, 115. https://doi.org/10.3390/agriculture10040115

Kolayli, S., & Keskin, M. (2020). Natural bee products and their apitherapeutic applications. *Studies in Natural Products Chemistry*, *66*, 175–196. https://doi.org/10.1016/B978-0-12-817907-9.00007-6

Köninger, J., Lugato, E., Panagos, P., Kochupillai, M., Orgiazzi, A., & Briones, M. J. I. (2021). Manure management and soil biodiversity: Towards more sustainable food systems in the EU. *Agricultural Systems*, *194*, 103251. https://doi.org/10.1016/j.agsy.2021.103251

Kool, A., Marinussen, M., & Blonk, H. (2021). LCI data for the calculation tool Foodprint for greenhouse gas emmissions of feed production and utilization. GHG emissions of N, P, and K fertilizer production. Blonk consultants. Retrieved from http://www.blonkconsultants.nl/wp-content/uploads/2016/06/fertilizer_production-D03.pdf

Lee, M. R. F., Parkinson, S., Fleming, H. R., Theobald, V. J., Leemans, D. K., & Burgess, T. (2016). The potential of blue lupins as a protein source, in the diets of laying hens. *Veterinary and Animal Science*, *1-2*, 29–35. https://doi.org/10.1016/j.vas.2016.11.004

Leeson, S., & Caston, L. (2008). Using minimal supplements of trace minerals as a method of reducing trace mineral content of poultry manure. *Animal Feed Science and Technology*, *142*, 339–347. https://doi.org/10.1016/j.anifeedsci.2007.08.004

Lin, Y., Watts, D. B., Van Santen, E., & Cao, G. (2018). Influence of poultry litter on crop productivity under different field conditions: A meta-analysis. *Agronomy Journal*, *110*, 807–818. https://doi.org/10.2134/agronj2017.09.0513

Lioutas, E. D., & Charatsari, C. (2018). Green innovativeness in farm enterprises: What makes farmers think green? *Sustainable Development*, *26*, 337–349. https://doi.org/10.1002/sd.1709

Liu, X., Cao, A., Yan, D., Ouyang, C., Want, Q., & Li, Y. (2019). Overview of mechanisms and uses of biopesticides. *International Journal of Pest Management*, *67*, 65–72. https://doi.org/10.1080/09670874.2019.1664789

LNV. (2018). *Agriculture, nature and food—Valuable and connected: The Netherlands as a leader in circular agriculture*. Ministry of Agriculture, Nature and Food Quality (LNV) of the Netherlands.

Loglio, G., Formato, G., Pietropaoli, M., Jannoni-Sebastiani, R., Carreck, N., & Van der Steen, J. (2019). An innovative home-made beebread collector as a tool for sampling and harvesting. *Bee World*, *96*, 16–18. https://doi.org/10.1080/0005772X.2018.1556905

Luyckx, L., De Leeuw, G. H. J., & Van Caneghem, J. (2020). Characterization of poultry litter ash in view of its valorization. *Waste and Biomass Valorization*, *11*, 5333–5348. https://doi.org/10.1007/s12649-019-00750-6

Mahmoud, U. T., Cheng, H. W., & Applegate, T. J. (2016). Functions of propolis as a natural feed additive in poultry. *World's Poultry Science Journal*, *72*, 37–48. https://doi.org/10.1017/S0043933915002731

Manceron, S., Ben-Ari, T., & Dumas, P. (2014). Feeding proteins to livestock: Global land use and food vs. feed competition. *Oilseeds & fats Crops and Lipids*, *21*, D408. https://doi.org/10.1051/ocl/2014020

Marzinzig, B., Brünjes, L., Biagioni, S., Behling, H., Link, W., & Westphal, C. (2018). Bee pollinators of faba bean (*Vicia faba* L.) differ in their foraging behaviour and pollination efficiency. *Agriculture, Ecosystems & Environment*, *264*, 24–33. https://doi.org/10.1016/j.agee.2018.05.003

Mishra, R. K., Bohra, A., Kamaal, N., Kumar, K., Gandhi, K., Sujayanand, G. K., Saabale, P. R., Satheesh Naik, S. J., Sarma, B. K., Kumar, D., Mishra, M., Srivastava, D. K., & Singh, N. P. (2018). Utilization of biopesticides as sustainable solutions for management of pests in legume crops: Achievements and prospects. *Egyptian Journal of Biological Pest Control*, *28*, 3. https://doi.org/10.1186/s41938-017-0004-1

Murcia-Morales, M., Van der Steen, J. J., Vejsnaes, F., Díaz Galiano, F. J., Flores, J. M., & Fernández-Alba, A. R. (2020). APIStrip, a new tool for environmental contamination sampling through honeybee colonies. *The Science of Total Environment*, *729*, 138948. https://doi.org/10.1016/j.scitotenv.2020.138948

Ngosong, C., Nfor, I. K., Tanyi, C. B., Olougou, M. N. E., Nanganoa, L. T., & Tening, A. S. (2020). Effect of poultry manure and inorganic fertilizer on earthworms and soil fertility: Implication on root nodulation and yield of climbing bean (*Phaseolus vulgaris*). *Fundamental and Applied Agriculture*, *5*, 88–98. https://doi.org/10.5455/faa.76612

Nayak, G. K., Roberts, S. P. M., Garratt, M., Breeze, T. D., Tscheulin, T., Harrison-Cripps, J., Vogiatzakis, I. N., Stirpe, M. T., & Potts, S. G. (2015). Interactive effect of floral abundance and seminatural habitats on pollinators in field beans (*Vicia faba*). *Agriculture, Ecosystems & Environment*, *199*, 58–66. https://doi.org/10.1016/j.agee.2014.08.016

Nguyen, V., Riley, S., Nagel, S., Fisk, I., & Searle, I. R. (2020). Common vetch: A drought tolerant, high protein neglected leguminous crop with potential as a sustainable food source. Frontiers. *Plant Science*, *11*, 818. https://doi.org/10.3389/fpls.2020.00818

Otiendo, M., Steffan-Dewenter, I., Potts, S. G., Kinuthia, W., Kasina, M. J., & Garratt, M. P. D. (2020). Enhancing legume crop pollination and natural pest regulation for improved food security in changing African landscapes. *Global Food Security*, *26*, 100394. https://doi.org/10.1016/j.gfs.2020.100394

Palmer, R. G., Perez, P. T., Ortiz-Perez, E., Maalouf, F., & Suso, M. J. (2009). The role of crop-pollinator relationships in breeding for pollinator-friendly legumes: From a breeding perspective. *Euphytica*, *170*, 35–52. https://doi.org/10.1007/s10681-009-9953-0

Parente, C. E. T., Brito, E. M. S., Caretta, C. A., Cervantes-Rodríguez, E. A., Fábila-Canto, A. P., Vollú, R. E., Seldin, L., & Malm, O. (2021). Bacterial diversity changes in agricultural soils influenced by poultry litter fertilization. *Brazilian Journal of Microbiology*, *52*, 675–686. https://doi.org/10.1007/s42770-021-00437-y

Pellegrini, P., & Fernández, R. J. (2018). Crop intensification, land use, and on-farm energy-use efficiency during the worldwide spread of the green revolution. *Proceedings of the National Academy of Sciences of the United States of America*, *115*, 2335–2340. https://doi.org/10.1073/pnas.171707211

Pelzer, E., Bourlet, C., Carlsson, G., Lopez-Bellido, R. J., Jensen, E. S., & Jeuffroy, M.-H. (2017). Design, assessment and feasibility of legume-based cropping systems in three European regions. *Crop and Pasture Science*, *68*, 902–914. https://doi.org/10.1071/CP17064

Preissel, S., Reckling, M., Schläfke, N., & Zander, P. (2015). Magnitude and farm-economic value of grain legume pre-crop benefits in Europe: A review. *Field Crops Research*, *175*, 64–79. https://doi.org/10.1016/j.fcr.2015.01.012

Proskina, L., & Cerina, S. (2017). Faba beans and field peas in poultry feed: Economic assessment. *Journal of the Science of Food and Agriculture*, *97*, 4391–4398. https://doi.org/10.1002/jsfa.8415

Rauw, W. M. (2015). Philosophy and ethics of animal use and consumption: From Pythagoras to Bentham. *CABI Reviews*, *10*, 016. https://doi.org/10.1079/PAVSNNR20151001

Rauw, W. M., Rydhmer, L., Kyriazakis, I., Øverland, M., Gilbert, H., Dekkers, J. C. M., Hermesch, S., Bouquet, A., Izquierdo, E. G., Louveau, I., Luis, G., & Gomez-Raya, L. (2020). Prospects of sustainability of pig production in relations to climate change and novel feed resources. *Journal of the Science of Food and Agriculture*, *100*, 3575–3586. https://doi.org/10.1002/jsfa.10338

Rivera-Gomis, J., Bubnic, J., Ribarits, A., Moosbeckhofer, R., Alber, O., Kozmus, P., Jannoni-Sebastianini, R., Haefeker, W., Köglberger, H., Skerl, M. I. S., Tiozzo, B., Pietropaoli, M., Lubroth, J., Raizman, E., Lietaer, C., Zilli, R., Eggenhoeffner, R., Higes, M., Muz, M. N., … Formato, G. (2019). Good farming practices in apiculture. *Revue Scientifique et Technique*, *38*, 1–27. https://doi.org/10.20506/rst.38.3.3032

Rodríguez-Sifuentes, L., Marszalek, J. E., Chuck-Hernández, C., & Serna-Saldívar, S. O. (2020). Legumes protease inhibitors as biopesticides and their defense mechanisms against biotic factors. *International Journal of Molecular Sciences*, *21*, 3322. https://doi.org/10.3390/ijms21093322

Roman, G. V., Epure, L. I., Toader, M., & Lombardi, A. R. (2016). Grain legumes—Main source of vegetable proteins for European consumption. *Agro-Life Scientific Journal*, *J5*, 178–183.

Rufí-Salís, M., Petit-Boix, A., Villalba, G., Gabarrell, X., & Leipold, S. (2021). Combining LCA and circularity assessments in complex production systems: The case for urban agriculture. *Resources, Conservation and Recycling*, *166*, 105359. https://doi.org/10.1016/j.resconrec.2020.105359

Różewicz, M., Grabiński, J., & Sułek, A. (2018). Possibilities and limitations in the use of legumes from domestic cultivation in poultry feed in the context of fodder protein deficit. *Polish Journal of Agronomy*, *35*, 32–44. https://doi.org/10.26114/pja.iung.364.2018.35.04

Saatkamp, H. W., Vissers, L. S. M., Van Horne, P. L. M., & De Jong, I. C. (2019). Transition from conventional broiler meat to meat from production concepts with higher animal welfare: Experiences from The Netherlands. *Animals*, *9*, 483. https://doi.org/10.3390/ani9080483

Saeed, M., Kalhoro, S. A., Naveed, M., Hassan, F. U., Umar, M., Rashid, M., Memon, S. A., Soomro, F., Arain, M. A., & Chao, S. (2019). Prospects of royal jelly as a potential natural feed additive in poultry diets. *World's Poultry Science Journal*, *74*, 499–508. https://doi.org/10.1017/S004393391800048X

Salem, M. A., Shawtari, F., Shamsudin, M. F., & Hussain, H. B. I. (2018). The consequences of integrating stakeholder engagement in sustainable development (environmental perspectives). *Sustainable Development*, *26*, 255–268.

Sasu-Boakye, Y., Cederberg, C., & Wirsenius, S. (2014). Localizing livestock protein feed production and the impact on land use and greenhouse gas emissions. *Animal*, *8*, 1339–1348. https://doi.org/10.1017/S1751731114001293

Schönhart, M., Schmid, E., & Schneider, U. A. (2011). CropRota—A crop rotation model to support integrated land use assessments. *European Journal of Agronomy*, *34*, 263–277. https://doi.org/10.1016/j.eja.2011.02.004

Slaton, N. A., Roberts, T. L., Golden, B. R., Ross, W. J., & Norman, R. J. (2013). Soybean response to phosphorus and potassium supplied as inorganic fertilizer or poultry litter. *Agronomy Journal*, *105*, 812–820. https://doi.org/10.2134/agronj2012.0490

Sigurnjak, I., Brienza, C., Snauwaert, E., De Dobbelaera, A., De Mey, J., Vaneeckhaute, C., Michels, E., Schoumans, O., Adani, F., & Meers, E. (2019). Production and performance of bio-based mineral fertilizers from agricultural waste using ammonia (tripping)-scrubbing technology. *Waste Management*, *89*, 265–274. https://doi.org/10.1016/j.wasman.2019.03.043

Smagghe, G., Mommaerts, V., Hokkanen, H., & Menzler-Hokkanen, I. (2012). Multitrophic interactions: The entomovector technology. In G. Smagghe & I. Diaz (Eds.), *Arthropod-plant interactions: Novel insights and approaches for IPM Progress in Biological Control* (Vol. 14, pp. 127–157). Springer Science+Business Media B.V.

Song, X. P., Hansen, M. C., Potapov, P., Adusei, B., Pickering, J., Adami, M., Lima, A., Zalles, V., Stehman, S. V., Di Bella, C. M., Conde, M. C., Copati, E. J., Fernandes, L. B., Hernandez-Serna, A., Jantz, S. M., Pickens, A. H., Turubanova, S., & Tyukavi, A. (2021). Massive soybean expansion in South America since 2000 and implications for conservation. *Nature Sustainability*, *4*, 784–792. https://doi.org/10.1038/s41893-021-00729-z

Suso, M. J., Bebeli, P. J., Christmann, S., Mateus, C., Negri, V., Pinheiro de Carvalho, M. A. A., Torricelli, R., & Veloso, M. M. (2016). Enhancing legume ecosystem serviced through an understanding of plant-pollinator interplay. Frontiers. *Plant Science*, *7*, 333. https://doi.org/10.3389/fpls.2016.00333

Tagarakis, A. C., Dordas, C., Lampridi, M., Kateris, D., & Bochtis, D. (2021). A smart farming system for circular agriculture. *Engineering Proceedings*, *9*, 10. https://doi.org/10.3390/engproc2021009010

Tang, X., Zhang, C., Yu, Y., Shen, J., Van der Werf, W., & Zhang, F. (2021). Intercropping legumes and cereals increases phosphorus use efficiency; a meta-analysis. *Plant and Soil*, *460*, 89–104. https://doi.org/10.1007/s11104-020-04768-x

Therond, O., Duru, M., Roger-Estrade, J., & Richard, G. (2017). A new analytical framework of farming system and agriculture model diversities. A review. *Agronomy for Sustainable Development*, *37*, 21. https://doi.org/10.1007/s13593-017-0429-7

Toop, T. A., Ward, S., Oldfield, T., Hull, M., Kirby, M. E., & Theodorou, M. K. (2017). AgroCycle—Developing a circular economy in agriculture. *Energy Procedia*, *123*, 76–80. https://doi.org/10.1016/j.egypro.2017.07.269

Van der Sluijs, J. P. (2020). Insect decline, an emerging global environmental risk. *Current Opinion in Environmental Sustainability*, *46*, 39–42. https://doi.org/10.1016/j.cosust.2020.08.012

Van Gelder, J. W., Kammeraat, K., & Kroes, H. (2008). Soy consumption for feed and fuel in the European Union. A research paper prepared for Milieudefensie (Friends of the Earth Netherlands). Retrieved from https://www.foeeurope.org/sites/default/files/press_releases/profundo20report20final1.pdf

Van Zanten, H. H. E., Meerburg, B. G., Bikker, P., Herrero, M., & De Boer, I. J. M. (2016). Opinion paper: The role of livestock in a sustainable diet: A land-use perspective. *Animal*, *10*, 547–549. https://doi.org/10.1017/S1751731115002694

Voisin, A. S., Guéguen, J., Huyghe, C., Jeuffroy, M. H., Magrini, M. B., Meynard, J. M., Mougel, C., Pellerin, S., & Pelzer, E. (2014). Legumes for feed, food, biomaterials and bioenergy in Europe: A review. *Agronomy for Sustainable Development*, *34*, 361–380. https://doi.org/10.1007/s13593-013-0189-y

Von Richthofen, J. S., Pahl, L., Bouttet, D., Casta, P., Cartrysse, C., Charles, R., & Lafarga, A. (2006). Economic and environmental value of European cropping systems that include grain legums? *Grain Legumes*, *45*, 13–22.

Ward, S. M., Holden, N. M., White, E. P., & Oldfield, T. L. (2016). The 'circular economy' applied to the agriculture (livestock production) sector—Discussion paper. Workshop on the Sustainability of the EU's Livestock Production Systems.

Yildiz, D. (2021). Global poultry industry and trends. Feed Additive. International Magazine for Animal Feed & Additives Industry. Retrieved from https://www.feedandadditive.com/global-poultry-industry-and-trends/

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