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Review: Opportunities and challenges for the pork industry from circular livestock waste management systems ☆

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A B S T R A C T

Slurry management is becoming increasingly important as countries work to decarbonise towards Net Zero goals. After feed, slurry management and application is one of the main contributors to the greenhouse gas emissions and environmental pollution associated with pork production. Whilst traditionally considered a waste product, slurry is rich in nutrients and could be harnessed to reduce environmental impacts and improve on-farm resilience. Along with reducing the environmental impacts of pork production, farmers are increasingly looking to diversify their income streams and pig slurry offers tremendous potential to achieve this. This review identifies the opportunities and challenges to the pork sector from circular, sustainable waste management systems through insect bioconversion or on-farm biogas production, with a focus on the United Kingdom. Insect bioconversion of pig slurry, through the use of Black Soldier Fly larvae, presents opportunities not only to reduce the overall volume of slurry on a farm but also to reduce heavy metal contamination, alter the microbiome and provide a myriad of additional products. These products include fertiliser in the form of insect frass, protein, oils, and chitin from the insect exoskeleton, which has applications in industries such as wastewater treatment, pharmaceuticals and healthcare. Through on-farm biogas generation, farmers, particularly those in rural areas, could reduce their reliance upon volatile energy prices and generate electricity and heat to power on-farm activities. With additional infrastructure, biogas could be upgraded to produce biofuel and CO_2 could be recovered, recycled, and sold into a variety of industries. Whilst there are still a number of outstanding questions that need to be answered and challenges that need to be addressed before the wide-scale rollout of these technologies, there is huge potential to harness the power of pig slurry. When designing the farm of the future, solutions will likely need to be tailored to an individual farm due to a range of variables including the stage of production, the number of pigs, the pig diet and the availability of co-products. However, despite these potential challenges, there is still considerable opportunity for the pork sector to harness this 'waste' product to decarbonise pig production and improve farm resilience.

Implications

There is growing pressure to decarbonise agriculture to meet Net Zero targets. After feed, most greenhouse gas emissions from pig production are primarily associated with slurry management and spreading. Bioconversion by insects or the generation of biogas from pig slurry provide viable options to reduce emissions and eutrophication, improve crop growth and generate additional income within the farm gate. Whilst there are still unanswered questions around the safety of rearing Black Soldier Fly larvae on pig slurry and the feasibility of wide-scale, on-farm energy generation, the valorisation of waste holds tremendous potential to provide resilience and diversification to the pork sector.

Introduction

Agriculture faces the challenge of producing enough nutritious, safe and affordable food to feed the growing world population whilst at the same time reducing the environmental impact and exploitation of natural resources associated with its production. Global demand for pork has led to rapid growth in its production by approximately 4.5 times between 1961 and 2021, from 24.8 to 109.2 million metric tonnes, representing approximately 33% of global meat production (Ndue and Pál, 2022). Estimates suggest that demand for meat will continue towards 2050 and beyond, but this will vary by commodity and country (Henchion et al., 2021;

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Komarek et al., 2021). Whilst meeting the global demand for food, it is essential that farming systems are sustainable and reduce emissions as low as possible if countries are to meet the legally binding targets set out in the 2015 Paris Agreement (UNFCCC, 2018).

There is global pressure to decarbonise agriculture with livestock production estimated to be responsible for 8–14.5% of global greenhouse gas emissions (**GHGs**) depending upon the method of calculation used (Caro et al., 2014; Gerber et al., 2013; O'Mara, 2011). Pig production contributes significantly less GHGs to the atmosphere than ruminant production (i.e. cattle, sheep, etc.) due to the inherent differences in the physiology of the animals. Whilst the majority of GHGs associated with pig production are attributable to feed at 31–76% (Andretta et al., 2021; Groen et al., 2016), this is followed by manure management (Lesschen et al., 2011). There is also concern around the impact of pig production on both water and air quality (Costantini et al., 2020; Li et al., 2022). Concerns around pig production include eutrophication of nutrients into waterways, acidification of soils and reduced air quality due to NH_3, as well as emission of gases such as CH_4, CO_2 and N_2O. These concerns are largely associated with the storage, handling and spreading of slurry. There is considerable opportunity to improve the utilisation of slurry on farm, to reduce environmental impact and to generate alternative income streams for farmers.

Overview of waste production

For centuries, animal slurries and manures have been used as an amendment to soil in place of, or alongside the use of inorganic fertiliser. The British Survey of Fertiliser Practice 2022, (DEFRA, 2022), estimated that approximately 67% of farms applied organic manures (e.g. manure, slurry or farmyard manure) to at least one field on their farm and it has been estimated that in the United Kingdom (**UK**), approximately 83 million tonnes of livestock manure is produced each year (Smith and Williams, 2016). The quality and quantity of animal waste produced will vary depending on multiple factors including the type, age, diet and breed of the animal reared (Antezana et al., 2016; Van Horn, 1998).

Waste from livestock, such as pig slurry, is rich in nitrogen and phosphorous as well as other macro and micronutrients, which provide essential nutrients to soils and growing crops. However, despite otherwise sound environmental practices, the concentration of constituents such as N (in the form of nitrate, NO_3^-) and P can be in excess of the requirements for the soil and crops where the slurry is spread, which may result in leeching or run-off into waterways, causing eutrophication of water sources. For example, in the UK, the failure of 31% of water to achieve good water quality status has been associated with poor management of agricultural and rural land (Environment Agency, 2018). Animal wastes may also cause soil contamination due to the presence of heavy metals and pathogens, the concentration of which vary with animal species and management practices. Pig slurry, for example, has been shown to contain a 2-fold higher concentration of both zinc and copper when compared with cattle (Jakubus et al., 2013), although these numbers are likely to have declined since the removal of zinc oxide from nursery diets in the EU from 2022.

In intensive pig production with slatted floors, slurry is typically held in pits under the animals and then pumped, or gravity fed into a storage tank where it is held until required. During storage, microbes present in the slurry continue to ferment the organic material present. This, alongside the mixing of urine and faeces, results in the formation and release of CH_4, CO_2, N_2O and NH_3. The release of these gases into the atmosphere results in pollution and odour, and a high concentration of NH_3 in pig buildings, for example, could have negative health implications for both pigs (Witt et al., 2024; Zhang et al., 2021a, b) and farm workers (discussed in Conti et al., 2021). Whilst farms manage in-room emissions through ventilation (either natural or mechanical), this can be a challenge in colder months when also trying to maintain room temperatures. Improving the management of slurry is therefore essential for reducing the environmental impact of pig production.

Along with reducing the environmental impact of pig production to reach Net Zero goals, diversification of income streams is becoming increasingly important for farms. Changes to slurry management present an opportunity to reduce an individual farm's environmental footprint, reduce emissions and improve profitability and resilience. Whilst slurry is often considered a waste product from pig production, there is scope to capture and valorise the nutrient content that remains. This review will consider the opportunities and challenges for on-farm valorisation of slurry from pig production within a sustainable, circular farming system. Here, we will discuss the bioconversion of slurry with insects as well as on-farm biogas production.

Insect bioconversion

Bioconversion of pig slurry

Pig slurry is rich in organic matter and contains macronutrients such as nitrogen (5.8% of DM) and phosphorous (3.4% of DM) as well as micronutrients including iron (1 871 mg/kg), copper (416 mg/kg) and zinc (1 806 mg/kg), despite a relatively high water content (DM content averaging 5.7%) (Fernández-Labrada et al., 2023), though this will vary between farms and pig type (Yagüe et al., 2012). Whilst application to land as a fertiliser is well established, the nutritive value of pig slurry makes it a potential feedstock for insect bioconversion. During the bioconversion process, insect larvae consume the substrate to produce insect protein and oils, chitosan and frass (insect excretions and moulted exoskeletons). Diverting slurry through a bioconversion process prior to land application can generate additional high-value products on farm (see Section: Bioconversion Diversification Streams) whilst still producing a viable fertiliser albeit with a much lower water content (40–90% DM; Gärttling and Schulz (2022)). Additionally, due to the relatively short rearing period of insect larvae on animal wastes (approx. 20 days; (Rehman et al., 2019)), the rapid turnover of slurry would reduce the harmful emissions associated with prolonged storage.

Whilst a number of insect species have been explored for their potential in insect farming systems, this review will focus on the Black Soldier Fly (*Hermetia illucens*).

An introduction to black soldier fly larvae

The Black Soldier Fly (**BSF**), *Hermetia illucens*, originates from the Americas (Sheppard et al., 1994), and is a non-pest, generalist feeder (Rindhe et al., 2019; Taufek et al., 2024). Females preferentially lay eggs in dry areas around decomposing organic matter (Booth and Sheppard, 1984), and the larvae undergo six instar stages before entering the prepupal stage (De Smet et al., 2018). Prepupae cease eating and migrate from the substrate to pupate (Georgescu et al., 2020). Adults do not need to feed and mate just once during their lifetime (Singh and Kumari, 2019). As such, the larval feeding stage (**BSFL**) is crucial for the insects' growth and energy storage. Crucial to larval growth is the main site of digestion, the midgut (Eke et al., 2023), which consists of three main sections, namely the anterior, middle and posterior midgut, that differ in morphology and pH (Bonelli et al., 2019). The midgut also displays morphological changes related to the type of substrate the larvae is feeding on, including changes to microvilli to aid absorption, as well as alterations in enzymatic activity (Bonelli et al., 2020). This is particularly significant given the generalist feeding ability of these larvae. Feeding efficiency of BSFL is dependent on a number of factors, including type (Liu et al., 2018) and moisture content of substrate (Cheng et al., 2017), rearing temperature (Sheppard et al., 2002) and fly strain (Zhou et al., 2013). The ability of larvae to survive and feed on different substrates, some of which will have high microbial loads, which could include pathogenic bacteria, is partially influenced by their immune system, including the production of antimicrobial peptides (Moretta et al., 2020) and through competition with their own microbiota (Shi et al., 2024).

Indeed, the microbiome of BSFL is critical to their successful bioconversion of substrates. Black Soldier Fly shows high enzymatic activity in the gut, including lipase and proteases (Kim et al., 2011), but are also able to digest tough fibres such as lignocellulose (Kariuki et al., 2023) and cellulose (Zhang et al., 2023) via the action of the microbiota; the composition of which is also largely affected by substrate type (Auger et al., 2023). As a result of these combined factors, BSFL can be reared on a large variety of substrates, including food waste (Cheng et al., 2017), livestock manure (Zhou et al., 2013) and wastewater (Grossule et al., 2023), and this has given them an important status within the insect farming sector.

Black soldier fly larvae conversion of pig slurry

Black Soldier Fly larvae can be reared on a number of different livestock wastes including pig slurry (Miranda et al., 2020). Studies generally report that larval survivorship on pig slurry is high (for example, in the range of 70–97%) (Miranda et al., 2019; Miranda et al., 2020; Oonincx et al., 2015), and developmental times are often found to be shorter than those reared on dairy manure (Miranda et al., 2020; Oonincx et al., 2015), though this is not always the case (Miranda et al., 2019). Newton et al. (2005) found that the mass of pig slurry can be reduced by BSFL by up to 56%, though in another study, DM reduction was lower at 37% (Oonincx et al., 2015). Other studies have also reported different waste reduction values (Miranda et al., 2019; Zhou et al., 2013). Thus, there are differences in DM bioconversion efficiencies between studies, for example, an efficiency of 12.5% was found by Parodi et al. (2021), whilst 4.5% was observed by Oonincx et al. (2015).

Many properties of the slurry, such as nitrogen levels (Oonincx et al., 2015), moisture content (Cheng et al., 2017), and even the stage of production that the slurry was collected from Hao et al. (2023b), can affect the bioconversion efficiencies of the larvae (Miranda et al., 2019; Oonincx et al., 2015). Fly strain has also been found to have an effect (Zhou et al., 2013), and the microbiota is also critical (Zhang et al., 2023). As a result, values reported in the literature can be variable. However, a number of studies have found bioconversion of pig slurry by BSFL can be successfully attained, and this has resulted in an increasing interest in this area in recent years, with a range of factors involved in this process, being investigated (Table 1).

Bioconversion diversification streams

Fertiliser

The process of insect bioconversion of pig slurry results in a number of products, which offer a variety of diversification streams on an individual farm (Fig. 1). These products include a low-moisture content fertiliser, high-value proteins, oils, and other insect products such as chitin, which has the potential for a myriad of downstream applications across a variety of different industries.

Fertilisers are used to provide crops with essential nutrients such as nitrogen and phosphorus, in order to stabilise and increase yields. The frass that is produced from insect bioconversion of livestock waste has the potential as a fertiliser (Lomonaco et al., 2024). For example, bio-stimulating substances present in the frass, such as humic acid, amino acids and chitin, could be beneficial for crop growth (Abd Manan et al., 2024), whilst the availability of nitrogen and soluble phosphorus, combined with a reduction in heavy metals, also increases its potential for fertiliser use (Amorim et al., 2024). Ammonia content of BSF frass can be lower than other manures (Abd Manan et al., 2024).

In addition, aromatic structures that increase the stability of organic matter (He et al., 2011) can be increased in animal manure by the addition of BSFL (Wang et al., 2021a, b). In one study, the uptake of nitrogen was increased in plants treated with frass compared to those treated with commercial fertiliser (Beesigamukama et al., 2020). Frass could also provide beneficial microbes that could positively impact plant growth, for example, BSFL residues can shift soil microbial communities more so than the addition of conventional composts, subsequently affecting plant yields (Fuhrmann et al., 2022). In general, the high dry and organic matter content of frass, the alkaline pH values and micronutrients are often within the range of commercial fertilisers (Gärttling and Schulz, 2022). Therefore, the use of frass could reduce reliance on other fertilisers as part of a circular agricultural system. As frass is usually a much drier substance than pig slurry, there may be reduced emissions associated with transport on farm due to the weight reduction in water content. The market size of frass has been valued at $96.12 million in 2023 and is predicted to grow to $135.88 million by 2030, with North America and Europe holding the greatest shares (VMR, 2023). Challenges include changing reliance on chemical fertilisers, scaling-up, and differences in regulations between countries (VMR, 2023).

Chitin and chitosan

The frass produced by BSFL bioconversion of waste is rich in the biopolymer, chitin, which is a significant component of insect exoskeletons and is shed during moulting (Soetemans et al., 2020). Much of the current developments around chitin production centre around its collection from crustacean waste (Amiri et al., 2022). With the global market of chitin and its derivatives valued at $5.01 billion, and projected to reach $13.12 billion by 2031 (VMR, 2024), insect farming could be another option for its production. Black Soldier Fly larvae contain around 8% chitin, with prepupae containing 11%, and frass typically having higher quantities due to the presence of shed exoskeletons (Soetemans et al., 2020). Chitin/chitosan extraction is established for aquaculture and can be used to estimate projected costs for insect farming, for example, the production of 1 kg of chitosan from shrimps, for a plant in Ecuador costs $8.39 (Riofrio et al., 2021), £10.5–12 in Colombia (Gómez-Ríos et al., 2017) and $14 in Spain (Moreno de la Cruz, 2019).

There are multiple potential downstream uses for chitin, and its derivatives, that offer diversification of income for the pig industry. Chitin can be integrated into biodegradable packaging material (Le et al., 2023), but can also be deacetylated into the copolymer chitosan. Chitosan has been shown to have antimicrobial properties (Guarnieri et al., 2022), to bind contaminants such as mercury, making it a possibility for wastewater purification (Bhatnagar and Sillanpää, 2009), and to be a target for biomedical products, owing to its chemical properties (Triunfo et al., 2022). Indeed, chitosan has applications in the pharmaceutical, cosmetics and textile industries (Morin-Crini et al., 2019; Rehman et al., 2023). There are even potential benefits for reducing crop pathogens and promoting plant growth (Morin-Crini et al., 2019; Sharp, 2013), with chitosan shown to influence defence gene expression, pathogen resistance enzymes and reactive oxygen species production in plants (Torres-Rodriguez et al., 2021). The wealth of opportunities for chitin/chitosan usage suggests that it could be a commercially viable by-product from agricultural systems using insects for waste reduction.

Table 1
Main findings and primary parameters investigated of literature incorporating Black Soldier Fly Bioconversion of Pig Slurry as part of the study.

Reference	Primary Parameters Investigated	Main Findings
Ao et al. (2021)	Microbiome	• *Enterococcus, Providencia* and *Morganella* dominant genera in the larval gut. • Proteobacteria decreased in manure-fed larvae.
Awasthi et al. (2020)	Pathogen Load	• Reduced abundance of pathogenic bacteria in larval-treated manure.
Beskin et al. (2018)	Waste Type on Emissions	• Volatile organic compounds were reduced by larvae addition to manure. • More volatile organic compounds are emitted from poultry manure than from swine or dairy. • Phenol, indole and 4-methylphenol were reduced to undetectable levels by larvae in swine manure.
Beyers et al. (2023)	Waste Type and Agro-waste disposal	• Effects on energy consumption and the environment for insect production vary between food source and the type of energy used during production.
Boafo et al. (2023)	Oviposition Preference	• Heaviest prepupal weight for larvae fed on pig manure and lowest on chicken manure. • Preferred oviposition substrate was millet porridge mash, which had a lower prepupal weight than pig manure.
Chen et al. (2019)	Emissions	• Total greenhouse gas emissions reduced compared to traditional composting at 75% moisture. • Methane emissions increased with moisture content of manure.
Choi (2024)	Larval Stages on Bioconversion	• Greater conversion ability of 2nd and 3rd instar larvae on pig manure. • 3rd instar larvae also largely reduced NDF and ADF.
Deng et al. (2024)	Plantation Waste addition to Manure	• Type of plantation waste added to pig manure affected the accumulation of heavy metals by larvae. • Bamboo chips addition had a positive effect on heavy metal accumulation. • Bacteria such as Proteobacteria are involved in the transformation of heavy metals in the residue.
El-Dakar et al. (2021)	Waste Type	• Growth increased in larvae reared on bird manure compared to goat and pig manure. • Higher fatty acids in prepupae fed on bird manure. • No significant difference in the ratio of essential amino acids for prepupae from different substrates.
Elhag et al. (2022)	Pathogens	• *Staphylococcus aureus* and *Salmonella* spp. significantly decreased in pig manure with larvae. • Isolated microbes from the larval gut shown to inhibit *Staphylococcus aureus* and *Escherichia coli in vitro*.
Ewusie et al. (2019)	Oviposition Preference	• Oviposition preference for pig waste trap. • Substrate of oviposition affected larval length growth in the first 10 days.
Ganda et al. (2019)	Waste Type	• Greater larval yields from crop and agri-food substrates than from manures.
Hao et al. (2023b)	Type of Pig Manure	• Lower larval weights for those reared on finishing pig manure, compared to younger stages. • Significant correlation between hemicellulose content and larval weight.
Hao et al. (2023a)	Disinfectants	• Effects of disinfectants on microbiome composition. • Larval growth was increased by potassium peroxymonosulfate. • Waste reduction ratio decreased by glutaraldehyde.
Hoek-van den Hil et al. (2023)	Waste Type and Pathogens	• Cadmium bioaccumulated in larvae. • Oxytetracycline detected in frass samples from pig manure treatments. • *Salmonella* spp. detected in pig manure and one larval sample.
Hoffmans et al. (2024)	Heavy metals and Veterinary Drugs	• Cadmium bioaccumulated in larvae. • Low levels of veterinary drug detection in substrates and larvae.
Huang et al. (2020)	Pathogens	• Reduced *Staphylococcus aureus* and *Salmonella* spp. in pig manure with larvae. • Toll pathway genes are involved in regulating of gut microbiome.
Jiang et al. (2022)	Heavy Metals	• Bioaccumulation of heavy metals depended on larval inoculation density. • Inoculation density of 0.40% had the greatest absorption effect of heavy metals for pupal yields.
Naser El Deen et al. (2023)	Waste Type	• Low growth rate of larvae reared on pig slurry mixed with silage grass. • Larvae also had undetectable fatty acids when reared on this mix. • Waste reduction index is low for larvae reared on the mix and for pig slurry alone compared to other substrates such as chicken feed.
Lalander et al. (2015)	*Salmonella* reduction	• Larvae reduced *Salmonella* spp. concentrations. • Viable virus concentrations decreased in substrate.
Li et al. (2011)	Biodiesel	• Highest yield of crude fats was extracted from larvae fed on chicken manure, followed by pig then cattle manure.
Li et al. (2023)	Mixed Wastes	• Adding wet distiller grains increased bioconversion rate of pig and cow manure. • Waste reduction rate was increased by 67% in pig manure when grains were added.
Li et al. (2024)	Heavy Metals	• Little accumulation of heavy metals in larvae. • Predicted gut enzymes with the ability to transport heavy metals such as Zn could reduce bioaccumulation in larvae.
Lin et al. (2023)	Heavy Metals	• Cadmium content of larvae high on pig manure. • High protein content in larvae-fed pig manure.
Liu et al. (2018)	Waste Type on Reduction and Larval Development	• Longer developmental time and lower weight gain on pig manure than on wheat middling. • Survival is similar on wheat middlings and pig manure, but lower on semi-digested grass. • Larvae reduced pig manure DM by 13.81%.
Liu et al. (2019)	Waste Reduction and Nutrients	• Larvae decreased nitrogen by 13.18% on pig manure. • Volatile fatty acids were reduced in manure.
Liu et al. (2020)	Humification and Trace Elements	• Larvae enhance the humification of manure. • Larvae increased the quantity of bioavailable trace elements in the residue.
Liu et al. (2021)	Cornstalk Addition	• Adding cornstalk to manures reduced methane and ammonia emissions, but increased CO_2. • Adding cornstalk influenced microbial communities in substrates.
Liu et al. (2022)	Metals and Bacteria	• Addition of cornstalk to manure substrates increased the toxic metal immobilisation rate. • Adding cornstalk affected bacterial diversity.
Matos et al. (2021)	Methane Emissions	• Larva reduced 32% of pig manure DM. • Methane was reduced by up to 86% in animal manure with larvae compared to traditional manure storage.
Mei et al. (2022)	Antibiotic Degradation	• Temperature significantly affected the degradation of tylosin and enrofloxacin antibiotics by larvae fed on swine manure. • Antibiotic resistance genes increased in expression in the gut of manure-fed larvae.
Miranda et al. (2020)	Waste Type on Larval Development	• Longer developmental time and lower survivorship on dairy manure compared to poultry and swine manure. • No significant difference in weight of prepupae on different manures.

Table 1 (*continued*)

Reference	Primary Parameters Investigated	Main Findings
Miranda et al. (2021)	Waste Reduction and Type for Different Study Sizes	• Higher reduction in N was found in dairy manure than in poultry and swine manure. • Scale of study affected P and K reductions.
Newton et al. (2005)	Waste Reduction	• Manure reduced by 56%. • N and P reduced in substrate by 55 and 44% respectively.
Nguyen et al. (2013)	Waste type on Larval Development	• Larvae reared on pig manure took longer to develop than those on other substrates such as kitchen waste. • Larvae reared on manure had lower final weights.
Nguyen et al. (2015)	Waste Type on Larval Development	• 44% greater waste reduction for manure compared to poultry feed. • Slower reduction of waste for larvae on pig manure compared to poultry feed. • No difference in larval weight.
Oonincx et al. (2015)	Waste Type and nutrients	• Higher survival on pig manure than chicken manure. • Longer development time on dairy manure. • DM reduced ~37% and N:P ratio reduced in all manure types tested.
Pang et al. (2020)	Carbon and Nitrogen and Gas Emissions	• C:N ratios in pig manure/corncobs mix affect greenhouse gas emissions from larval bioconversion. • Greenhouse gas emissions reduced compared to traditional composting.
Parodi et al. (2020)	Larval Substrate Preference	• Larvae showed a preference to pig manure over plant by-product diet. • Preference for manure increased with age.
Parodi et al. (2021)	Waste reduction, nutrients and emissions	• Larvae reduced pig manure DM by 12%. • Larvae reduced N and P in substrate. • CO_2 emissions increased from manure with larvae compared to manure without larvae. • No difference in CH_4 emissions.
Parodi et al. (2022)	Ammonia-Nitrogen Uptake	• 13% of NH_3-N in pig manure assimilated into larvae.
Peng et al. (2022)	Frass Properties	• Effects of pig manure thickness on bioconversion efficiency.
Ramírez-Méndez et al. (2022)	Waste Type	• Greatest weight gain in larvae fed on restaurant waste. • Lowest on dairy manure. • Bioconversion efficiency is faster on pig manure than on dairy manure.
Shao et al. (2024)	Stage of Pig and Bacteria	• Manure from different stages of pig-affected larval conversion, with that of growing pigs showing the highest overall values. • Stage also affected larval gut microbiome composition. • Cellulose-degrading bacteria isolated from larval guts.
Shen et al. (2024)	Fatty Acids	• Larval density did not affect fatty acid composition. • Scaling the system up decreased larval survival and reduced fatty acids.
Veldkamp et al. (2021)	Waste Type	• Lower larval growth rate on pig manure than chicken feed. • Larvae growth rate was not different from chicken feed if pig manure was mixed with chicken feed. • Mixed manure and chicken feed also had increased bioconversion efficiency compared to separate chicken feed and pig manure.
Wang et al. (2019)	Waste Type	• Shorter development time on food waste and pig manure than on cow manure. • Reproductive rate is also higher for food waste and pig manure-reared flies than for cow manure. • Fatty acid and amino acid content altered between prepupae reared on different feedstuffs.
Wang et al. (2021a)	Properties of Residue	• Increased aromatic components of manure after larval bioconversion. • Decrease in proteinaceous components.
Wang et al. (2021b)	Heavy Metals	• High bioaccumulation of Cd in larvae. • Heavy metals also transferred to faeces.
Wang et al. (2022)	Cadmium Accumulation	• Addition of Cd to pig manure did not influence larval growth. • Larvae fed on pig manure bioaccumulated Cd. • Only small amounts of Cd from manure-fed larval frass entered maize plants when treated with it as a fertiliser.
Wang et al. (2024)	Microbiome	• Moisture content affected the conversion efficiency of pig manure. • Microbiome composition altered on different moisture levels of pig manure.
Wu et al. (2021)	Microbiome and metals.	• Larvae reared on pig manure accumulated Cu and Zn. • Larval faeces contained lower abundances of potential pathogens than the pig manure.
Wu et al. (2024)	Frass Quality	• Pig manure lost more N during bioconversion than chicken manure. • Higher humification in frass compared to compost.
Xiao et al. (2020)	Waste Type	• Adding rice bran improved the conversion efficiency of pig and chicken manure. • Adding cow manure reduced conversion efficiency.
Zhan et al. (2020)	Microbiome	• Greater complexity of the microbiome for dairy and swine manure-fed larvae compared to those fed on poultry manure. • Larvae fed dairy manure show differences in gene expression profiles compared to larvae fed on other manures.
Zhang et al. (2022)	Pathogens	• Larvae reduced *Staphylococcus aureus* and *Salmonella* spp. in pig manure. • Gut microbes required for inhibition of *Staphylococcus. aureus* and *Salmonella* spp.
Zhang et al. (2024)	Transcriptome and Metabolome	• More downregulated differentially expressed genes in larvae reared on pig manure compared to swill. • Upregulation of genes associated with stress response and antioxidants in pig manure-fed larvae.
Zhao et al. (2023)	Antibiotic Resistance	• Larvae reduced the abundance of antimicrobial resistance genes by 93.2%. • Larval conversion also reduced the number of main antibiotic-resistant bacteria.
Zhou et al. (2013)	Fly strain	• Fly strain affected the development time and weight of larvae. • Reduction of DM from swine manure ranged from 28.8 to 53.4% depending on strain. • DM reduction also differed with manure type.

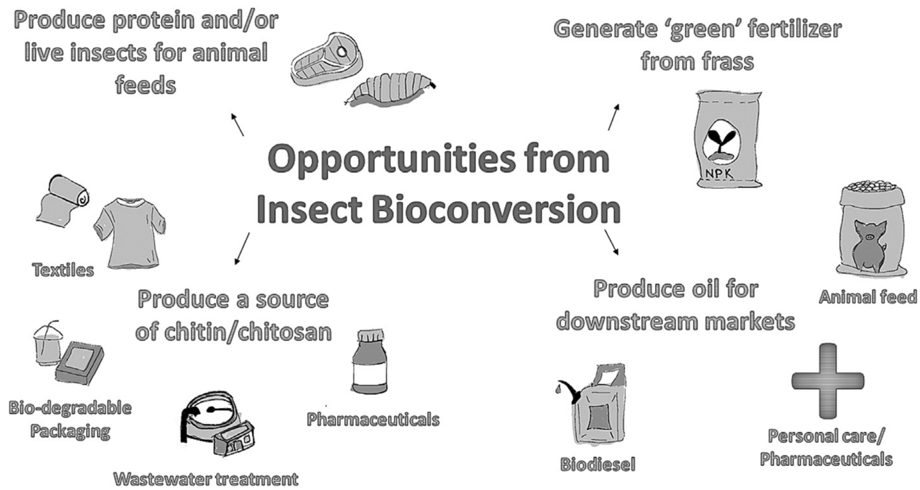

Fig. 1. A schematic of the different opportunities available to the pork industry through on-farm Black Soldier Fly bioconversion of pig slurry. Examples of subsequent downstream markets for products are provided.

Protein

Demand for animal feed is increasing with the global growing human population, and there is a rising need to establish economically viable, sustainable systems to cope with this demand (Barragan-Fonseca et al., 2017). Insect protein could reduce the reliance on soya imports (Wilkinson and Young, 2020) which are often associated with land use change and GHGs associated with their importation. Insect protein can be used as an alternative in animal feed, and as of 2017, insects fed on plant-based substrates have been permitted for use as feed for aquaculture, poultry and pig feed in the European Union (**EU**; EU 2017/893 and EU 2021/1372) (EU, 2021). The UK, however, retains greater restrictions on using insect protein in livestock feed of animals reared for human consumption (Tiwasing and Pate, 2024).

Black Soldier Fly Larvae contain high amounts of amino acids (Crosbie et al., 2020) and fatty acids, especially lauric acid (Danieli et al., 2019; Ewald et al., 2020), as well as vitamins such as thiamin (B_1) and vitamin C (Zulkifli et al., 2022), and minerals such as phosphorus and calcium (Chia et al., 2020; Makkar et al., 2014), strengthening its potential as an animal feed source. Replacement of fish meal in pig diets with BSFL has been shown to increase BW, with faster weight gain in finisher pigs (Chia et al., 2021), and the addition of BSF oil to the diet can increase the daily gain of nursery pigs (van Heugten et al., 2022), and support growth without negative effects on gut morphology (Crosbie et al., 2021).

However, the substrate that BSFL are reared on has a large effect on their nutritional composition (Barragan-Fonseca et al., 2017; Ewald et al., 2020). As such, depending on the consistency and availability of the substrate, larvae may vary in their specific nutrient composition and digestibility, and studies suggest that it may be more useful to add BSFL as a partial replacement for other sources of protein in the pig diet (as reviewed by Barragan-Fonseca et al. (2017) (see also Table 2 for examples of the nutritional content of larvae reared on pig slurry). It is important to note, that there is additional work needed to determine whether larvae meet international standards around the heavy metal, pathogen, parasite and antimicrobial resistance levels found in BSFL reared on pig slurry. For example, the reported heavy metal content of larvae reared on slurry varies between studies, and there is a lack of consistency in the specific metals that are analysed (Table 3). Additionally, determination of the fate of pharmaceutical and chemical residues that may be present in the pig slurry is required before this protein stream can be unlocked.

Oils

Oils extracted from BSFL are high in fatty acids, such as lauric, oleic, linoleic and palmitic acids, omega-3 and omega-6, and show high antioxidant activity (Muangrat and Pannasai, 2024). Studies have shown that these oils can be used in aquaculture feeds (Li et al., 2016) and for poultry (Kim et al., 2020). For example, replacing soybean oil with BSFL oil in turkey diets was found to increase amylase activity, and reduce *Bacteroides-Prevotella* growth in the cecum (Kierończyk et al., 2022). BSFL oil also has potential applications in human skincare where it has been shown to inhibit growth in human keratinocyte cells, an important factor in psoriasis (Muangrat and Pannasai, 2024). In mice, BSFL oil has been shown to produce an anti-inflammatory response (Richter et al., 2023). There is an additional application for BSFL oil in the healthcare sector, where it has been shown to accelerate wound healing (Rahayu et al., 2024).

Furthermore, larvae oil can be used to produce biodiesel (Mohan et al., 2023). The addition of BSFL oil to diesel has been shown to lower smoke emissions and fuel consumption (Rehman et al., 2018). The generation of biodiesel from larvae can produce fuel that meets the standards of a number of countries and can use less energy than other biodiesel-producing systems (as reviewed in Mohan et al. (2023)). Biodiesel from BSFL fat has been shown to have similar properties to biodiesel from rapeseed oil, as well as higher saturated fatty acid methyl esters which may confer oxidative stability (Li et al., 2011), and has potentially reduced climate change effects compared to rapeseed and soybean oil; however, pretreatment steps and chemical usage contribute to its overall impact (Liew et al., 2023).

Current challenges for implementation

Whilst BSFL demonstrate huge potential as a method to valorise pig slurry, there are a number of potential challenges and current unknowns that need to be resolved before large-scale implementation can begin. A list of these potential challenges is shown in Table 4 along with opportunities for future research. One of the main areas of concern for rearing BSFL on pig slurry is the safety of the products produced and this raises questions about their downstream applications. For example, there is some evidence to suggest that BSFL are able to bio-accumulate heavy metals present in pig slurry (Diener et al., 2015). Heavy metals may be naturally occurring in livestock feed ingredients or may be added as supplements to enhance the health and growth performance of the animals (Nicholson et al., 2006). Pig slurry has been found to

Table 2
Nutritional composition of Black Soldier Fly Larvae reared on pig slurry (all nutrient values are expressed on a DM basis, except for DM or where otherwise stated).

Item	Reference
DM	
27.6 (SD ± 0.4) (%)	Parodi et al. (2021)
20.2 (SD: ±0.46) (%)	Oonincx et al. (2015)
20.3 ± 0.8 (%)	Hoek-van den Hil et al. (2023)
~22 (%)	Naser El Deen et al. (2023)
21 (%)	Veldkamp et al. (2021)
Energy	
2 042 ± 33 kJ/100 g	Parodi et al. (2021)
Protein	
34.7% (se: ± 0.5)	Boafo et al. (2023)
43.2%	Newton et al. (2005)
42.59% (se: ± 0.71) to 46.60 (se: ± 0.54)	Wang et al. (2024)
32.27% ± 0.23 to 33.16 ± 0.29	Zhou et al. (2013)
Fats	
31.8% (se: ±0.8)	Boafo et al. (2023)
6.05% (SD: ± 0.46) to 8.92% (SD: ± 0.56)	Wang et al. (2024)
Omega Fatty Acids	
Omega 3: Linoleic acid = 1.96% (SD: ± 0.23)	El-Dakar et al., 2021
Omega3: Linolenic acid = 0.04% (SD: ± 0.06)	El-Dakar et al., 2021
Omega3 = 0.15(%DM)	Naser El Deen et al., 2023
Omega6 = 1.77 (%DM)	Naser El Deen et al., 2023
Phosphorus	
1.2% (SD: ± 0.1) (per 100 g of DM)	Parodi et al., 2021
1.99% (SD: ±0.190)	Oonincx et al., 2015
0.88 (%DM)	Newton et al., 2005
1.37% (SD: ± 0.08) to 2.08 (SD: ± 0.10)	Wang et al., 2024
Nitrogen	
6.90 (%DM) (SD: ±0.215)	Oonincx et al., 2015
6.9% (SD: ± 0.2)	Parodi et al., 2021
Potassium	
1.6% (SD: ± 0.1)	Parodi et al., 2021
1.16 (%DM)	Newton et al., 2005
Amino Acids	
Alanine	
6.87 ± 0.15 (Mean (g/100 g) ± SD)a	El-Dakar et al., 2021
2.82 ± 0.07 to 2.93 ± 0.12 (Mean % amino acids ± SD)	Jiang et al., 2022
Arginine	
5.14 ± 0.03a	El-Dakar et al., 2021
1.63 ± 0.05 to 1.75 ± 0.16	Jiang et al., 2022
1.77 (% amino acids)	Newton et al., 2005
Aspartic acid	
9.41 ± 0.13a	El-Dakar et al., 2021
3.28 ± 0.08 to 3.48 ± 0.16	Jiang et al., 2022
Cystine	
0.21 ± 0.03 to 0.22 ± 0.02	Jiang et al., 2022
Glutamic acid	
10.57 ± 0.08a	El-Dakar et al., 2021
4.12 ± 0.09 to 4.60 ± 0.20	Jiang et al., 2022
Glycine	
5.41 ± 0.02a	El-Dakar et al., 2021
2.27 ± 0.06 to 2.42 ± 0.06	Jiang et al., 2022
Histidine	
3.22 ± 0.08a	El-Dakar et al., 2021
0.78 ± 0.04 to 0.90 ± 0.07	Jiang et al., 2022
0.96	Newton et al., 2005
Isoleucine	
4.13 ± 0.03a	El-Dakar et al., 2021
1.05 ± 0.06 to 1.11 ± 0.12	Jiang et al., 2022
1.51	Newton et al., 2005
Leucine	
7.08 ± 0.04a	El-Dakar et al., 2021
2.47 ± 0.06 to 2.48 ± 0.11	Jiang et al., 2022
2.61	Newton et al., 2005
Lysine	
6.17 ± 0.08a	El-Dakar et al., 2021
1.86 ± 0.11 to 1.94 ± 0.07	Jiang et al., 2022
2.21	Newton et al., 2005
Methionine	
4.46 ± 0.04a	El-Dakar et al., 2021
4.01 ± 0.21 to 4.10 ± 0.27	Jiang et al., 2022
0.83	Newton et al., 2005
Phenylalanine	
4.90 ± 0.10a	El-Dakar et al., 2021
1.48 ± 0.03 to 1.58 ± 0.08	Jiang et al., 2022
1.49	Newton et al., 2005
Proline	
11.15 ± 0.12a	El-Dakar et al., 2021
2.01 ± 0.03 to 2.07 ± 0.08	Jiang et al., 2022
Serine	
4.19 ± 0.02a	El-Dakar et al., 2021
1.80 ± 0.04 to 1.89 ± 0.05	Jiang et al., 2022
Threonine	
4.12 ± 0.02a	El-Dakar et al., 2021
1.47 ± 0.04 to 1.52 ± 0.05	Jiang et al., 2022
1.41	Newton et al., 2005
Tryptophan	
0.59	Newton et al., 2005
Tyrosine	
7.55 ± 0.03a	El-Dakar et al., 2021
2.19 ± 0.06 to 2.46 ± 0.17	Jiang et al., 2022
Valine	
5.61 ± 0.03a	El-Dakar et al., 2021
1.50 ± 0.07 to 1.56 ± 0.13	Jiang et al., 2022
2.23	Newton et al., 2005

a = Amino acid contents from El-Dakar et al. (2021) were determined by the standard method GB 5009.124-2016 and are expressed per protein content.

contain high levels of zinc and copper (Provolo et al., 2018), and contributes to heavy metal input to agricultural soils (Nicholson et al., 2006). Long-term use can result in copper accumulation that could be toxic to crops (Drescher et al., 2022). Utilising BSFL to valorise animal wastes could result in heavy metal bioaccumulation in the larvae or they may excrete these metals into the substrate (Jiang et al., 2022). Studies have found that the amount of bioaccumulation differs between metals, for example, Diener et al. (2015) found an accumulation of cadmium, but not zinc or lead, and larval-feeding substrate has also been shown to affect this (Biancarosa et al., 2018; Elechi et al., 2021). Further, Jiang et al. (2022) showed that cadmium, copper, chromium and zinc were removed from pig slurry that had been bio-converted by insects. Hoffmans et al. (2024) detected heavy metals, such as manganese, arsenic and lead in the frass of larvae reared on pig waste, and noted although frass can be used in the EU as a fertiliser if heated to 70 °C for 1 h (amendment Regulation (EU) 2021/1925) in order to control pathogens, the regulation does not set limits for metal concentrations in the frass.

An additional concern is around the presence of pathogens. Slurry contains a rich microbiota excreted from the pig which may include pathogenic species, or species which have the potential to be pathogenic, found as commensal members of the pig microbiome. For example, genera such as *Escherichia coli, Campylobacter, Salmonella and Staphylococcus* are all commonly observed in pig gut samples (Adekolurejo et al., 2023; Sutton et al., 2021). Although there are limited studies to date, there is evidence to show that pig slurry that has been bio-converted by insect larvae shows decreased levels of bacteria such as *Salmonella* and *Staphylococcus aureus* (Elhag et al., 2022; Lalander et al., 2015; Zhang et al., 2022). It is currently unclear, however, what microorganisms are present and viable in the larvae themselves as well as the frass produced and what impact (if any) this may have on, for example, insect growth or soil communities.

Finally, important consideration are the costs involved in construction and running of insect farms. A joint World Wildlife Fund and Tesco report estimated that for a medium-sized insect farm, it would require about £10 m in construction costs, with approximate operational costs in the first year of £2.5 million, with the report also suggesting the potential for 237 000 tonnes of insect protein to be produced by 2050 in the UK (World Wildlife Fund and Tesco, 2021). The cost of production of larvae was estimated at £540 per tonne by 2030, with insect oil sales valued at £586-655 per tonne and frass at £5 per tonne (World Wildlife Fund and Tesco, 2021). In recent years, there have been some insect farming businesses that have stopped production or are struggling to be profitable (Shah, 2024), and more research on cost-effectiveness and scaling is required (Madau et al., 2020). Sales of larvae may start from around $400 per tonne, but prices depend on location and market, which need to be balanced by operational costs such as those for energy generation, water and feedstocks (for non-circular systems) (Niyonsaba et al., 2021).

Bioenergy production

On-farm energy generation of biogas from pig slurry

An alternative route to valorise pig slurry comes through the generation of energy on farm, in the form of biogas. Biogas is a renewable energy resource that has an important role to play in the green energy transition (Rafiee et al., 2021). Biogas is generated from the breakdown of biological material, ("feedstocks"), such as animal manures under anaerobic conditions to produce CH_4, CO_2 and other trace gases. Biogas can be used to generate commodities such as electricity, heat and fuel. By using waste from animal production as a feedstock for biogas production alongside, or in place of crops, this can reduce competition for land through demand for the growth of cash crops (Gaworski et al., 2017) and allow crop residues to remain on, or be ploughed into the soil.

The generation of biogas from pig slurry can reduce the amount of methane that enters the atmosphere and reduce a farm's reliance on fossil fuels. Other benefits include a reduction in odour, reduced contamination of groundwater through runoff, improved air quality (Nagy et al., 2012) and the generation of digestate, which can be harnessed as a bio-fertiliser (Monard et al., 2020).

The use of animal waste for the generation of biogas is a cost-effective method to reduce GHGs and re-capture nutrients required for plant growth. Studies have shown that biogas generation from pig slurry produced biogas ranging in methane content from 32.4 to 68% (Luján-Facundo et al., 2019; Silva et al., 2018) although depending upon the type of anaerobic digestion (**AD**) technology used, this can be improved (Häner et al., 2022). A theoretical analysis of pig slurry determined a maximum methane yield of approximately 83% (Santos et al., 2022). Pig slurry has been identified as having a high buffering capacity, which may reduce the risk of failures of anaerobic plants by preventing the accumulation of volatile fatty acids and the associated decline in pH (Cuetos et al., 2011). It is important to note that acidification of pig slurry, to reduce NH_3 release, prior to use in anaerobic digestion has been shown in some cases to lower biogas potential (Sommer et al., 2015).

Opportunities from producing biogas from pig slurry

Whilst conventional, large-scale anaerobic digestion plants are both cost and resource prohibitive for individual farmers (Wilkinson, 2011), small-scale, modularised AD technologies or wheel and spoke developments, may provide a range of benefits to individual farmers and the pork sector more broadly (Fig. 2). There are a number of potential diversification opportunities available to pig farmers through harnessing waste as a source of energy and these include generating electricity, income, heat, fuel, fertiliser, saleable CO_2 and reducing emissions associated with slurry storage.

By harnessing the fermentative digestion of nutrients present in pig slurry, the generation of biogas can be used to power a combined heat and power (**CHP**) engine, to generate both electricity

Table 3
Heavy metal content of Black Soldier Fly larvae reared on pig slurry.

Item	Arsenic	Cadmium	Lead	Manganese	Zinc	Selenium	Mercury	Chromium	Copper	Iron	Nickel	Reference
Mean ± SD (mg/kg; substrate dependent)	0.31 ± 0.04	0.61 ± 0.02 to 0.85 ± 0.11	1.06 ± 0.18	640.8 ± 22.4 to 974.5 ± 160.9	510.4 ± 56.5	0.33 ± 0.06 to 0.80 ± 0.09						Hoffmans et al., 2024
Mean ± SD (mg/kg)	<0.10	0.22 ± 0.06	0.27 ± 0.06				<0.004					Hoek-van den Hil et al., 2023
Mean ± SD (mg/kg; density-dependent)	none	3.56 ± 1.18 to 23.46 ± 3.62	0.44 ± 0.06 to 0.55 ± 0.1		0.46 ± 0.05 to 0.74 ± 0.02			0.35 ± 0.03 to 0.57 ± 0.05	0.44 ± 0.03 to 0.66 ± 0.04			Jiang et al., 2022
mg/kg	0.30	0.24	0		538.34		0.001	25.99	521.16	1452.2	6.28	Lin et al., 2023
mg/kg (read from graph)	27–30	2.4–3.2	3.0–3.6	700–900	380–460			2–6	100–120	800–1 200	1–3	Li et al., 2024
Ppm				348	271					776		Newton et al., 2005
mg/kg	1.01	0.29						11.56				Wang et al., 2021a, b
% accumulation		38.8%										Wang et al., 2022
mg/kg					356.2				475.9			Wu et al., 2021

Table 4
Potential challenges that may or currently curtail the growth of the Black Soldier fly bioconversion of pig slurry including potential avenues for future research and current unknown and under-researched areas of knowledge.

Potential challenge	What don't we know and opportunities for future research
Presence of heavy metals in insects and/or frass	• What is the heavy metal content of different insect frasses? • How does heavy metal accumulation vary across slurry sourced from different farms, animal breeds, diet types, etc.? • What factors affect bioaccumulation of heavy metals into larval tissue, e.g. density? • How does heavy metal accumulation affect down-stream processing opportunities? • How can we mitigate against larval uptake of heavy metals (where appropriate)? • How can we appropriately utilise insect bioaccumulation of heavy metals to 'clean-up' animal wastes? • Can heavy metals be extracted and utilised from insects postharvesting? Is there a market for this? • What is the welfare impact on the larvae? • What are the risks to downstream users or consumers of insect products?
Presence of pathogenic bacteria or those of concern to the food industry	• What factors affect the pathogenic load of insect larvae after consuming pig slurry? • How does this vary with different slurry types? • What effect does the presence of pathogenic bacteria have on the immune system of the larvae – what are the repercussions of this on insect growth? • Do insects harbour more pathogenic bacteria when reared on animal wastes? • What does the presence of potentially pathogenic or undesirable microbes look like before and after insect bioconversion? • Are the pathogenic/undesirable microbes viable after the processing of insect frass? • If necessary, what processing steps would be required to sterilise the insects and/or frass before downstream applications?
Viral, fungal, parasite and prion contamination	• Majority of the work looking at the microbiome in insect larvae reared on pig slurry has concentrated on the bacterial populations but what happens to fungal and viral communities? • What is the biological relevance of the fungal/viral load? • Whilst there are no known naturally occurring prion diseases in pigs, and pigs show high resilience to infection with prions (Espinosa et al., 2020), is there a risk of prion transmission or proliferation within an insect bioconversion cycle? • What effect does insect bioconversion have on the proliferation of parasites such as *Ascaris* spp.? • What additional processing would be needed to prevent land contamination with parasites? How does this compare to the application of raw pig slurry?
Antimicrobial resistance risks and proliferation	• What effect do veterinary medicines use on farms that are biologically active in slurry have on antimicrobial resistance genes in insects and their frass? • What effect does the presence of detergents from room washing have on insect growth, microbial populations and antimicrobial resistance? • How does the level of mobile genetic elements vary across a bioconversion cycle? • Do Black Soldier Fly larvae act as a reservoir for antimicrobial resistance genes? • What is the risk of co-selection for antimicrobial resistance genes in the presence of heavy metals found in the slurry? • How do antimicrobial resistance genes move from slurry to insect to frass to soil to plant? • How can we mitigate against these risks? • How do the production system, farm, pig diet and stage of production affect these risks?
Accumulation of polychlorinated biphenyls (PCBs), dioxins and pharmaceuticals	• How do pharmaceuticals used on farm affect larval growth and development? • Does insect bioconversion of pig slurry result in a higher concentration of pharmaceuticals in the larvae or insect frass? • Larvae can show bioaccumulation of PCBs on food waste (Van der Fels-Klerx et al., 2020) but is there an accumulation of PCBs from pig slurry and what other factors affect this?
Suitability of frass as a fertiliser	• How variable is the NPK ratio of frass when insects are provided with pig slurry as a substrate? • How does the diet of the pig influence this? • What effect does frass application as a fertiliser have on different soil microbial communities? • How does the presence of phytotoxins influence plant growth? • How can further processing e.g. composting or heat treatment affect their concentration? • How does the addition of frass as a fertiliser affect crop development? • Chitosan can affect defence plant gene expression of plants (Torres-Rodriguez et al., 2021), but what other effects does the application of frass to crops have on plant gene expression? • What is the eutrophication potential of frass compared to pig slurry? • What is the cost-benefit of frass vs pig manure when taking into account additional steps, e.g. heat treatments? • What are the greenhouse gas emissions associated with frass compared to pig slurry and inorganic fertiliser? • How does using a mixture of traditional fertilisers and frass impact these factors?
Protein production	• Will protein from insects reared on currently non-permissible feedstocks such as pig slurry be allowed to enter the food and feed chain? • What safety measures need to be documented to allow this protein to be utilised? • How can insect protein be utilised outside of consumption? • How much insect protein could feasibly be produced from pig slurry? • How much demand would there be for this from farmers and the public in general?
Rearing Black Soldier Fly larvae	• Black Soldier Fly larvae are a tropical species, requiring a high temperature and humidity in order for them to survive – how much energy does this require? • How does the energy requirement change throughout the year? • Is this sustainable through the colder months? • How can renewable energy be used to power an insect bioconversion unit? • What is the impact of the gases produced from insect rearing compared to storage and spreading of raw pig slurry? • What personal protective equipment and health and safety requirements would a farmer need in place in order to rear insects on farm? • How should wastewater generated, e.g. from cleaning between batches be disposed of? Can it be safely used for irrigation?

(*continued on next page*)

Table 4 (*continued*)

Potential challenge	What don't we know and opportunities for future research
Lack of infrastructure and knowledge	• Whilst there is research looking at rearing Black Soldier Fly larvae on pig slurry, more work is needed to standardise protocols and answer the current unknowns. • How can we support farmers to invest in insect bioconversion facilities? Does it require incentivisation? • What infrastructure is needed to process insect larvae and/or insect frass for downstream applications? • How do we support the development of the insect market?
Unknown legislation, welfare of insects as a mini-livestock species	• UK legislation tightly regulates insect production and curtails the use of insects reared on pig slurry • What legislation is there to protect insects as mini-livestock? • How might legislation change in the future? • If insects are determined to feel pain, how will insects be harvested humanely on a large scale? • How will differences in legislation in different countries affect trade in the industry?
Suitability of the feedstock for insect rearing	• Is pig slurry a viable option for large-scale insect production? • How can we handle the moisture content of slurry? • How can we reduce the variability in the slurry produced to ensure consistent growth and development of the larvae? • Does pig slurry require a co-product added to maximise economic return on insect production?

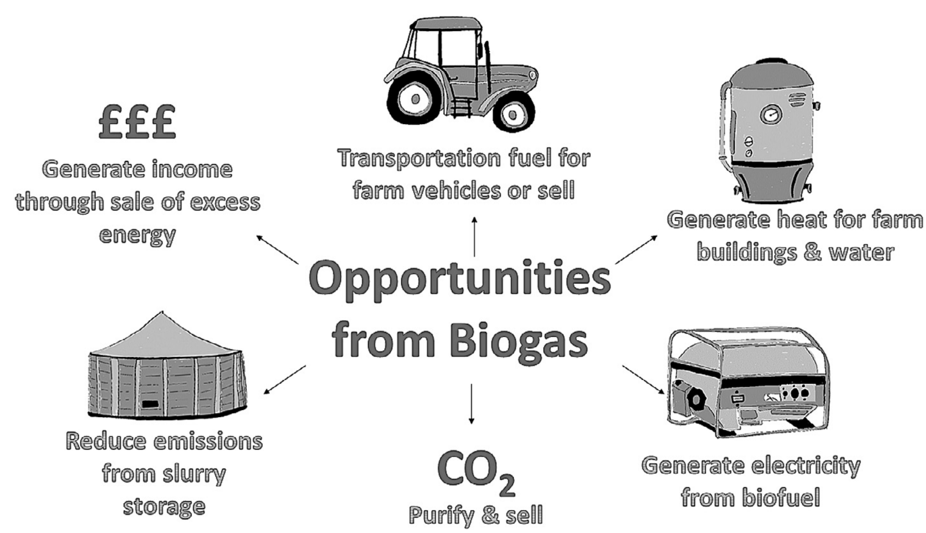

Fig. 2. A schematic of the different opportunities available to the pork industry through the use of pig slurry to generate biogas and the subsequent downstream uses.

and heat or alternatively, can be used to power a combustion engine, fuel cell or gas turbine to produce electricity alone (Kang et al., 2014; León and Martín, 2016; Patania et al., 2012; Wu et al., 2016). On-farm generation can provide farmers with a more stable, reliable energy supply, which is of particular interest to farmers in more rural areas, and those with limited access to the grid (O'Connor et al., 2021). Through CHP, heat can also be generated and used to warm water, for example, which could be used in farm buildings, or used to heat pig rooms, reducing energy consumption from fossil fuels. However, differences in the potential may occur between effluents from different life stages (Gopalan et al., 2013).

Alternatively, the biogas produced can be upgraded through pretreatment and separation steps (e.g. removal of water vapour and CO_2) to produce biomethane (renewable natural gas) which can be fed directly into the grid as a source of income (Hengeveld et al., 2014; Rotunno et al., 2017). Biomethane can also be compressed to generate fuel, which can be used to power on-farm vehicles. During the separation process, CO_2 can be recovered and recycled and undergo additional purification steps. Ultimately, if the processing technology is available, CO_2 from biogas production can be purified to a food-grade quality, producing additional revenue for farmers. Additional uses for CO_2 include the production of dry ice and stunning in abattoirs and CO_2 is required in multiple industries such as food and drink manufacturing, the manufacturing of pharmaceuticals, chemical product synthesis, fire extinguishers and enhanced oil recovery (Supekar and Skerlos, 2014; Valluri et al., 2022). Methods to capture CO_2 from biogas have been discussed elsewhere (Kanso et al., 2024).

As mentioned previously, by diverting slurry directly into anaerobic digestion, GHGs associated with slurry storage can be reduced. An Irish case study showed that mono-digestion of pig slurry reduced GHGs by 48% (190 tonne CO_2 equivalent) compared with spreading directly to land (Zhang et al., 2021a, b). Modelling of biogas generation from available pig slurry in Cyrpus estimated that approximately 20% of the country's energy requirements could be met through renewable biogas generation from AD of pig slurry alone (Theofanous et al., 2014). This highlights the potential for utilisation of pig waste.

At the end of the AD process, digestate remains, which similar to frass, can be applied to land as a biofertiliser due to its high nutrient concentrations (Czekała, 2022). Digestate has been shown to have a lower pathogenic load than raw slurry (Pourcher et al., 2023). However, pathogens of concern to human health do still persist (Nag et al., 2020), and digestate has been shown to have a more appealing nutrient profile, with higher concentrations of molecules with higher biological stability such as lignin (Tambone et al., 2009). Digestate from pig slurry showed similar biomass yields in wheat plants when compared with a mineral fertiliser, outperforming cattle manure-derived digestate when applied to sandy loam soils (Doyeni et al., 2021). Digestate from pig slurry was also suggested to be a useful basal fertiliser in rice paddies when used alongside urea and some additional top-dressed compound-fertilisers, with no detrimental effects on plant growth as well as improved cooking and eating qualities of the rice (Zhang et al., 2017). Digestate produced on farms could be sold providing an additional income stream to farmers.

Challenges for producing biogas from pig slurry

As with insect bioconversion, there are a number of challenges that may prohibit or limit the uptake of biogas production on pig farms. Many of these focus around the suitability of pig slurry as a feedstock. Firstly, animal slurries are highly variable from farm to farm (Prado et al., 2022) and therefore, variation in energy production is likely to be observed. This may be due to the breed stocked, the diet fed to the animals or the stage of production that a given farm rears. Slurry composition may also vary with season (Kowalski et al., 2013) and it is important to consider when the slurry is obtained for biogas production. In order to generate the most biogas, slurry storage time should be kept as short as possible to minimise the loss of gases, or alternatively, slurry should be treated in such a way to minimise fermentative digestion e.g. cooling (Blázquez et al., 2021; Blázquez et al., 2022) which requires additional infrastructure. Alternatively, slurry additives can be used which limit gas production during storage (Im et al., 2021; Thorn et al., 2022). Room management may also affect slurry composition; chemicals and detergents used to washrooms between batches of animals may suppress the biogas potential of the slurry due to the presence of compounds that inhibit microbial growth. Therefore, it is important to consider when slurry is drawn out of pits for biogas generation relative to cleaning.

Slurry also has a low DM content of approximately 3–5% (KeChrist et al., 2017), and as such, has a relatively low amount of volatile solids available for biogas generation (Marchetti et al., 2022). Because of this, some authors suggest that biogas production from pig slurry requires the addition of co-products to allow it to be viable (Guo et al., 2020; Tian et al., 2023). Pig slurry also has high levels of nitrogen due to the amount of CP fed to the animals to maximise growth performance and lean tissue deposition. This leads to a higher amount of ammonia in the slurry relative to carbon, leading to a suppression of methanogenesis and therefore lower biogas yields (Cuetos et al., 2011; Gaworski et al., 2017).

There are also challenges around the cost of implementation – can a farm afford to instal this technology on their unit and what is the return on investment? The answer to this will likely be dependent upon the size of the farm and the access to substrate for AD. Smaller farms (<500 sows) may require additional inputs (e.g. farmyard manure, agri-food waste, crop residues) to maximise the generation of biogas, depending upon the energy generation required. Increasing the amount of biogas produced on farms within a country, or a particular region, may also be limited by the current energy infrastructure and technologies available. For example, selling energy back to the grid may not always be possible depending upon the capacity at any given time, therefore limiting potential income streams if battery storage is not available. It has been suggested that pig slurry should instead be used to generate an inoculum for anaerobic digestion plants as opposed to acting as a substrate for digestion itself due to the beneficial microbial community that pig slurry contains (Marchetti et al., 2022). In this situation, it may be more economically viable for farmers to sell their slurry to a business that specialises in generating the microbial inoculum. This may be an opportunity for some farms, but it is unlikely to require the sheer volume of slurry being produced within a country at any given time.

Considerations for a farm of the future

When designing future farms, it is evident that we must ensure that the farm sits within a renewable, sustainable, potentially circular system. In order to do this, we must take into account energy usage, generation and disposal of waste materials. The solutions and opportunities for waste management on farms are likely to vary depending on a number of factors. For example, the route taken may differ depending upon the stage of production found on an individual farm. BSFL have been shown to grow quicker on slurry derived from pigs of a younger age (Hao et al., 2023b; Shao et al., 2024), coinciding with higher amounts of CP in the diets at this stage. Therefore, breeding units or those with finishing pigs may be better suited to send slurry directly to AD due to the higher fibre diets fed to these animals or additional proteinaceous co-products may be needed in addition to pig slurry to enhance insect bioconversion. Units with younger, growing pigs however would benefit from capturing the excess nitrogen that passes through the animal and converting this into insect biomass, reducing their environmental impact through lowering N loading onto land, whilst units producing animals on a straw-based system may have different process flows to those on slatted floors.

As technologies develop, it may be possible to link both insect bioconversion units and AD plants within the farm gate. Under these circumstances, the challenges around energy generation for the insect bioreactor could be met by the AD process, for example by providing the necessary heat to grow the insect larvae, whilst the digestate from the AD plant may provide a substrate for insect bioconversion due to their generalist feeding ability. More research is required to understand how these systems may link.

There is also a substantial opportunity to consider how we can feed the pig to manipulate the waste produced. Is it possible to alter the properties of slurry, via the diet, to enhance biogas potential or the growth of BSFL without compromising the health, welfare or efficiency of the animal? If we could achieve this through the incorporation of agri-food by-products such as those produced from the dairy industry or food processing, we could further enhance the circularity of pork production whilst adding further value to animal slurries. Through unlocking the potential of pig slurry, farmers may be able to convert this 'waste' product into a viable end product, be that through insect bioconversion or as energy to support on-farm activities whilst ensuring net zero targets can be achieved.

Conclusions

It is important to note that whilst bioconversion and biogas generation from pig slurry offer potential opportunities for the pork sector, they are in varying degrees of market readiness depending on individual country legislations and current capabilities. However, there is tremendous scope to capture the nutrients in slurry to produce a range of diversification streams through insect bioconversion, or on-farm energy generation. Whilst more research is needed to ensure that these circular waste management streams are cost-effective, sustainable and safe (in the case of the BSFL), the opportunity to the pork sector to harness this 'waste' product offers huge potential as steps to decarbonise pig production and improve farm resilience.

Ethics Approval

Not applicable.

Data and model availability statement

Not applicable. Information can be made available from the authors upon request.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) did not use any AI and AI-assisted technologies.

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Declaration of interest

None.

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References

Abd Manan, F., Yeoh, Y.K., Chai, T.T., Wong, F.C., 2024. Unlocking the potential of black soldier fly frass as a sustainable organic fertilizer: a review of recent studies. Journal of Environmental Management 367, p121997.
Adekolurejo, O.O., McDermott, K., Greathead, H.M.R., Miller, H.M., Mackie, A.R., Boesch, C., 2023. Effect of red-beetroot-supplemented diet on gut Microbiota composition and metabolite profile of weaned pigs—A pilot study. Animals 13, 2196.
Amiri, H., Aghbashlo, M., Sharma, M., Gaffey, J., Manning, L., Moosavi Basri, S.M., Kennedy, J.F., Gupta, V.K., Tabatabaei, M., 2022. Chitin and chitosan derived from crustacean waste valorization streams can support food systems and the UN Sustainable development goals. Nature Food 3, 822–828.
Amorim, H.C.S., Ashworth, A.J., Arsi, K., Rojas, M.G., Morales-Ramos, J.A., Donoghue, A., Robinson, K., 2024. Insect frass composition and potential use as an organic fertilizer in circular economies. Journal of Economic Entomology 117, 1261–1268.
Andretta, I., Hickmann, F.M.W., Remus, A., Franceschi, C.H., Mariani, A.B., Orso, C., Kipper, M., Létourneau-Montminy, M.-P., Pomar, C., 2021. Environmental impacts of pig and poultry production: insights from a systematic review. Frontiers in Veterinary Science 8, 750733.
Antezana, W., De Blas, C., García-Rebollar, P., Rodríguez, C., Beccaccia, A., Ferrer, P., Cerisuelo, A., Moset, V., Estellés, F., Cambra-López, M., Calvet, S., 2016. Composition, potential emissions and agricultural value of pig slurry from Spanish commercial farms. Nutrient Cycling in Agroecosystems 104, 159–173.
Ao, Y., Yang, C., Wang, S., Hu, Q., Yi, L., Zhang, J., Yu, Z., Cai, M., Yu, C., 2021. Characteristics and nutrient function of intestinal bacterial communities in black soldier fly (*Hermetia illucens L.*) larvae in livestock manure conversion. Microbial Biotechnology 14, 886–896.
Auger, L., Deschamps, M.-H., Vandenberg, G., Derome, N., 2023. Microbiota is structured by gut regions, life stage, and diet in the black soldier Fly (*Hermetia illucens*). Frontiers in Microbiology 14, 1221728.
Awasthi, M.K., Liu, T., Awasthi, S.K., Duan, Y., Pandey, A., Zhang, Z., 2020. Manure pretreatments with black soldier fly *Hermetia illucens* L. (Diptera: Stratiomyidae): a study to reduce pathogen content. Science of the Total Environment 737, 139842.
Barragan-Fonseca, K.B., Dicke, M., van Loon, J.J.A., 2017. Nutritional value of the black soldier fly (*Hermetia illucens* L.) and its suitability as animal feed – a review. Journal of Insects as Food and Feed 3, 105–120.
Beesigamukama, D., Mochoge, B., Korir, N.K., Fiaboe, K.K.M., Nakimbugwe, D., Khamis, F.M., Subramanian, S., Dubois, T., Musyoka, M.W., Ekesi, S., Kelemu, S., Tanga, C.M., 2020. Exploring black soldier Fly frass as novel fertilizer for improved growth, yield, and nitrogen use efficiency of maize under field conditions. Frontiers in Plant Science 11, 574592.
Beskin, K.V., Holcomb, C.D., Cammack, J.A., Crippen, T.L., Knap, A.H., Sweet, S.T., Tomberlin, J.K., 2018. Larval digestion of different manure types by the black soldier fly (Diptera: Stratiomyidae) impacts associated volatile emissions. Waste Management 74, 213–220.
Beyers, M., Coudron, C., Ravi, R., Meers, E., Bruun, S., 2023. Black soldier fly larvae as an alternative feed source and agro-waste disposal route – A life cycle perspective. Resources, Conservation and Recycling 192, 106917.
Bhatnagar, A., Sillanpää, M., 2009. Applications of chitin- and chitosan-derivatives for the detoxification of water and wastewater — A short review. Advances in Colloid and Interface Science 152, 26–38.
Biancarosa, I., Liland, N.S., Biemans, D., Araujo, P., Bruckner, C.G., Waagbø, R., Torstensen, B.E., Lock, E.J., Amlund, H., 2018. Uptake of heavy metals and arsenic in black soldier fly (*Hermetia illucens*) larvae grown on seaweed-enriched media. Journal of the Science of Food and Agriculture 98, 2176–2183.
Blázquez, C.S., Borge-Diez, D., Nieto, I.M., Maté-González, M.Á., Martín, A.F., González-Aguilera, D., 2021. Investigating the potential of the slurry technology for sustainable pig farm heating. Energy 234, 121258.
Blázquez, C.S., Borge-Diez, D., Nieto, I.M., Maté-González, M.Á., Martín, A.F., González-Aguilera, D., 2022. Geothermal heat pumps for slurry cooling and farm heating: impact and carbon footprint reduction in pig farms. Sustainability 14, 5792.
Boafo, H.A., Gbemavo, D.S.J.C., Timpong-Jones, E.C., Eziah, V., Billah, M., Chia, S.Y., Aidoo, O.F., Clottey, V.A., Kenis, M., 2023. Substrates most preferred for black soldier fly *Hermetia illucens* (L.) oviposition are not the most suitable for their larval development. Journal of Insects as Food and Feed 9, 183–192.
Bonelli, M., Bruno, D., Caccia, S., Sgambetterra, G., Cappellozza, S., Jucker, C., Tettamanti, G., Casartelli, M., 2019. Structural and functional characterization of *Hermetia illucens* Larval midgut. Frontiers in Physiology 10, 204.
Bonelli, M., Bruno, D., Brilli, M., Gianfranceschi, N., Tian, L., Tettamanti, G., Caccia, S., Casartelli, M., 2020. Black soldier fly larvae adapt to different food substrates through morphological and functional responses of the midgut. International Journal of Molecular Sciences 21, 4955.
Booth, D.C., Sheppard, C.J.E.E., 1984. Oviposition of the black soldier fly, *Hermetia illucens* (Diptera: Stratiomyidae): eggs, masses, timing, and site characteristics. Environmental Entomology 13, 421–423.
Caro, D., Davis, S.J., Bastianoni, S., Caldeira, K., 2014. Global and regional trends in greenhouse gas emissions from livestock. Climatic Change 126, 203–216.
Chen, J., Hou, D., Pang, W., Nowar, E.E., Tomberlin, J.K., Hu, R., Chen, H., Xie, J., Zhang, J., Yu, Z., Li, Q., 2019. Effect of moisture content on greenhouse gas and NH_3 emissions from pig manure converted by black soldier fly. Science of the Total Environment 697, 133840.
Cheng, J.Y.K., Chiu, S.L.H., Lo, I.M.C., 2017. Effects of moisture content of food waste on residue separation, larval growth and larval survival in black soldier fly bioconversion. Waste Management 67, 315–323.
Chia, S.Y., Tanga, C.M., Osuga, I.M., Cheseto, X., Ekesi, S., Dicke, M., van Loon, J.J.A., 2020. Nutritional composition of black soldier fly larvae feeding on agro-industrial by-products. Entomologia Experimentalis et Applicata 168, 472–481.
Chia, S.Y., Tanga, C.M., Osuga, I.M., Alaru, A.O., Mwangi, D.M., Githinji, M., Dubois, T., Ekesi, S., van Loon, J.J.A., Dicke, M., 2021. Black soldier fly larval meal in feed enhances growth performance, carcass yield and meat quality of finishing pigs. Journal of Insects as Food and Feed 7, 433–448.
Choi, I.H., 2024. Evaluation of the decomposition ability and characteristics of pig manure treated with different larval instar stages of black soldier fly (L.). Entomological Research 54, 12731.
Conti, C., Costantini, M., Fusi, A., Manzardo, A., Guarino, M., Bacenetti, J., 2021. Environmental impact of pig production affected by wet acid scrubber as mitigation technology. Sustainable Production and Consumption 28, 580–590.
Costantini, M., Bacenetti, J., Coppola, G., Orsi, L., Ganzaroli, A., Guarino, M., 2020. Improvement of human health and environmental costs in the European Union by air scrubbers in intensive pig farming. Journal of Cleaner Production 275, 124007.
Crosbie, M., Zhu, C., Shoveller, A.K., Huber, L.-A., 2020. Standardized ileal digestible amino acids and net energy contents in full fat and defatted black soldier fly larvae meals (*Hermetia illucens*) fed to growing pigs. Translational Animal Science 4, txaa104.
Crosbie, M., Zhu, C., Karrow, N.A., Huber, L.A., 2021. The effects of partially replacing animal protein sources with full fat black soldier fly larvae meal (*Hermetia illucens*) in nursery diets on growth performance, gut morphology, and immune response of pigs. Translational Animal Science 5, txab057.

Cuetos, M.J., Fernández, C., Gómez, X., Morán, A., 2011. Anaerobic co-digestion of swine manure with energy crop residues. Biotechnology and Bioprocess Engineering 16, 1044–1052.
Czekała, W., 2022. Digestate as a source of nutrients: nitrogen and its fractions. Water 14, 4067.
Danieli, P.P., Lussiana, C., Gasco, L., Amici, A., Ronchi, B., 2019. The effects of diet formulation on the yield, proximate composition, and fatty acid profile of the black soldier fly (*Hermetia illucens L.*) prepupae intended for animal feed. Animals 9, 178.
De Smet, J., Wynants, E., Cos, P. and Van Campenhout, L. 2018. Microbial community dynamics during rearing of black soldier fly larvae (*Hermetia illucens*) and impact on exploitation potential. *Applied and Environmental Microbiology.* **84**, 02722–02717.
DEFRA. 2022. The British survey of fertiliser practice, fertiliser use on farm crops for crop year 2022, Retrieved on 8th April 2025 from https://www.gov.uk/government/statistics/british-survey-of-fertiliser-practice-2022.
Deng, B., Liu, Z., Gong, T., Xu, C., Zhang, X., Cao, H., Yuan, Q., 2024. Addition of plantation waste to the bioconversion of pig manure by black soldier fly larvae: effects on heavy metal content and bioavailability. Waste Management 176, 64–73.
Diener, S., Zurbrügg, C., Tockner, K., 2015. Bioaccumulation of heavy metals in the black soldier fly, *Hermetia illucens* and effects on its life cycle. Journal of Insects as Food and Feed 1, 261–270.
Doyeni, M.O., Baksinskaite, A., Suproniene, S., Tilvikiene, V., 2021. Effect of animal waste based digestate fertilization on soil microbial activities, greenhouse gas emissions and spring wheat productivity in loam and sandy loam soil. Agronomy 11, 1281.
Drescher, G.L., Moura-Bueno, J.M., Dantas, M.K.L., Ceretta, C.A., De Conti, L., Marchezan, C., Ferreira, P.A.A., Brunetto, G., 2022. Copper and zinc fractions and adsorption in sandy soil with long-term pig manure application. Archives of Agronomy and Soil Science 68, 1930–1946.
Eke, M., Tougeron, K., Hamidovic, A., Tinkeu, L.S.N., Hance, T., Renoz, F., 2023. Deciphering the functional diversity of the gut microbiota of the black soldier fly (*Hermetia illucens*): recent advances and future challenges. Animal Microbiome 5, 40.
El-Dakar, M.A., Ramzy, R.R., Plath, M., Ji, H., 2021. Evaluating the impact of bird manure vs. mammal manure on *Hermetia illucens* larvae. Journal of Cleaner Production 278, 123570.
Elechi, M.C., Kemabonta, K.A., Ogbogu, S.S., Orabueze, I.C., Adetoro, F.A., Adebayo, H. A., Obe, T.M., 2021. Heavy metal bioaccumulation in prepupae of black soldier fly *hermetia illucens* (Diptera: Stratiomyidae) cultured with organic wastes and chicken feed. International Journal of Tropical Insect Science 41, 2125–2131.
Elhag, O., Zhang, Y., Xiao, X., Cai, M., Zheng, L., Jordan, H.R., Tomberlin, J.K., Huang, F., Yu, Z., Zhang, J., 2022. Inhibition of zoonotic pathogens naturally found in pig manure by black soldier fly larvae and their intestine bacteria. Insects 13, 66.
Environment Agency. 2018. State of the environment: water quality. EA Report, 10702, Retrieved on 8th April 2025 from https://assets.publishing.service.gov.uk/media/5b03e097ed915d3968dc5a78/State_of_the_environment_water_quality_report.pdf.
Espinosa, J.C., Marín-Moreno, A., Aguilar-Calvo, P., Benestad, S.L., Andreoletti, O., Torres, J.M., 2020. Porcine prion protein as a paradigm of limited susceptibility to prion strain propagation. The Journal of Infectious Diseases 223, 1103–1112.
EU. 2021. EU 2021/1372. Publications Office of the European Union, Retrieved on 8th April 2025 from: https://eur-lex.europa.eu/eli/reg/2021/1372/oj/eng.
Ewald, N., Vidakovic, A., Langeland, M., Kiessling, A., Sampels, S., Lalander, C., 2020. Fatty acid composition of black soldier fly larvae (*Hermetia illucens*) – possibilities and limitations for modification through diet. Waste Management 102, 40–47.
Ewusie, E.A., Kwapong, P.K., Ofosu-Budu, G., Sandrock, C., Akumah, A.M., Nartey, E. K., Tetegaga, C., Agyakwah, S.K., 2019. The black soldier fly, *Hermetia illucens* (Diptera: Stratiomyidae): trapping and culturing of wild colonies in Ghana. Scientific African 5, 00134.
Fernández-Labrada, M., López-Mosquera, M.E., García, L., Barrio, J.C., López-Fabal, A., 2023. Hazards of swine slurry: heavy metals, bacteriology, and overdosing—Physicochemical models to predict the nutrient value. Animal Science Journal 94, 13849.
Fuhrmann, A., Wilde, B., Conz, R.F., Kantengwa, S., Konlambigue, M., Masengesho, B., Kintche, K., Kassa, K., Musazura, W., Späth, L., Gold, M., Mathys, A., Six, J., Hartmann, M., 2022. Residues from black soldier fly (*Hermetia illucens*) larvae rearing influence the plant-associated soil microbiome in the short term. Frontiers in Microbiology 13, 994091.
Ganda, H., Zannou-Boukari, E.T., Kenis, M., Chrysostome, C.A.A.M., Mensah, G.A., 2019. Potentials of animal, crop and agri-food wastes for the production of fly larvae. Journal of Insects as Food and Feed 5, 59–68.
Gärttling, D., Schulz, H., 2022. Compilation of black soldier fly frass analyses. Journal of Soil Science and Plant Nutrition 22, 937–943.
Gaworski, M., Jabłoński, S., Pawlaczyk-Graja, I., Ziewiecki, R., Rutkowski, P., Wieczyńska, A., Gancarz, R., Łukaszewicz, M., 2017. Enhancing biogas plant production using pig manure and corn silage by adding wheat straw processed with liquid hot water and steam explosion. Biotechnology for Biofuels 10, 259.
Georgescu, B., Struţi, D., Păpuc, T., Ladoşi, D., Boaru, A.J., 2020. Body weight loss of black soldier fly Hermetia illucens (Diptera: Stratiomyidae) during development in non-feeding stages: implications for egg clutch parameters. European Journal of Entomology 117, 216–225.
Gerber, P.J., Steinfeld, H., Henderson, B., Mottet, A., Opio, C., Dijkman, J., Falcucci, A., Tempio, G., 2013. Tackling climate change through livestock: a global assessment of emissions and mitigation opportunities. Food and Agriculture Organization of the United Nations, Rome, Italy.
Gómez-Ríos, D., Barrera-Zapata, R., Ríos-Estepa, R.J.F., Processing, B., 2017. Comparison of process technologies for chitosan production from shrimp shell waste: a techno-economic approach using Aspen Plus®. Food and Bioproducts Processing 103, 49–57.
Gopalan, P., Jensen, P.D., Batstone, D.J., 2013. Anaerobic digestion of swine effluent: impact of production stages. Biomass and Bioenergy 48, 121–129.
Groen, E.A., van Zanten, H.H.E., Heijungs, R., Bokkers, E.A.M., de Boer, I.J.M., 2016. Sensitivity analysis of greenhouse gas emissions from a pork production chain. Journal of Cleaner Production 129, 202–211.
Grossule, V., Fang, D., Lavagnolo, M.C., 2023. Treatment of wastewater using black soldier Fly larvae: effect of organic concentration and load. Journal of Environmental Management 338, 117775.
Guarnieri, A., Triunfo, M., Scieuzo, C., Ianniciello, D., Tafi, E., Hahn, T., Zibek, S., Salvia, R., De Bonis, A., Falabella, P., 2022. Antimicrobial properties of chitosan from different developmental stages of the bioconverter insect *Hermetia illucens*. Scientific Reports 12, 8084.
Guo, H.G., Chen, Q.L., Hu, H.W., He, J.Z., 2020. High-solid anaerobic co-digestion of pig manure with lignite promotes methane production. Journal of Cleaner Production 258, 120695.
Häner, J., Weide, T., Naßmacher, A., Hernández Regalado, R.E., Wetter, C., Brügging, E., 2022. Anaerobic digestion of pig slurry in fixed-bed and expanded granular sludge bed reactors. Energies 15, 4414.
Hao, J., Liu, S., Guo, Z., Zhang, Y., Zhang, W., Li, C., 2023a. Effects of disinfectants on larval growth and gut microbial communities of black soldier fly larvae. Insects 14, 250.
Hao, J., Liu, S., Luo, A., Zhao, J., Shi, S., Zhang, Y., Li, C., 2023b. Assessing nursery-finishing pig manures on growth of black soldier fly larvae. Animals 13, 452.
He, X., Xi, B., Wei, Z., Guo, X., Li, M., An, D., Liu, H., 2011. Spectroscopic characterization of water extractable organic matter during composting of municipal solid waste. Chemosphere 82, 541–548.
Henchion, M., Moloney, A.P., Hyland, J., Zimmermann, J., McCarthy, S., 2021. Review: Trends for meat, milk and egg consumption for the next decades and the role played by livestock systems in the global production of proteins. Animal 15, 100287.
Hengeveld, E.J., van Gemert, W.J.T., Bekkering, J., Broekhuis, A.A., 2014. When does decentralized production of biogas and centralized upgrading and injection into the natural gas grid make sense? Biomass and Bioenergy 67, 363–371.
Hoek-van den Hil, E.F., Meijer, N.P., Van Rozen, K., Elissen, H., van Wikselaar, P.G., Brust, H., Te Loeke, N.A.J.M., de Rijk, T., Tienstra, M., van de Schans, M.G.M., Wanrooij, J., Van der Weide, R., Veldkamp, T., van der Fels-Klerx, H.J., 2023. Safety of black soldier fly (*Hermetia illucens)* larvae reared on waste streams of animal and vegetal origin and manure. Journal of Insects as Food and Feed 10, 771–783.
Hoffmans, Y., Veldkamp, T., Meijer, N.P., Brust, G.M.H., van der Schans, M.G.M., Prins, T.W., van Rozen, K., Elissen, H., van Wikselaar, P., van der Weide, R., van der Fels-Klerx, H.J., Hoek-van den Hil, E.F., 2024. Can black soldier fly larvae (*Hermetia illucens*) be reared on waste streams for food and feed? – A safety perspective. Journal of Insects as Food and Feed 10, 1211–1221.
Huang, Y., Yu, Y., Zhan, S., Tomberlin, J.K., Huang, D., Cai, M., Zheng, L., Yu, Z., Zhang, J., 2020. Dual oxidase duox and toll-like receptor 3 TLR3 in the toll pathway suppress zoonotic pathogens through regulating the intestinal bacterial community homeostasis in *Hermetia illucens* L. PLoS One 15, 0225873.
Im, S., Mostafa, A., Kim, D.-H., 2021. Use of citric acid for reducing CH_4 and H_2S emissions during storage of pig slurry and increasing biogas production: lab- and pilot-scale test, and assessment. Science of the Total Environment 753, 142080.
Jakubus, M., Dach, J., Starmans, D.J., 2013. Bioavailability of copper and zinc in pig and cattle slurries. Fresenius Environmental Bulletin 22, 995–1002.
Jiang, D., Jiang, K., Li, R., Zhao, L., Liu, Z., Xiong, B., Jin, D., Hao, X., Zhu, L., Kang, B., Bai, L., 2022. Influence of different inoculation densities of black soldier fly larvae (*Hermetia illucens*) on heavy metal immobilization in swine manure. Environmental and Science Pollution Research 29, 54378–54390.
Kang, J.Y., Kang, D.W., Kim, T.S., Hur, K.B., 2014. Comparative economic analysis of gas turbine-based power generation and combined heat and power systems using biogas fuel. Energy 67, 309–318.
Kanso, M., Tiruta-Barna, L., Robles-Rodriguez, C.E., 2024. A technical and environmental analysis of carbon capture technologies applied to biogas: a simulation approach. Sustainable Production and Consumption 49, 625–640.
Kariuki, E.G., Kibet, C., Paredes, J.C., Mboowa, G., Mwaura, O., Njogu, J., Masiga, D., Bugg, T.D.H., Tanga, C.M., 2023. Metatranscriptomic analysis of the gut microbiome of black soldier fly larvae reared on lignocellulose-rich fiber diets unveils key lignocellulolytic enzymes. Frontiers in Microbiology 14, 1120224.
KeChrist, O., Sampson, M., Golden, M., Nwabunwanne, N., 2017. Slurry utilization and impact of mixing ratio in biogas production. Chemical Engineering & Technology 40, 1742–1749.
Kierończyk, B., Sypniewski, J., Mikołajczak, Z., Rawski, M., Pruszyńska-Oszmałek, E., Sassek, M., Kołodziejski, P., Józefiak, D., 2022. Replacement of soybean oil with cold-extracted fat from *Hermetia illucens* in young turkey diets: effects on performance, nutrient digestibility, selected organ measurements, meat and liver tissue traits, intestinal microbiota modulation, and physiological and immunological status. Animal Feed Science and Technology 286, 115210.
Kim, W., Bae, S., Park, K., Lee, S., Choi, Y., Han, S., Koh, Y., 2011. Biochemical characterization of digestive enzymes in the black soldier fly, *Hermetia illucens* (Diptera: Stratiomyidae). Journal of Asia-Pacific Entomology 14, 11–14.

Kim, Y.B., Kim, D.H., Jeong, S.B., Lee, J.W., Kim, T.H., Lee, H.G., Lee, K.W., 2020. Black soldier fly larvae oil as an alternative fat source in broiler nutrition. Poultry Science 99, 3133–3143.

Komarek, A.M., Dunston, S., Enahoro, D., Godfray, H.C.J., Herrero, M., Mason-D'Croz, D., Rich, K.M., Scarborough, P., Springmann, M., Sulser, T.B., Wiebe, K., Willenbockel, D., 2021. Income, consumer preferences, and the future of livestock-derived food demand. Global Environmental Change 70, 102343.

Kowalski, Z., Makara, A., Fijorek, K., 2013. Changes in the properties of pig manure slurry. Acta Biochimica Polonica 60, 845–850.

Lalander, C.H., Fidjeland, J., Diener, S., Eriksson, S., Vinnerås, B., 2015. High waste-to-biomass conversion and efficient Salmonella spp. reduction using black soldier fly for waste recycling. Agronomy for Sustainable Development 35, 261–271.

Le, T.M., Tran, C.L., Nguyen, T.X., Duong, Y.H.P., Le, P.K., Tran, V.T., 2023. Green preparation of chitin and nanochitin from black soldier fly for production of biodegradable packaging material. Journal of Polymers and the Environment 31, 3094–3105.

León, E., Martín, M., 2016. Optimal production of power in a combined cycle from manure based biogas. Energy Conversion and Management 114, 89–99.

Lesschen, J.P., van den Berg, M., Westhoek, H.J., Witzke, H.P., Oenema, O., 2011. Greenhouse gas emission profiles of European livestock sectors. Animal Feed Science and Technology 166–167, 16–28.

Li, S., Ji, H., Zhang, B., Tian, J., Zhou, J., Yu, H., 2016. Influence of black soldier fly (*Hermetia illucens*) larvae oil on growth performance, body composition, tissue fatty acid composition and lipid deposition in juvenile Jian carp (Cyprinus carpio var. Jian). Aquaculture 465, 43–52.

Li, T., Khan, S., Wei, M., Li, H., Wen, T., Guo, J., Jin, D., 2023. Utilizing black soldier fly larvae to improve bioconversion and reduce pollution: a sustainable method for efficient treatment of mixed wastes of wet distiller grains and livestock manure. Molecules 28, 5735.

Li, Y., Wang, M., Chen, X., Cui, S., Hofstra, N., Kroeze, C., Ma, L., Xu, W., Zhang, Q., Zhang, F., Strokal, M., 2022. Multi-pollutant assessment of river pollution from livestock production worldwide. Water Research 209, 117906.

Li, T., Yang, W., Gao, Q., Wei, M., Li, H., Ma, X., Wen, T., Guo, J., Jin, D., 2024. Reducing the mass and decreasing the bioavailability of heavy mental from organic wastes treated by black soldier fly larvae. Ecotoxicology and Environmental Safety 269, 115821.

Li, Q., Zheng, L., Cai, H., Garza, E., Yu, Z., Zhou, S., 2011. From organic waste to biodiesel: black soldier fly, *Hermetia illucens*, makes it feasible. Fuel 90, 1545–1548.

Liew, C.S., Mong, G.R., Lim, J.W., Raksasat, R., Rawindran, H., Leong, W.H., Manogaran, M.D., Chai, Y.H., Ho, Y.C., Rahmah, A.U.J.W.M., 2023. Life cycle assessment: sustainability of biodiesel production from black soldier fly larvae feeding on thermally pre-treated sewage sludge under a tropical country setting. Waste Management 164, 238–249.

Lin, C., Xia, X., Li, Y., Ma, R., Zhu, L., Li, X., Tang, Y., Wang, C., 2023. Heavy metals transport patterns and risk evaluation in the pig manure- black soldier fly-tilapia food chain. Environmental Pollution 337, 122565.

Liu, T., Awasthi, M.K., Chen, H., Duan, Y., Awasthi, S.K., Zhang, Z., 2019. Performance of black soldier fly larvae (Diptera: Stratiomyidae) for manure composting and production of cleaner compost. Journal of Environmental Management 251, 109593.

Liu, T., Awasthi, M.K., Awasthi, S.K., Zhang, Y., Zhang, Z., 2020. Impact of the addition of black soldier fly larvae on humification and speciation of trace elements during manure composting. Industrial Crops and Products 154, 112657.

Liu, T., Kumar Awasthi, M., Verma, S., Qin, S., Awasthi, S.K., Liu, H., Zhou, Y., Zhang, Z., 2021. Evaluation of cornstalk as bulking agent on greenhouse gases emission and bacterial community during further composting. Bioresource Technology 340, 125–713.

Liu, T., Awasthi, M.K., Wang, X., Awasthi, S.K., Jiao, M., Shivpal, V., Zhou, Y., Liu, H., Zhang, Z., 2022. Effects of further composting black soldier fly larvae manure on toxic metals and resistant bacteria communities by cornstalk amendment. Science of the Total Environment 806, 150–699.

Liu, Z., Minor, M., Morel, P.C.H., Najar-Rodriguez, A.J., 2018. Bioconversion of three organic wastes by black soldier fly (Diptera: Stratiomyidae) Larvae. Environmental Entomology 47, 1609–1617.

Lomonaco, G., Franco, A., De Smet, J., Scieuzo, C., Salvia, R., Falabella, P., 2024. Larval frass of *Hermetia illucens* as organic fertilizer: composition and beneficial effects on different crops. Insects 15, 293.

Luján-Facundo, M.J., Iborra-Clar, M.I., Mendoza-Roca, J.A., Also-Jesús, M., 2019. Alternatives for the management of pig slurry: phosphorous recovery and biogas generation. Journal of Water Process Engineering 30, 100473.

Madau, F.A., Arru, B., Furesi, R., Pulina, P., 2020. Insect farming for feed and food production from a circular business model perspective. Sustainability 12, 5418.

Makkar, H.P.S., Tran, G., Heuzé, V., Ankers, P., 2014. State-of-the-art on use of insects as animal feed. Animal Feed Science and Technology 197, 1–33.

Marchetti, R., Vasmara, C., Orsi, A., 2022. Inoculum production from pig slurry for potential use in agricultural biogas plants. Sustainable Energy Technologies and Assessments 52, 102310.

Matos, J.S., de Aráujo, L.P., Allaman, I.B., Lôbo, I.P., de Oliva, S.T., Tavares, T.M., de Almeida Neto, J.A., 2021. Evaluation of the reduction of methane emission in swine and bovine manure treated with black soldier fly larvae (*Hermetia illucens* L.). Environmental Monitoring and Assessment 193, 480.

Mei, H., Li, C., Li, X., Hu, B., Lu, L., Tomberlin, J.K., Hu, W., 2022. Characteristics of tylosin and enrofloxacin degradation in swine manure digested by black soldier fly (*Hermetia illucens* L.) larvae. Environmental Pollution 293, 118495.

Miranda, C.D., Cammack, J.A., Tomberlin, J.K., 2019. Life-history traits of the black soldier fly, *Hermetia illucens* (L.) (Diptera: Stratiomyidae), reared on three manure types. Animals 9, 281.

Miranda, C.D., Cammack, J.A., Tomberlin, J.K., 2020. Mass production of the black soldier fly, *Hermetia illucens* (L.), (Diptera: Stratiomyidae) reared on three manure types. Animals 10, 1243.

Miranda, C.D., Crippen, T.L., Cammack, J.A., Tomberlin, J.K., 2021. Black soldier fly, *Hermetia illucens* (L.) (Diptera: Stratiomyidae), and house fly, Musca domestica L. (Diptera: Muscidae), larvae reduce livestock manure and possibly associated nutrients: an assessment at two scales. Environmental Pollution 282, 116976.

Mohan, K., Sathishkumar, P., Rajan, D.K., Rajarajeswaran, J., Ganesan, A.R., 2023. Black soldier fly (*Hermetia illucens*) larvae as potential feedstock for the biodiesel production: recent advances and challenges. Science of the Total Environment 859, 160235.

Monard, C., Jeanneau, L., Le Garrec, J.L., Le Bris, N., Binet, F., 2020. Short-term effect of pig slurry and its digestate application on biochemical properties of soils and emissions of volatile organic compounds. Applied Soil Ecology 147, 103376.

Moreno de la Cruz, J., 2019. Estudio de viabilidad de una planta de producción de Quitosano. Master thesis. The Technical University of Madrid, Madrid, Spain.

Moretta, A., Salvia, R., Scieuzo, C., Di Somma, A., Vogel, H., Pucci, P., Sgambato, A., Wolff, M., Falabella, P., 2020. A bioinformatic study of antimicrobial peptides identified in the black soldier fly (BSF) *Hermetia illucens* (Diptera: Stratiomyidae). Scientific Reports 10, 16875.

Morin-Crini, N., Lichtfouse, E., Torri, G., Crini, G., 2019. Applications of chitosan in food, pharmaceuticals, medicine, cosmetics, agriculture, textiles, pulp and paper, biotechnology, and environmental chemistry. Environmental Chemistry Letters 17, 1667–1692.

Muangrat, R., Pannasai, S., 2024. Exploring the potential of black soldier fly larvae oil: supercritical CO_2 extraction, physicochemical analysis, antioxidant properties, shelf life, and keratinocyte growth inhibition. Journal of Agriculture and Food Research 15, 101008.

Nag, R., Whyte, P., Markey, B.K., O'Flaherty, V., Bolton, D., Fenton, O., Richards, K.G., Cummins, E., 2020. Ranking hazards pertaining to human health concerns from land application of anaerobic digestate. Science of the Total Environment 710, 136297.

Nagy, G., Wopera, A.J.M.S.Engineering, 2012. Biogas production from pig slurry-feasibility and challenges. Materials Science and Engineering 37, 65–75.

Naser El Deen, S., van Rozen, K., Elissen, H., van Wikselaar, P., Fodor, I., van der Weide, R., Hoek-van den Hil, E.F., Rezaei Far, A. and Veldkamp, T. 2023. Bioconversion of different waste streams of animal and vegetal origin and manure by black soldier fly larvae *Hermetia illucens L.* (Diptera: Stratiomyidae). *Insects.* **14**, 14020204.

Ndue, K., Pál, G., 2022. Life cycle assessment perspective for sectoral adaptation to climate change: environmental impact assessment of pig production. Land 11, 827.

Newton, L., Sheppard, C., Watson, W.D., Burtle, G., Dove, R., 2005. Using the black soldier fly, *Hermetia illucens*, as a value-added tool for the management of swine manure. Journal of the Animal and Poultry Waste Management Center 17, 18.

Nguyen, T.T.X., Tomberlin, J.K., Vanlaerhoven, S., 2013. Influence of resources on *Hermetia illucens* (Diptera: Stratiomyidae) larval development. Journal of Medical Entomology 50, 898–906.

Nguyen, T.T.X., Tomberlin, J.K., Vanlaerhoven, S., 2015. Ability of black soldier fly (Diptera: Stratiomyidae) larvae to recycle food waste. Environmental Entomology 44, 406–410.

Nicholson, F.A., Smith, S.R., Alloway, B.J., Carlton-Smith, C., Chambers, B.J., 2006. Quantifying heavy metal inputs to agricultural soils in England and Wales. Water and Environment Journal 20, 87–95.

Niyonsaba, H.H., Höhler, J., Kooistra, J., Van der Fels-Klerx, H.J., Meuwissen, M.P.M., 2021. Profitability of insect farms. Journal of Insects as Food and Feed 7, 923–934.

O'Mara, F.P., 2011. The significance of livestock as a contributor to global greenhouse gas emissions today and in the near future. Animal Feed Science and Technology 166–167, 7–15.

O'Connor, S., Ehimen, E., Pillai, S.C., Black, A., Tormey, D., Bartlett, J., 2021. Biogas production from small-scale anaerobic digestion plants on European farms. Renewable and Sustainable Energy Reviews 139, 110580.

Oonincx, D.G.A.B., van Huis, A., van Loon, J.J.A., 2015. Nutrient utilisation by black soldier flies fed with chicken, pig, or cow manure. Journal of Insects as Food and Feed 1, 131–140.

Pang, W., Hou, D., Nowar, E.E., Chen, H., Zhang, J., Zhang, G., Li, Q., Wang, S., 2020. The influence on carbon, nitrogen recycling, and greenhouse gas emissions under different C/N ratios by black soldier fly. Environmental Science and Pollution Research 27, 42767–42777.

Parodi, A., Van Dijk, K., Van Loon, J.J.A., De Boer, I.J.M., Van Schelt, J., Van Zanten, H.H. E., 2020. Black soldier fly larvae show a stronger preference for manure than for a mass-rearing diet. Journal of Applied Entomology 144, 560–565.

Parodi, A., Gerrits, W.J.J., Van Loon, J.J.A., De Boer, I.J.M., Aarnink, A.J.A., Van Zanten, H.H.E., 2021. Black soldier fly reared on pig manure: bioconversion efficiencies, nutrients in the residual material, greenhouse gas and ammonia emissions. Waste Management 126, 674–683.

Parodi, A., Yao, Q., Gerrits, W.J.J., Mishyna, M., Lakemond, C.M.M., Oonincx, D.G.A.B., Van Loon, J.J.A., 2022. Upgrading ammonia-nitrogen from manure into body proteins in black soldier fly larvae. Resources, Conservation and Recycling 182, 106343.

Patania, F., Gagliano, A., Nocera, F., Galesi, A., 2012. Feasibility study of biogas in CHP plant for a pig farm. Renewable Energy and Power Quality Journal 10, 196.
Peng, C., Zhou, T., Song, S., Sun, S., 2022. Analysis and experiment of feeding material process of Hermetia illucens L. frass bucket wheel based on DEM. Computers and Electronics in Agriculture 196, 106855.
Pourcher, A.-M., Druilhe, C., Le Maréchal, C., Repérant, E., Boscher, E., Ziebal, C., Martin, L., Lebreton, M., Rouxel, S., Houdayer, C., Le Roux, S., Derongs, L., Poëzévara, T., Sarrazin, M., Nagard, B., Heurtevent, L., Denis, M., 2023. Quantification of indicator and pathogenic bacteria in manures and digestates from three agricultural biogas plants over a one-year period. Waste Management 169, 91–100.
Prado, J., Ribeiro, H., Alvarenga, P., Fangueiro, D., 2022. A step towards the production of manure-based fertilizers: disclosing the effects of animal species and slurry treatment on their nutrients content and availability. Journal of Cleaner Production 337, 130369.
Provolo, G., Manuli, G., Finzi, A., Lucchini, G., Riva, E., Sacchi, G.A., 2018. Effect of pig and cattle slurry application on heavy metal composition of maize grown on different soils. Sustainability 10, 2684.
Rafiee, A., Khalilpour, K.R., Prest, J., Skryabin, I., 2021. Biogas as an energy vector. Biomass and Bioenergy 144, 105935.
Rahayu, R., Utari, S.D., Santoso, P., Zaini, E., Jessica, A.J., 2024. Effectiveness of black soldier fly (*Hermetia illucens*) prepupa oil emulgel for burn wound recovery. Tropical Journal of Natural Product Research 8, 6589–6593.
Ramírez-Méndez, V., Guzmán-Plazola, R., Pérez-Panduro, A. and Sánchez-Escudero, J.J.H.i. 2022. Organic waste bioconversion and weight gain dynamics of the black soldier fly. *Agrociencia*. **56**, 1459.
Rehman, K.u., Liu, X., Wang, H., Zheng, L., Rehman, R.u., Cheng, X., Li, Q., Li, W., Cai, M., Zhang, J. and Yu, Z. 2018. Effects of black soldier fly biodiesel blended with diesel fuel on combustion, performance and emission characteristics of diesel engine. *Energy Conversion and Management.* **173**, 489–498.
Rehman, K.u., Ur Rehman, R., Somroo, A.A., Cai, M., Zheng, L., Xiao, X., Ur Rehman, A., Rehman, A., Tomberlin, J.K., Yu, Z. and Zhang, J. 2019. Enhanced bioconversion of dairy and chicken manure by the interaction of exogenous bacteria and black soldier fly larvae. *Journal of Environmental Management.* **237**, 75–83.
Rehman, K.u., Hollah, C., Wiesotzki, K., Heinz, V., Aganovic, K., Rehman, R.u., Petrusan, J.-I., Zheng, L., Zhang, J., Sohail, S., Mansoor, M.K., Rumbos, C.I., Athanassiou, C. and Cai, M. 2023. Insect-derived Chitin and Chitosan: a still unexploited resource for the edible insect sector. *Sustainability*. **15**, 4864.
Richter, H., Gover, O., Schwartz, B., 2023. Anti-inflammatory activity of black soldier fly oil associated with modulation of TLR signaling: a metabolomic approach. International Journal of Molecular Sciences 24, 10634.
Rindhe, S., Chatli, M.K., Wagh, R., Kaur, A., Mehta, N., Kumar, P., Malav, O.J.I.J.o.C.M. and Sciences, A. 2019. Black soldier fly: a new vista for waste management and animal feed. *International Journal of Current Microbiology and Applied Sciences.* **8**, 1331–1334.
Riofrio, A., Alcivar, T., Baykara, H., 2021. Environmental and economic viability of chitosan production in guayas-ecuador: a robust investment and life cycle analysis. ACS Omega 6, 23038–23051.
Rotunno, P., Lanzini, A., Leone, P., 2017. Energy and economic analysis of a water scrubbing based biogas upgrading process for biomethane injection into the gas grid or use as transportation fuel. Renewable Energy 102, 417–432.
Santos, A.D., Silva, J.R., Castro, L.M., Quinta-Ferreira, R.M., 2022. A biochemical methane potential of pig slurry. Energy Reports 8, 153–158.
Shah, S., 2024. Insect farming: investment trends and projected production capacity. *Rethink Priorities*. Retrieved 8th April 2025 from doi:https://rethinkpriorities.org/research-area/investments-into-insect-farming/.
Shao, M., Zhao, X., Rehman, K.U., Cai, M., Zheng, L., Huang, F., Zhang, J., 2024. Synergistic bioconversion of organic waste by black soldier fly (*Hermetia illucens*) larvae and thermophilic cellulose-degrading bacteria. Frontiers in Microbiology 14, 1288227.
Sharp, R.G., 2013. A review of the applications of chitin and its derivatives in agriculture to modify plant-microbial interactions and improve crop yields. Agronomy 3, 757–793.
Shen, W., Ma, X., Liu, H., Jia, C., Xue, R., Ouyang, H., Li, Y., Sun, S., Dong, X., Ji, F., Xu, J., Xu, W., 2024. Fatty acid bioconversion and scaling-up effects of swine manure treatment with black soldier fly larvae. Biomass 4, 1031–1046.
Sheppard, C.D., Newton, L.G., Thompson, S.A., Savage, S., 1994. A value added manure management system using the black soldier fly. Bioresource Technology 50, 275–279.
Sheppard, D.C., Tomberlin, J.K., Joyce, J.A., Kiser, B.C., Sumner, S.M., 2002. Rearing methods for the black soldier fly (Diptera: Stratiomyidae). Journal of Medical Entomology 39, 695–698.
Shi, C., Xie, P., Ding, Z., Niu, G., Wen, T., Gu, W., Lu, Y., Wang, F., Li, W., Zeng, J., Shen, Q., Yuan, J., 2024. Inhibition of pathogenic microorganisms in solid organic waste via black soldier fly larvae-mediated management. Science of the Total Environment 913, 169767.
Silva, F.P., de Souza, S.N.M., Kitamura, D.S., Nogueira, C.E.C., Otto, R.B., 2018. Energy efficiency of a micro-generation unit of electricity from biogas of swine manure. Renewable and Sustainable Energy Reviews 82, 3900–3906.
Singh, A., Kumari, K., 2019. An inclusive approach for organic waste treatment and valorisation using black soldier fly larvae: a review. Journal of Environmental Management 251, 109569.
Smith, K.A., Williams, A.G., 2016. Production and management of cattle manure in the UK and implications for land application practice. Soil Use and Management 32, 73–82.
Soetemans, L., Uyttebroek, M., Bastiaens, L., 2020. Characteristics of chitin extracted from black soldier fly in different life stages. International Journal of Biological Macromolecules 165, 3206–3214.
Sommer, S.G., Hjorth, M., Leahy, J.J., Zhu, K., Christel, W., Sørensen, C.G., Sutaryo, 2015. Pig slurry characteristics, nutrient balance and biogas production as affected by separation and acidification. The Journal of Agricultural Science 153, 177–191.
Supekar, S.D., Skerlos, S.J., 2014. Market-driven emissions from recovery of carbon dioxide gas. Environmental Science & Technology 48, 14615–14623.
Sutton, T.A., O'Neill, H.V.M., Bedford, M.R., McDermott, K., Miller, H.M., 2021. Effect of xylanase and xylo-oligosaccharide supplementation on growth performance and faecal bacterial community composition in growing pigs. Animal Feed Science and Technology 274, 114822.
Tambone, F., Genevini, P., D'Imporzano, G., Adani, F., 2009. Assessing amendment properties of digestate by studying the organic matter composition and the degree of biological stability during the anaerobic digestion of the organic fraction of MSW. Bioresource Technology 100, 3140–3142.
Taufek, N.M., Mohamad Zulkifli, N.F.N., Hamizah, A.N., 2024. Upcycling of food waste generated from the fresh market by utilising black soldier fly larvae: influence on growth, bioconversion, and nutritional composition. Journal of Environmental Management 349, 119467.
Theofanous, E., Kythreotou, N., Panayiotou, G., Florides, G., Vyrides, I., 2014. Energy production from piggery waste using anaerobic digestion: current status and potential in cyprus. Renewable Energy 71, 263–270.
Thorn, C.E., Nolan, S., Lee, C.S., Friel, R., O'Flaherty, V., 2022. Novel slurry additive reduces gaseous emissions during storage thereby improving renewable energy and fertiliser potential. Journal of Cleaner Production 358, 132004.
Tian, P., Gong, B., Bi, K., Liu, Y., Ma, J., Wang, X., Ouyang, Z., Cui, X., 2023. Anaerobic co-digestion of pig manure and rice straw: optimization of process parameters for enhancing biogas production and system stability. International Journal of Environmental Research and Public Health 20, 804.
Tiwasing, P., Pate, L., 2024. Exploring edible insects as feed in the UK: current challenges and future prospects. Journal of Insects as Food and Feed 11, 1–17.
Torres-Rodriguez, J.A., Reyes-PéRez, J.J., Castellanos, T., Angulo, C., QuiñOnes-Aguilar, E.E., Hernandez-Montiel, L.G., 2021. A biopolymer with antimicrobial properties and plant resistance inducer against phytopathogens: chitosan. Notulae Botanicae Horti Agrobotanici Cluj-Napoca 49, 12231.
Triunfo, M., Tafi, E., Guarnieri, A., Salvia, R., Scieuzo, C., Hahn, T., Zibek, S., Gagliardini, A., Panariello, L., Coltelli, M.B., De Bonis, A., Falabella, P., 2022. Characterization of chitin and chitosan derived from Hermetia illucens, a further step in a circular economy process. Scientific Reports 12, 6613.
UNFCCC. 2018. *The Paris Agreement.* [Online]. Retrieved 16 December 2024 from: https://unfccc.int/documents/184656.
Valluri, S., Claremboux, V., Kawatra, S., 2022. Opportunities and challenges in CO_2 utilization. Journal of Environmental Sciences 113, 322–344.
Van der Fels-Klerx, H., Meijer, N., Nijkamp, M., Schmitt, E., Van Loon, J.J.J.o.I.a.F., Feed, 2020. Chemical food safety of using former foodstuffs for rearing black soldier fly larvae (*Hermetia illucens*) for feed and food use. Journal of Insects as Food and Feed 6, 475–488.
van Heugten, E., Martinez, G., McComb, A., Koutsos, L., 2022. Improvements in performance of nursery pigs provided with supplemental oil derived from black soldier fly (*Hermetia illucens*) Larvae. Animals 12, 3251.
Van Horn, H. 1998. Factors affecting manure quantity, quality, and use. In: *Proceedings of the mid-south ruminant nutrition conference, Dallas-Ft. Worth*, Retrieved 8th April 2025 from: https://www.txanc.org/proceedings/1998/vanhorn3.pdf.
Veldkamp, T., van Rozen, K., Elissen, H., van Wikselaar, P., van der Weide, R., 2021. Bioconversion of digestate, pig manure and vegetal residue-based waste operated by black soldier fly larvae, *Hermetia illucens L.* (Diptera: Stratiomyidae). Animals 11, 3082.
VMR, 2023. Global insect frass (biofertilisers) market by type (molitor larvae, mealworm), by application (seed treatment, soil treatment), by geographic scope and forecast. *Verified Market Reports.* Retrieved 8th April 2025 from: https://www.verifiedmarketreports.com/product/insect-frass-biofertilisers-market/.
VMR. 2024. Chitin and Chitosan derivatives market size by type (chitin, chitosan, glucosamine), by application (food & beverages, animal feed, agriculture), by geographic scope and forecast. *Verified Market Research.* Retrieved 8th April 2025 from https://www.verifiedmarketresearch.com/product/chitin-and-chitosan-derivatives-market/.
Wang, Q., Ren, X., Sun, Y., Zhao, J., Awasthi, M.K., Liu, T., Li, R., Zhang, Z., 2021a. Improvement of the composition and humification of different animal manures by black soldier fly bioconversion. Journal of Cleaner Production 278, 123397.
Wang, L., Wang, S., Yang, R., Zhang, B., Xu, L., Hu, Q., Zhao, Z., Cao, Z., 2024. Effect of moisture content on larval gut microbiome and the conversion of pig manure by black soldier fly. Science of the Total Environment 912, 169579.
Wang, S.Y., Wu, L., Li, B., Zhang, D., 2019. Reproductive potential and nutritional composition of *Hermetia illucens* (Diptera: Stratiomyidae) prepupae reared on different organic wastes. Journal of Economic Entomology 113, 527–537.
Wang, X.-B., Wu, N., Cai, R.-J., Geng, W.-N., Xu, X.-Y., 2021b. Changes in speciation, mobility and bioavailability of Cd, Cr and As during the transformation process of pig manure by black soldier fly larvae (*Hermetia illucens*). Journal of Integrative Agriculture 20, 1157–1166.
Wang, X., Wu, N., Ma, Y., Wang, Z., Cai, R., Xu, X., 2022. Migration and transformation of Cd in pig manure-Insect frass (*Hermetia illucens*)-soil-maize system. International Journal of Environmental Research and Public Health 20, 60.

Wilkinson, K.G., 2011. A comparison of the drivers influencing adoption of on-farm anaerobic digestion in Germany and Australia. Biomass and Bioenergy 35, 1613–1622.

Wilkinson, J.M., Young, R.H., 2020. Strategies to reduce reliance on soya bean meal and palm kernel meal in livestock nutrition. Journal of Applied Animal Nutrition 8, 75–85.

Witt, J., Krieter, J., Schröder, K., Büttner, K., Hölzel, C., Krugmann, K., Czycholl, I., 2024. Comparison of three different measuring devices of ammonia and evaluation of their suitability to assess animal welfare in pigs. Livestock Science 279, 105372.

World Wildlife Fund, Tesco, 2021. The future of feed: A WWF roadmap to accelerating insect protein in UK feeds. World Wildlife Fund, London, UK.

Wu, N., Wang, X., Yan, Z., Xu, X., Xie, S., Liang, J., 2021. Transformation of pig manure by passage through the gut of black soldier fly larvae (*Hermetia illucens*): metal speciation, potential pathogens and metal-related functional profiling. Ecotoxicology and Environmental Safety 211, 111925.

Wu, N., Ma, Y., Yu, X., Wang, X., Wang, Q., Liu, X., Xu, X., 2024. Black soldier fly larvae bioconversion and subsequent composting promote larval frass quality during pig and chicken manure transformation process. Bioresource Technology 402, 130777.

Wu, B., Zhang, X., Shang, D., Bao, D., Zhang, S., Zheng, T., 2016. Energetic-environmental-economic assessment of the biogas system with three utilization pathways: combined heat and power, biomethane and fuel cell. Bioresource Technology 214, 722–728.

Xiao, Y., Geng, W., Yang, Y., Wang, X., Xu, X., 2020. Study on the difference of transformation of livestock and poultry feces by black soldier fly. IOP Conference Series: Earth and Environmental Science 450, 012122.

Yagüe, M.R., Bosch-Serra, À.D., Boixadera, J., 2012. Measurement and estimation of the fertiliser value of pig slurry by physicochemical models: usefulness and constraints. Biosystems Engineering 111, 206–216.

Zhan, S., Fang, G., Cai, M., Kou, Z., Xu, J., Cao, Y., Bai, L., Zhang, Y., Jiang, Y., Luo, X., Xu, J., Xu, X., Zheng, L., Yu, Z., Yang, H., Zhang, Z., Wang, S., Tomberlin, J.K., Zhang, J., Huang, Y., 2020. Genomic landscape and genetic manipulation of the black soldier fly *Hermetia illucens*, a natural waste recycler. Cell Research 30, 50–60.

Zhang, H., Ji, W., Li, X., Feng, Y., Wang, J., Liu, H., Bao, J., 2021a. Immunosuppression, oxidative stress, and apoptosis in pig kidney caused by ammonia: application of transcriptome analysis in risk assessment of ammonia exposure. Toxicology and Applied Pharmacology 428, 115675.

Zhang, Y., Jiang, Y., Wang, S., Wang, Z., Liu, Y., Hu, Z., Zhan, X., 2021b. Environmental sustainability assessment of pig manure mono- and co-digestion and dynamic land application of the digestate. Renewable and Sustainable Energy Reviews 137, 110476.

Zhang, J., Wang, M., Cao, Y., Liang, P., Wu, S., Leung, A.O.W., Christie, P., 2017. Replacement of mineral fertilizers with anaerobically digested pig slurry in paddy fields: assessment of plant growth and grain quality. Environmental Science and Pollution Research 24, 8916–8923.

Zhang, J., Luo, Z., Li, N., Yu, Y., Cai, M., Zheng, L., Zhu, F., Huang, F., Tomberlin, J., Rehman, K., Yu, Z., Zhang, J., 2023. Cellulose-degrading bacteria improve conversion efficiency in the co-digestion of dairy and chicken manure by black soldier fly larvae. Journal of Environmental Management 348, 119156.

Zhang, Y., Xiao, X., Elhag, O., Cai, M., Zheng, L., Huang, F., Jordan, H.R., Tomberlin, J.K., Sze, S.-H., Yu, Z., Zhang, J., 2022. Hermetia illucens L. larvae–associated intestinal microbes reduce the transmission risk of zoonotic pathogens in pig manure. Microbial Biotechnology 15, 2631–2644.

Zhang, B., Yang, R., He, S., Dai, S., Hu, Q., Li, X., Su, H., Shi, J., Zhao, Z., Wu, D., 2024. Swill and pig manure substrates differentially affected transcriptome and metabolome of the black soldier fly larvae. International Journal of Molecular Sciences 25, 12147.

Zhao, Z., Yu, C., Yang, C., Gao, B., Jiménez, N., Wang, C., Li, F., Ao, Y., Zheng, L., Huang, F., Tomberlin, J.K., Ren, Z., Yu, Z., Zhang, J., Cai, M., 2023. Mitigation of antibiotic resistome in swine manure by black soldier fly larval conversion combined with composting. Science of the Total Environment 879, 163065.

Zhou, F., Tomberlin, J.K., Zheng, L., Yu, Z., Zhang, J., 2013. Developmental and waste reduction plasticity of three black soldier fly strains (Diptera: Stratiomyidae) raised on different livestock manures. Journal of Medical Entomology 50, 1224–1230.

Zulkifli, N., Seok-Kian, A.Y., Seng, L.L., Mustafa, S., Kim, Y.S., Shapawi, R., 2022. Nutritional value of black soldier fly (*Hermetia illucens*) larvae processed by different methods. PLoS One 17, 0263924.