



# Upcycling former food products in livestock diets: a one health approach to prevent resource-depleting farming systems

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## ABSTRACT

The growing demand for animal-source foods (ASFs) intensified competition between the food and feed sectors, straining limited natural resources. Integrating One Health principles -acknowledging the interconnectedness of human, animal, and environmental health -can enhance sustainability in ASF production. This study evaluates the potential of former food products (FFPs), safe but non-marketable foodstuffs, to replace up to 30 % of conventional pig feed. Using data centered around 2018 for EU27 and US industrial pig systems, results show 11–42 % savings in land and water use, equivalent to 5.3Mha of land and 27.6 km<sup>3</sup> of water annually. Reducing feed imports increases local resource availability and decreases reliance on virtual resources. An in vivo trial confirmed that FFP-based diets maintain pig growth performance, metabolism, and welfare. These findings underscore the environmental benefits of FFPs and their potential to align ASF production with circular economy and One Health principles, mitigating global sustainability challenges.

## 1. Introduction

The global food economy is changing, especially under the pressure of the growing population and rising incomes, which are increasingly driven by the change in diets and patterns of food consumption towards animal products (Ankeny, 2021; FAO, 2018b; Henchion et al., 2017; Komarek et al., 2021; Milford et al., 2019; Miller et al., 2022; Whitnall and Pitts, 2019). Global meat consumption increased by 58 % over 20 years until 2018 (FAOSTAT, 2018). While this trend reflects rising living standards, it also presents substantial environmental and health challenges, particularly concerning resource use and waste management (Beal et al., 2023).

The increasing consumption of animal-source foods (ASFs) has a number of different detrimental environmental impacts (FAO, 2018a). As they are the largest user of agricultural land and a significant consumer of freshwater globally (FAO, 2013; FAO and Steinfeld, 2006; Karlsson and Röös, 2019), livestock have a heavy impact on natural resources (FAO, 2018a). Pastures and croplands used to feed livestock are constantly expanding, and thus are major drivers of land-use change and deforestation (FAO, 2013, 2018b; FAO and Steinfeld, 2006; Karlsson and Röös, 2019). While concentrate feeds such as grains improve

livestock productivity (Schader et al., 2015), they are resource-intensive and compete with crops for human consumption, thus exacerbating these issues (Gerbens-Leenes et al., 2013; A. Y. Hoekstra, 2012; van Zanten et al., 2016). Sustainable strategies that balance human, animal, and environmental health are needed to reduce the number of resource-depleting farming systems (Govoni et al., 2023).

One promising approach aligns with the One Health (Adisasmito et al., 2022) and the One Nutrition (Pinotti et al., 2025) frameworks, which recognize the interconnectedness of these domains. Circular practices, such as using lower-impact feed as ex-foods or food leftovers to replace food-competing feeds in livestock rations, seem promising while perfectly matching the circular economy criteria (Georganas et al., 2020; Govoni et al., 2023; Kummur et al., 2012; Luciano et al., 2020; Pinotti et al., 2021; Saleemdeen et al., 2017; Shurson, 2020). As omnivorous animals are widely consumed globally and fed food-competing feed-rich diets, pigs are ideally the most suitable species to convert food losses into high-quality animal protein.

These food losses differ from those associated with food waste and the related swill feeding. Swill feeding, which means feeding cooked food waste to livestock, has not been used by industrialized livestock systems for many years (zu Ermgassen et al., 2016). In the three largest

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pigmeat-producing areas of the world, which account for over 70 % of global production (FAOSTAT, 2018; zu Ermgassen et al., 2016), swill feeding is strictly forbidden (i.e. EU27) or restricted (i.e. China and the US) (APHIS - USDA, 2009; Harvard University and University of Arkansas, 2016; MARA, 2018; zu Ermgassen et al., 2016). Overall, it has been estimated that in 2018 in these three areas, pig farming alone required approximately 64 Mha of agricultural land and 333 km<sup>3</sup> of water to produce feed crops, most of which are human-edible (Govoni et al., 2022).

Ex-food, which is incorrectly referred to as food waste and technically termed by the EU law as former food products (FFPs) (Pinotti et al., 2023), thus offers an interesting option. By definition, FFPs are *food-stuffs, other than catering reflux, which were manufactured for human consumption in full compliance with the EU food law but which are no longer intended for human consumption for practical or logistical reasons or due to problems of manufacturing or packaging defects or other defects and which do not present any health risks when used as feed* (Pinotti et al., 2021). FFPs, which are allowed as animal feed by EU law, include manufacturing food waste but not swill feed (Commission Regulation (EU), 2017). The European Former Foodstuff Processors Association (EFFPA) reports that 5 Mt of FFPs annually are currently recycled as animal feed, however much more are available to be legally recycled under existing legislation (EFFPA, 2019). In the US, food leftovers such as bakery meal are commonly used for animal feeding and are exempt from the half-hour boiling federal protocol (Luciano, Espinosa, et al., 2022). >500,000 tons of this meal are produced annually in the US (Liu et al., 2018). In China, on the other hand, despite the ban on swill feeding due to the spread of African Swine Fever disease, properly heat-treated food waste is allowed as animal feed. Only some information on the legislation, availability, and current use of similar ex-foods is available.

To date, studies on the chemical and nutritional composition and the possible risks associated with using ex-foods as animal feed are becoming fairly widespread (Luciano, Espinosa, et al., 2022; Pinotti et al., 2021; Sandström et al., 2022; Wang et al., 2015). Some studies have used FFPs from bakery and confectionery food industries as feed ingredients for pigs. Animal growth performance has been monitored together with the potential metabolic impact of FFPs throughout the animal's productive life (Luciano et al., 2021; Mazzoleni et al., 2023). The authors found no difference regarding welfare and well-being traits between FFP-fed animals and control groups, thereby showing that FFPs could be used without detrimentally affecting animal health. zu Ermgassen et al. (2016) examined the environmental benefits if swill feeding was reallocated by EU law as animal feed. The results showed that the land requirement of EU pork production would potentially shrink by 21.5 %. Other authors proposed low-opportunity-cost biomass (LCB) (co-products, plant-sourced food waste, and slaughter by-products) as animal feed (van Selm et al., 2022; Van Zanten et al., 2018). The use of LCB can reduce GHG emissions and involve less cropland use. In a previous paper (Govoni et al., 2023) we evaluated the land and water savings of replacing energy-rich feed crops with potentially available agricultural by-products. Potentially, 12 % of land and green water and 14 % of blue water could be preserved with an 11 % replacement. However, co- and by-products are already available in animal diets, while swill and food waste are far from being readmitted by EU law. However, research is still scarce on the actual potential savings of natural resources through the use of ex-foods in compliance with the law.

The aim of this study was therefore to quantify the potential savings of natural resources (i.e., land and water) achievable from using ex-food in pig diets. The EU27 countries and the US were selected for analysis. Due to the gaps in legislation and current use of ex-foods, China was excluded from the study. The analysis focuses on data centered around 2018 to ensure consistency with the baseline scenario. Specifically, we

referred to the results obtained by Govoni et al. (2022) on the natural resources required to produce pig feed in 2018 in EU27 and the US with traditional pig diets, assessing the potential savings achievable through the introduction of ex-foods into the same diets. A partial substitution of selected energy feed ingredients, of up to 30 %, was thus simulated as already tested in recent studies (Luciano et al., 2021; Luciano, Espinosa, et al., 2022; Mazzoleni et al., 2023). Feed ingredients were converted to raw materials (e.g. crops) and trade matrices were used to trace the origin of such products and, accordingly, site-specific data on soil, climate, and crop calendar data were collected. Then, information on the country- and production system-specific pig diets, and crop- and country-specific yield data were combined with a spatially distributed and physically based agro-hydrological model (Chiarelli et al., 2020) to estimate the potential savings of natural resources. The aim was also to investigate the effects of a reduction in pig feed demand on the international feed trade dynamics and the associated virtual trade in natural resources. Lastly, the potential metabolic impact of the inclusion of FFPs in post-weaning piglet diets was evaluated and discussed to support environmental data.

## 2. Method and materials

### 2.1. Traditional diets and ex-food replacement

Traditional pigs' diets were based on the composition proposed by the Global Livestock Environmental Assessment Model (GLEAM) developed by the FAO (FAO, 2022). The feed ratios were adjusted according to the country feed use reported in the FAO national Food Balance Sheets (FBS) (FAOSTAT, 2018), as corrected by Govoni et al. (2022). These diets are country-specific and production system-specific. In the present study, fattening to finishing diets were considered.

It is well known that a balanced diet is essential for feed efficiency and adequate weight gain. An insufficient quantity or a low-quality source of protein results in poor growth, insufficient feed use, increased carcass fatness, and reduced reproductive performance. The diets meet the appropriate nutrient requirements for growing pigs, and thus also ensuring good quality of the derived animal products (i.e., pork meat). All the new diets were thus simulated, adapted, and comparable to the traditional (control, CTR) diets, while suitable for weaning and growing pigs.

For the EU27 scenario, FFPs are considered the main substitute for energy sources (e.g. cereals) (EFFPA, 2019). FFPs can include pasta, bread, biscuits, breakfast cereals, chocolate bars, savory snacks, and sweets. In the US scenario, bakery meals are used as a cereal substitute. Bakery meal is mostly bread removed from the food market as it becomes unsellable after only 24 h, however, it can also consist of other ingredients such as dough, flour, sugar, and other edible ingredients, such as icing, burnt or broken products (Crawshaw, 2003; Y. Liu et al., 2018; Luciano, Espinosa, et al., 2022; Ottoboni et al., 2019). Specifically, in three studies (Luciano et al., 2021; Luciano, Espinosa, et al., 2022; Mazzoleni et al., 2023) 30 % of conventional energy ingredients were replaced with ex-foods, thus systematically replacing the main sources of carbohydrates and energy. The inclusion of wheat, barley, and maize was reduced by 23 % and 60 % respectively (Pinotti et al., 2023). To simulate the new diets a feed formulation software, namely Plurimix® (Fabermatica, Cremona, Italy), was used. The Plurimix system is one of the most common and well-known reference business software used for livestock. Based on the express needs of customers in the animal feed industry, it was developed with the contribution of many leading companies in the sector. Plurimix ensures complete and optimal rationalization of production phases and creates complete diets either by mixing ingredients or by providing their chemical composition and using specific and generic equations to calculate energy, amino acid,

and phosphorus values. Based on diet composition, the digestible and metabolizable energy values for pigs were estimated using the following equations:

$$DE \left( \frac{MJ}{kg DM} \right) = 4168 - (91 \times \% \text{ ash}) + (19 \times \% \text{ CP}) + (39 \times \% \text{ EE}) - (36 \times \% \text{ NDF})$$

$$ME \left( \frac{MJ}{kg DM} \right) = DE - (6.8 \times \% \text{ CP})$$

where: DE - digestible energy; CP - crude protein; EE - ether extract; NDF - neutral detergent fiber; ME - metabolizable energy; DM – dry matter. The DE and ME equations were proposed by NRC (NRC, 2012). Energy and chemical constituents are expressed on a DM basis in all equations.

In the analysis, pig production is differentiated into backyard, intermediate, and industrial systems as suggested by Gilbert et al. (2015). However, for the sake of homogeneity, ex-foods were only introduced in industrial production systems, and not in intermediate systems since they are too variable. Backyard systems were also not considered since they are mainly subsistence-driven and there is no direct connection between the feed supply and the food industry.

Furthermore, ex-food substitutions are not applied to all the EU27 countries, but only to Austria, Belgium, Denmark, France, Germany, Hungary, Italy, the Netherlands, Poland, Portugal, Romania, and Spain, which together account for 93 % of the EU27 pigmeat production.

The ingredients included in the selected diets are fed to the animals mainly in the form of processed products, and more rarely as a whole crop. Therefore, these products were converted into the corresponding quantities of raw materials, using the DM content and conversion factors (FAO, 1996). In addition, when different co- and by-products are obtained from the same crop (e.g. straw, oilseed cakes, molasses), an allocation method adapted from Gerber et al. (2013) and the GLEAM model was used to designate the different shares of resources to each feed crop item. This method takes into account the feed use fraction, economic value, mass fraction, and the value ratio of the different co-products (Govoni et al., 2024). Non-vegetable ingredients (fishmeal) and dietary supplements (synthetic and complements) were excluded as well as swill feeding when allowed (backyard systems) as they do not directly contribute to the consumption of water and agricultural land associated with the feed sector. Regarding ex-foods, we assumed that the land and water resources used in their original production are not allocated to the feed sector, as these products were initially intended for the human food supply chain and only later reclassified as former foodstuffs or bakery meal. This approach follows the *zero-allocation* principle, as recommended by the Global Feed LCA Institute (GFLI) (Blonk et al., 2018), based on the FAO/LEAP guidelines (FAO, 2016). According to these guidelines, zero allocation can be applied when the co-product has low economic value, is not intentionally produced, and does not require modifications in the upstream process. FFPs such as dry bakery products, biscuits, and other manufacturing leftovers fall into this category. Similarly, LCA standards such as ISO 14,044 (ISO, 2006) and the Ecoinvent allocation rules (ecoinvent, 2024) support this methodology for unplanned co-products. While we acknowledge that FFPs do have an environmental footprint associated with their original production, our system boundaries focus specifically on the livestock sector. Consequently, they contribute to the pressure on natural resources due to humans and not the animal food sector.

The new total demand for pig feed in 2018 was therefore recalculated based on the number of animals slaughtered in each production system, the conversion of ingredients into raw materials, and the life cycle of the animals involved. The latter was taken from a previous work (Govoni et al., 2022), and adapted from GLEAM (FAO, 2022). Unlike the other European countries, the rearing of heavy pigs in Italy prevails over lean, which means the animals reach 160–170 kg instead of 100–120 kg before being slaughtered, thus leading to a longer life cycle (Bava et al.,

2017; ERSFAF, 2019).

Countries' domestic production of feed materials is usually not sufficient to meet the total local demand for pig feed. The international trade in animal feed is steadily increasing, alongside the production of ASFs. This has led to a split in the pig feed demand into domestic and imported feed. Our calculation followed the approach of Govoni et al. (2021, 2022, 2023), including all partner countries involved in the trade of raw materials reported in the FAO Detailed Trade Matrix (DTM) (FAOSTAT, 2018), and skimming the latter from all re-import and re-export data (Kastner et al., 2011).

## 2.2. Land use and savings

Feed production requires fertile land to be cultivated to obtain raw materials. The local land consumed is obtained from the proportion of pig feed produced domestically, while the remaining share includes land virtually imported from partner countries. The conversion from feed to agricultural land needed is carried out through the use of crop-specific and country-specific agricultural yields. Land use linked to the consumption of a specific crop (whether fed as a whole or as a by-product) was split into two components: land consumed domestically (local yield) (LL) and land virtually transferred from other countries through feed trade (yield of the exporter country) (VL).

$$LL_{c,i} [ha] = \frac{dom_{c,i}}{yield_{c,i}}$$

$$VL_{c,i} [ha] = \sum_c \frac{imp_{c,i}}{yield_{c,i}}$$

where *yield* data are from FAOSTAT (FAOSTAT, 2018) of the crop *i*, in country *c*. *Dom* (domestic) and *imp* (import) shares of feed crop demand were split according to the FAO national FBS (FAOSTAT, 2018; Govoni et al., 2022).

The potential land savings are equal to the difference between the total demand for land with the traditional diets from Govoni et al. (2022) and that after replacement. Land savings may also be distributed differently between domestic and virtual land consumption, thus changing the current scenario of international feed trade.

## 2.3. Water use and water saving

The production of raw materials used as feed requires not only fertile land but also water to grow plants. These volumes are calculated using the agro-hydrological model WATNEEDS (Chiarelli et al., 2020, Galli et al., 2025), which is crop-specific, spatially distributed, and physically based. This model subdivides crop water use into two components. Green water (GW) represents the water volume supplied directly by precipitation and then absorbed as soil moisture by roots, while blue water (BW) is the volume provided by irrigation (Hoekstra, 2003). This model can be used to estimate the actual evapotranspiration (ET), calculate the crop water requirements (CWR), and the irrigation requirements (BW) based on soil and crop-specific data, and climate inputs as an average for the period 2013–18. The model assesses the vertical component of the soil water balance with a resolution of 5 arc-min (approximately 10 km), after taking as input the global maps of crop-specific irrigated and rainfed areas from the MIRCA2000 dataset (Portmann et al., 2010). The monthly outputs of crop GW and BW requirement obtained with climate and soil gridded data (Batjes, 2006; Chen et al., 2008; Climate Hazards Group, 2015; Funk et al., 2015; Harris et al., 2014) were averaged to obtain mean countries' values, then multiplied by the amount of land cultivated with that specific crop, in that specific country. As for the land use, both GW and BW use components were split into local water (LGW, LBW) and virtual water trade (VGW, VBW).

$$LGW_{c,i} [km^3] = \left( GW_{c,i} \times 10 \times LL_{c,i} \times Rainf_{c,i} + GW_{c,i} \times 10 \times LL_{c,i} \times Irrig_{c,i} \right) \times 10^{-9}$$

$$LBW_{c,i} [km^3] = \left( GW_{c,i} \times 10 \times LL_{c,i} \times Irrig_{c,i} \right) \times 10^{-9}$$

$$VGW_{c,i} [km^3] = \sum_c \left( GW_{c,i} \times 10 \times LL_{c,i} \times Rainf_{c,i} + GW_{c,i} \times 10 \times LL_{c,i} \times Irrig_{c,i} \right) \times 10^{-9}$$

$$VBW_{c,i} [km^3] = \sum_c \left( GW_{c,i} \times 10 \times LL_{c,i} \times Irrig_{c,i} \right) \times 10^{-9}$$

where  $GW$  and  $BW$  represent the water [mm] needed to grow the crop  $i$ , in country  $c$ , as output of the model, while  $Rainf$  and  $Irrig$  are the percentages of each crop that is cultivated as rainfed or irrigated in each region (Portmann et al., 2010).

Since it has been estimated that 98 % of the water consumed for animal products comes from the feed they eat (Mekonnen and Hoekstra, 2012), drinking, service, and feed-mixing water are disregarded.

As for land savings, water volumes (both  $BW$  and  $GW$ ) that can be saved are calculated as the difference in demand compared to the traditional scenario (Govoni et al., 2022), evaluating the change in the current virtual water trade associated with pig feed.

#### 2.4. In vivo trial and sample analyses

Following the environmental evaluation, we applied FFPs as feed ingredients to determine their impact on the welfare of farm animals in terms of growth performance and feeding behavior as well as their well-being with regard to metabolic and physiological states. An in vivo feeding trial was thus designed and performed at the Animal Research facility of the University of Milan located in Lodi (Italy). The trial was authorized by the Italian Ministry of Health in agreement with the Italian Regulation regarding ethical issues (405/2019-PR). The trial involved 36 post-weaning female piglets (Large White  $\times$  Landrace breed, 28-d old) with an initial body weight of 6.5 ( $\pm$  1.1) kg. The piglets were divided into three experimental groups, each receiving a different diet for a total experimental period of 6 weeks: i) CTR, control group fed conventional cereals; ii) FFP-B, experimental group fed control diet with 30 % cereals replaced with a blend of bakery-derived FFPs; iii) FFP-C, experimental group fed control diet with 30 % cereals replaced by a blend of confectionery-derived FFPs. The inclusion of FFPs in experimental diets was balanced to obtain an isoenergetic and isonitrogenous diet with a similar content of sodium chloride. The growth performance of the animals (body weight, average daily gain, feed intake, average daily feed intake) was monitored throughout the experimental period and the results are detailed in Luciano et al. (2021). At the beginning, half, and end of the experimental period (day 1, 21, and 42, respectively), blood samples were collected from all animals involved in the trial to isolate plasma and measure the concentrations of several metabolites involved in health maintenance and physiological homeostasis. The overall mean values of the metabolites are reported in Luciano et al. (2021) without specifying the plasma concentration of the metabolites in the three time points. The data collected during the trial were analyzed with the software IBM SPSS (version 27). Data was checked for normality and then analyzed via analysis of variance (ANOVA) considering the correlation of treatment and time factors, with a  $P < 0.05$  as an indication of significant difference. The same plasma samples were also used to perform an untargeted metabolomics-based analysis to obtain a broader overview of the metabolic state of the animals. The results of the metabolomics investigation are reported in detail in Manoni et al. (2024). Briefly, an ultra-high-performance liquid chromatography coupled with double mass spectrometry with electrospray ionization

(UHPLC/ESI-MS-MS) was applied. The CORTECS UPLC T3 column (Waters) was used for the ultra-high-performance liquid chromatography (UHPLC) separation step, while the ExionLC AD system (SCIEX) coupled with a TripleTOF 6600 system (SCIEX) equipped with Turbo V™ ion source (SCIEX) were used for the electrospray ionization double mass spectrometry (ESI-MS-MS) analysis of the plasma samples. A Principal Component Analysis (PCA) was performed to determine the overall difference in the plasma metabolome of the three experimental groups throughout the feeding period. The software MS-DIAL (version 4.24) was used for the analysis of spectrometric data and the software MetaboAnalyst (version 5.0) was used for data interpretation.

### 3. Results

The global pig stock in 2018 consisted of over 970 million animals, with nearly 1.5 billion pigs slaughtered (FAOSTAT, 2018). The distribution of these animals was far from homogeneous: almost half of the pigs were reared in China, followed by the EU27 (17 %) and the US (8 %). The EU27 countries and the US accounted for a pig feed demand of 105.5 Mt in 2018 (Govoni et al., 2022). A diet including 30 % ex-foods, confined to industrially-reared pigs, could save up to 30.5 Mt. A 29 % saving in feed demand is linked to the widespread diffusion of industrial farming systems (>90 %) in the US and the EU27 countries, which is not yet the case in China and many other countries. The distribution of feed savings is strongly dependent on the industrial pig systems, where the replacement is implemented. The feed crops saved could lead to the annual recovery of an agricultural area not much larger than the size of Costa Rica, i.e. 5.3 Mha (22 % saving). In addition, 27.6 km<sup>3</sup> of water resources could be saved. Specifically, 1.3 km<sup>3</sup> of saved freshwater or irrigation water (BW) could annually ensure the human right to safe drinking water and sanitation (100 L/capita/day according to the World Health Organization) for >35 million people. This would also clearly lead to reduced food waste for an equal amount of ex-foods that would no longer need to be disposed of, by reintroducing them into the food chain. The composition of FFPs and bakery meals suggests that cereals would be saved the most in EU27 and the US. Although ex-foods are mainly made up of cereal products, many are also rich in fat because of the vegetable oils and/or fats of different origins (e.g., butter). The soybean ratio fed to pigs as whole oil-rich seed was thus replaced with dehydrated soybean meal in the revised diets. This replacement could lead to high savings of some ingredients accompanied by a slight increase in other products but usually involving domestic crops, thus helping with the decrease in import dependency and virtual resource trade. The underlying rationale is to maintain adequate nutritional intake and balanced diets. In fact, feed savings reflect a drop in crops imported by individual countries, especially in the EU27. This is less

**Table 1**

Use of land, GW, and BW for pig feed production, comparing traditional and replacement scenarios.

		Domestic resources		Imported (virtual) resources		Total resources	
		CTR Diet*	FFP Diet	CTR Diet*	FFP Diet	CTR Diet*	FFP Diet
<b>LAND</b>	<b>US</b>	6.7	5.6	0.2	0.2	6.9	5.8
	<b>EU27</b>	6.5	4.6	11.2	8.9	17.7	13.5
<b>GREEN WATER (km<sup>3</sup>)</b>	<b>US</b>	37.7	31.7	0.8	0.8	38.5	32.5
	<b>EU27</b>	31.8	22.6	55.9	44.8	87.7	67.4
<b>BLUE WATER (km<sup>3</sup>)</b>	<b>US</b>	1.8	1.4	0.0	0.0	1.9	1.4
	<b>EU27</b>	1.5	0.9	1.5	1.2	3.0	2.1

\* CTR Diet refers to results from Govoni et al. 2022 (Govoni et al., 2022). CTR – Control diet; FFP – Former food diet.

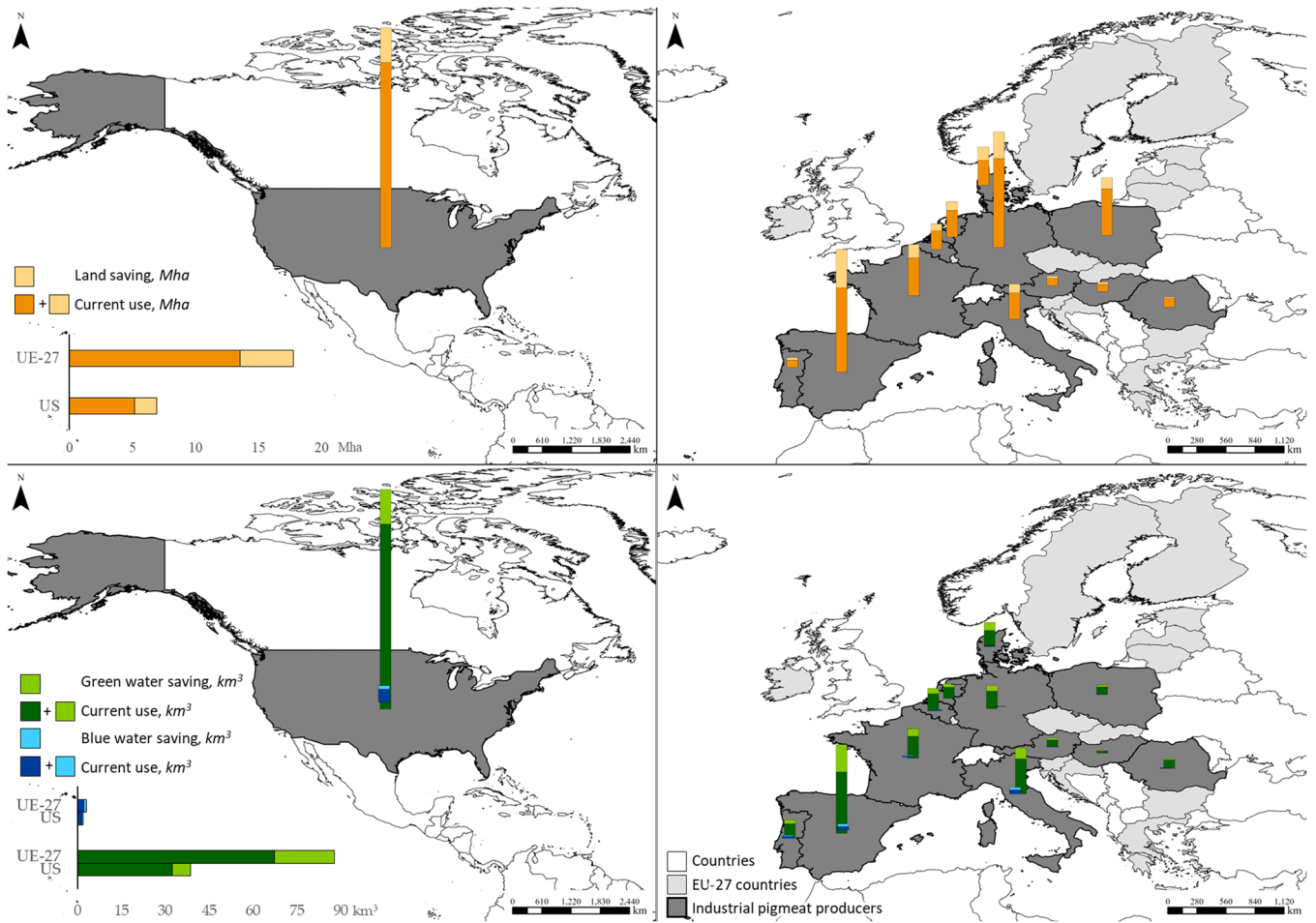


Fig. 1. Land, GW, and BW use associated with pig feed production and the potential savings using ex-foods in the US and EU27.

evident in the US where savings concentrate on domestic cereal crops. Starting with land savings, 4.2 Mha and 1.1 Mha of agricultural land could be freed up in the EU27 and the US, respectively (Table 1, Fig. 1). While cereals would experience the greatest fall in volume, replacing soybeans saves more agricultural land per unit of product replaced. This is due to the general low agricultural yield (2–4 tons/ha) of soybeans compared to cereals (6–12 tons/ha) (FAOSTAT, 2018). Virtual land savings are more consistent than domestic ones in the EU27, while in the US, import flows meet <1 % of the demand, even without replacements. Virtual land savings could change the current international feed trade dynamics (Govoni et al., 2022). The virtual land flows would remain above 400,000 ha only for those flows directed to Spain (from Brazil, Argentina, and the US) and Brazil to Germany. All the other flows in the

traditional scenario (Govoni et al., 2022) would fall below this threshold (Fig. 2). Our findings highlight that important water savings can be made in the EU27 and the US. Savings can be split into BW (1.3 km<sup>3</sup>) and GW (26.3 km<sup>3</sup>) volumes. The EU27 would save the highest amounts of water (20.3 km<sup>3</sup> and 0.9 km<sup>3</sup> of GW and BW, respectively). The US would save 6 km<sup>3</sup> of GW and 0.4 km<sup>3</sup> of BW (Table 1, Fig. 1). In the EU27, the potential decrease in domestic feed demand can turn into both GW and BW savings within the continent. On the other hand, a lower demand, especially for soybeans, would result in high savings of virtual GW due to imports from South America, where this crop is rainfed. After the replacement, virtual GW flows still exceeding 2.5 km<sup>3</sup> would result from Brazil to Spain and Germany, while those from Argentina and the US

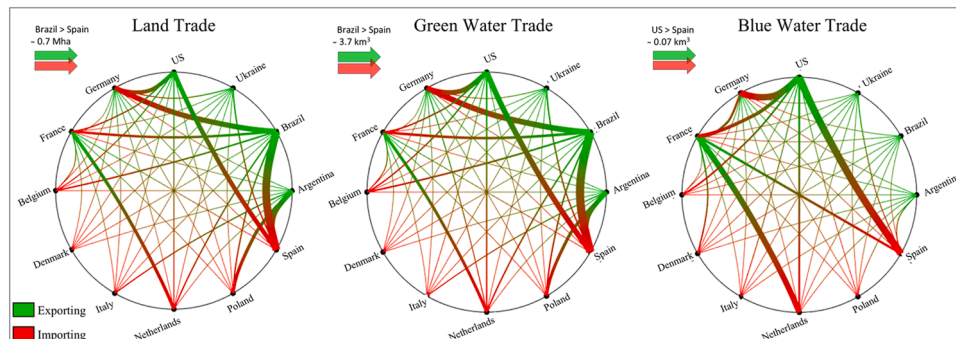
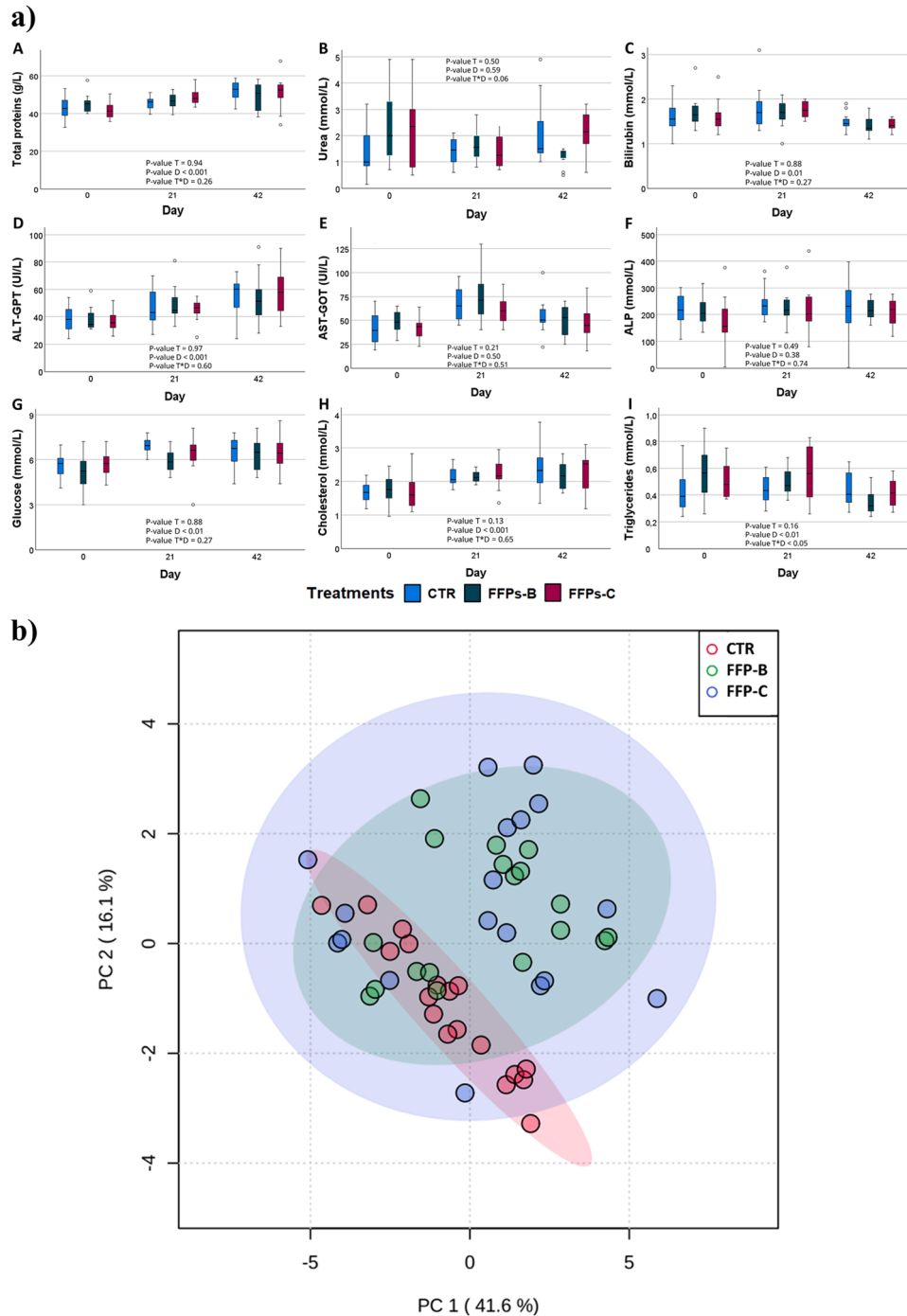


Fig. 2. Virtual land, GW, and BW trade associated with pig feed demand that could be saved in the US and EU27.

would decrease. On the other hand, virtual BW flows over 0.05 km<sup>3</sup> would result from the US to Spain and Germany (Fig. 2). EU27 imports stand out as being heavily dependent not only on overseas countries with rainfed plantations (Brazil and Argentina) but also on the US and other European countries where irrigation is more frequent such as France. Fig. 2 shows that Argentina, Brazil, Ukraine, and the US are net exporters of natural resources, France and Germany are both importers and exporters, while the other European countries are net importers. While on average in the EU27 feed crops do not need to increase to balance diets, in the US there might be a slight increase in sorghum,

which, however, is produced locally and only irrigated by 10 %. This increase is not particularly relevant to BW use and trade in resources.

The results of the in vivo trial revealed no significant alteration in growth performance and feeding behavior was observed between CTR- and FFP-fed piglets from both experimental groups (salty and sweet FFP diets) as detailed by Luciano et al. (2021). Plasma metabolite concentrations did not significantly differ among the diets in terms of treatment factors or correlations between treatment and time factors, except for the triglyceride level, which significantly varied ( $P < 0.05$ ) across treatment and time factors. However, all the parameters were significant for the time



**Fig. 3.** a) Boxplots of the plasma metabolite concentrations investigated in the three experimental groups and the three time points (days 1, 21, and 42). Abbreviations: ALT-GPT = alanine aminotransferase- glutamic pyruvic transaminase; AST-GOT = aspartate aminotransferase-glutamate-oxaloacetate; ALP = alkaline phosphatase. CTR = Control diet; FFPs-B = Salty former food diet; FFPs-C=Sweet former food diet. b) PCA score plots of the three experimental groups CTR, FFP-B and FFP-C without considering the time factor.

factor except for urea, aspartate aminotransferase-glutamate-oxaloacetate transaminase (AST-GOT) and alkaline phosphatase (ALP) (Fig. 3).

Following the metabolic investigation of specific targets for animal health, liver function and overall homeostasis, the results of the untargeted metabolomics are reported below. Principal component analysis (PCA) showed that the CTR groups differed, whereas no differences were detected between the two FFP groups (Fig. 3).

#### 4. Discussion

To meet the rising demand for ASFs, the livestock sector has intensified its resource use, which has therefore increased competition with other users and environmental services (Di Paola et al., 2017; FAO, 2018b). Overall, the sustainable animal nutrition strategy investigated here illustrates that opportunities exist to reduce natural resource consumption and feed-food competition in the livestock sector. This strategy, when implemented in the industrial pig production systems of the US and the EU27, could lead to saving 5.3 Mha of agricultural land and 27.6 km<sup>3</sup> of water (Table 1). It should be noted that based on current production estimates, up to 25 % of the FFP demand in the EU (5 out of 19.8 Mt) and 5 % of the bakery meal demand in the US (0.5 out of 10.6 Mt) could potentially be met with currently available former foods. These values provide a rough approximation of a plausible implementation scenario under present conditions. Nevertheless, the practical implementation of such circular strategies must also consider the spatial disconnect between feed co-product availability and livestock production sites, which remains a recognized barrier to nutrient recycling. Recent studies have proposed strategies such as spatially explicit planning (Akram et al., 2019), the manureshed approach (Spiegel et al., 2020), and regional logistics coordination to overcome these limitations. In the European context, policy tools like the Integrated Nutrient Management Action Plan (INMAP) aim to support cross-sectoral integration and encourage nutrient recirculation across regions. While challenges remain, targeted planning and policy support can significantly enhance the feasibility of circular feed systems.

Sustainable animal nutrition is on the rise, also thanks to the increasing knowledge of the properties of the practice. In addition, the COVID-19 pandemic highlighted how environmental health is tightly connected to both animal and human health and the need for the concept of sustainability to be redefined (Hakovirta and Denuwara, 2020; Rulli et al., 2021, Rulli et al., 2017; Rulli et al., 2025). Interruptions in food supply chains and shifts in food distribution patterns and flows have exacerbated food safety and food security issues and have increased food waste (ReFED, 2020). Researchers have recommended adopting a more holistic approach to the food industry, interconnected with the economy, environment, society, and human health. The aim is to improve the efficiency of the food supply chain and reduce inefficiencies in the use of natural resources (Shurson, 2020). Ex-food can be used as a high-quality animal feed that requires no additional land and water for production, and which leads to resource savings while reducing food waste. These advantages are achievable without any detrimental effect on animal health welfare (Dou et al., 2018; Georganas et al., 2020; Luciano et al., 2021; Luciano, Espinosa, et al., 2022; Mazzoleni et al., 2023; Pinotti et al., 2021) and product quality (Tretola et al., 2024).

##### 4.1. Animal welfare and well-being

The main concerns regarding the use of ex-foods are the welfare and well-being of the animals. Recent studies have demonstrated that FFPs can be included in the diets of post-weaning piglets and growing and finishing pigs at an inclusion level of up to 30 % without causing any significant harmful effects (Luciano et al., 2021; Mazzoleni et al., 2023). At this inclusion level, post-weaning piglets and pigs are able to grow as animals not fed diets containing ex-foods (Luciano et al., 2021; Luciano, Espinosa, et al., 2022; Mazzoleni et al., 2023). Similar findings were also

reported in Hartinger et al. (2024) for which the 30 % inclusion of FFP in the diet of fattening pigs was found to be beneficial for the fecal microbiome, increasing feed efficiency without impairing animal performance. The 30 % inclusion rate was considered suitable to be tested because lower inclusion rates were considered unsuitable to generate significant benefits in terms of water and land savings, although no clear minimum thresholds are available in literature. Instead, higher inclusion rates (>30 % until complete substitution of cereals) were shown to compromise the growth performance of pigs fed FFP (Luciano, Tretola, et al., 2022). The targeted investigation of plasma metabolites in FFP-fed post-weaning piglets in this study showed no significant changes compared to the control group. This is important since the plasma metabolites investigated are involved in multiple physiological aspects, such as liver functionality (ALT-GPT, AST-GOT, ALP, bilirubin), lipid regulation (cholesterol, triglycerides), protein metabolism (total proteins, urea) and glycemia (glucose). However, the sole determination of the growth performance and plasma metabolites might not be exhaustive in terms of the animals' health status because some undesired physiological effects might be missed. Specifically, FFPs derive from the industrial production of processed and ultra-processed foods, which contain potentially hazardous molecules for animal health such as cocoa-derived caffeine and theobromine (Manoni, Altomare, et al., 2024). The consumption of these molecules by humans is related to the onset of inflammatory conditions and subsequent gut disorders. As reported here, the metabolomics investigation showed that by widening the field of observation to the entire plasma metabolome through untargeted analyses, differences were found between the control group and the FFP groups, which probably would not be detected by examining only a subset of plasma metabolites. As detailed in Manoni et al. (2024), despite the differences indicated by the PCA, the only two metabolites that showed significant differences in the treatment factor were caffeine and theobromine, which were originally contained in the foods used to formulate FFPs. Data on the potential effects of these metabolites on animal behavior is currently under investigation. To further validate the results, other studies have also investigated the potential undesired effects of FFPs on the physiology and metabolism of growing to finishing pigs fed with FFPs (Manoni et al., 2024; Tretola et al., 2024) and on meat quality (Tretola et al., 2024). In Manoni et al. (2024), the authors performed a proteomic and peptidomic investigation of liver and plasma samples, respectively. No significant changes to important liver proteins and plasma peptides were found with 30 % FFPs in pig diets. Tretola et al. (2024) reported that the inclusion of 30 % FFPs did not affect fecal microbiota abundance or biodiversity, production of volatile fatty acids, or intestinal epithelial integrity in pigs. They also reported that feeding pigs with 30 % FFPs did not influence meat quality traits (e.g. pH, temperature, thawing and cooking loss, drip loss, and shear force), but slightly altered the lipid profile and meat sensory traits of pork meat without harmful consequences (Tretola et al., 2024). Considering all the results, and the minor alterations, in most cases the inclusion of 30 % FFPs did not negatively affect the physiological and metabolic status of the animals involved.

##### 4.2. Alternatives to ex-food replacement and environmental comparisons

FFPs or bakery meals constitute only one example. We compared our results with those obtained in our previous work (Govoni et al., 2023) where we substituted energy-rich feeds with agricultural by-products, considering southern and western Europe. The replacement was applied not just to pigs, but also to cattle (producing meat and dairy) and chickens (producing meat and eggs). Table 2 reports the average feed replacement rate, depending on the regional stocks for the different animal species. The environmental benefits of conventional feed replacement were found to vary across regions, depending on the agricultural by-products and FFP availability, the feed crops that could be replaced, their origin, the agricultural yields, and the diffusion of irrigation systems (higher in southern Europe). In both instances, cereals

**Table 2**

Comparison between results of Govoni et al. (2023) and those obtained in this study on conventional feed replacement and potential environmental savings (land, green water, and blue water).

		Agricultural by-products From Govoni et al. (2023)	Former food products* From this study	Swill feeding (food waste) From zu Ermgassen et al. (2016)
Livestock species involved		Cattle, pig, chicken	Pig	Pig
<b>Southern Europe</b>	Feed replacement	6.6 % - 8.9 %	30.0 %	20.3 %
	Land saving	5.7 % - 7.6 %	28.4 %	19.6 % – 23.5 %
	GW saving	5.7 % - 7.6 %	27.4 %	
	BW saving	5.8 % - 7.8 %	39.2 %	
<b>Western Europe</b>	Feed replacement	11.7 % - 15.0 %	30.0 %	20.3 %
	Land saving	10.2 % - 13.0 %	24.7 %	19.6 % – 23.5 %
	GW saving	10.2 % - 13.0 %	23.9 %	
	BW saving	10.3 % - 13.4 %	29.1 %	

Southern Europe: Albania, Croatia, Cyprus, Greece, Italy, Malta, Montenegro, Portugal, Serbia, Slovenia, Spain.

\* Missing values from non-EU27 countries (Albania, Montenegro, and Serbia).

Western Europe: Austria, Belgium, France, Germany, Luxembourg, Netherlands, Switzerland. \*Missing values from non-EU27 countries (Switzerland).

were the most commonly substituted ingredient, with the highest share in animal diets and the highest yields achieved (lower land and GW savings), and among the most irrigated crops (higher BW savings). Similar results were also obtained by zu Ermgassen et al. (2016) with swill feeding, despite the latter being currently forbidden by EU law (Table 2).

Adopting the principles of the circular economy, other biomasses such as plant by-products (PBPs) from the food processing industries, could be recycled as feedstuff (Salami et al., 2019). For example, PBPs from the processing of vegetables (e.g., fresh-cut leafy salad) were proposed as a potential ruminant feedstuff. Their chemical composition makes them comparable to fresh forage. Although at a very early stage, the potential of this new biomass seems high, and its reuse in animal diets could also save water, (Pinotti et al., 2020; Salami et al., 2019). However, environmental assessments on the replacement of conventional feeds with these products are still lacking.

#### 4.3. Land and water footprints of different livestock diets and systems

The land and water footprints of ASFs vary greatly across countries, animal species, and production systems (Mekonnen and Hoekstra, 2012). The production system is highly important for several reasons, such as growth performance, dressing percentage, diet composition, and feed conversion ratio (FCR). Pig diets, as well as diets of most livestock, tend to include higher rations of concentrated feed moving from backyard to industrial systems (Mekonnen and Hoekstra, 2012; Mottet et al., 2017). This composition includes a reduction in FCR: a lower amount of feed consumed per unit of animal product produced, thus more efficient feed users. However, a higher inclusion of concentrated feeds means more food-competing feeds. As with any resource use, generally, the total water and land footprint of livestock decreases from backyard to industrial systems (Mekonnen and Hoekstra, 2012). That is true for ruminants moving from pasture to intensive systems, but not always for monogastric species. The BW footprint increases from backyard to industrial systems due to the increase in concentrated feed such as grains and oilseeds which are often irrigated (Gerbens-Leenes et al., 2013; Mekonnen and Hoekstra, 2012; Portmann et al., 2010). An increase in industrial pig systems in the inclusion of by-products, crop residues, or other low-water and low-land consumption ingredients such as ex-foods (footprint equal to zero if intended as food and not feed products) may help overcome the disadvantages of the systems without impairing the growth performance, feed efficiency, and productivity of pigs (Sandström et al., 2022). Fig. 4 shows some examples, considering the US and Germany where >99 % of the pigs are reared in industrial systems, and Poland where this value is around 65 % (Gilbert et al., 2015). Industrial systems with traditional diets (Industrial – CTR) are always found to be the most impactful strategy with the higher inclusion of concentrate feeds. This also applies to intermediate systems

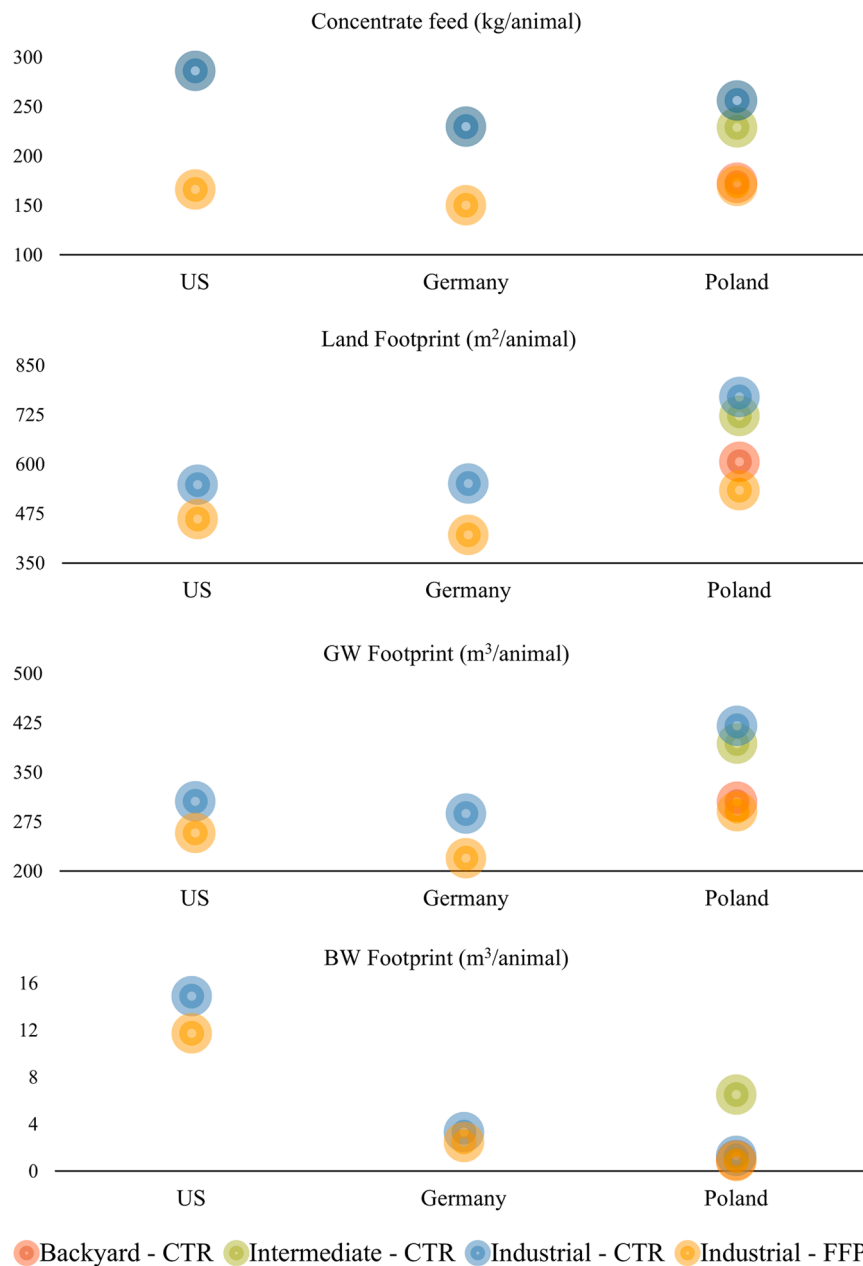
(Intermediate – CTR) in Poland where the use of rice involves higher irrigation requirements (BW footprint). However, the substitution of FFPs or bakery meals in industrial systems (Industrial – FFP) seems an appropriate strategy to partially overcome both the problem of unfavorable FCRs in backyard systems due to the inclusion of by-products and crop residues and the high environmental footprint of concentrate feed in industrial systems.

#### 4.4. Feed trade dynamics and environmental implications

Another important aspect is linked to the feed trade. International trade is now essential to ensure food security in many countries, however, it involves several sustainability issues. Some land- and water-abundant countries are facing challenges linked to the relentless agricultural expansion. This is usually driven not by the need to meet food security and safety standards but by the non-primary needs of other countries. That is the case for Brazil, where to the detriment of the forest, agricultural expansion is boosted by the demand for soybeans in China and several European countries for their livestock sector (Gale et al., 2019; Taherzadeh and Caro, 2019) (Fig. 2). Ex-foods can lead to a decrease in feed flows as well as in virtual trade and pressure on natural resources. Since ex-food as defined in this study does not involve swill feeding, the Chinese pig system could, in principle, benefit from using ex-foods for animal feed. However, the potential inclusion of ex-foods in Chinese pig diets is difficult to estimate for several reasons. Although large-scale intensive pork production systems have been gradually replacing family-based backyard farms since the 1990 s, as of 2017 only about 45 % of pig producers in China raised >500 pigs annually (Zhang et al., 2021), compared to over 90 % in the US and EU27. Furthermore, domestic pigs have been identified as a major source of African Swine Fever transmission, prompting the Ministry of Agriculture and Rural Affairs to issue a ban on swill feeding (J. Liu et al., 2020). Nevertheless, heat-treated former food products are allowed under specific safety conditions, and some local pilot initiatives and research efforts are already exploring the reuse of food industry leftovers in livestock diets. If properly scaled and supported by robust regulatory frameworks, such practices could contribute to reducing land and water resource use in China, reinforcing the trends observed in our analysis for the EU and the US (Bai et al., 2023). The existing barriers therefore represent not only a limitation, but also a key area of opportunity, to be addressed through further research and targeted policy guidance aimed at building safer and more sustainable production systems.

## 5. Conclusion

As the demand for ASFs will increase over the next 50 years, identifying practices that reduce the environmental footprint of the current systems of animal production is crucial. The strategy investigated in this



**Fig. 4.** Land and water (BW and GW) footprint of pig's concentrate feed production in the US, Germany, and Poland, comparing the three different production systems with the traditional (CTR) and substituted (FFP) diets.

study highlights the potential of One Health principles to advance sustainable ASF production systems. We demonstrated that including low-impact products such as ex-foods in animal diets, in compliance with the law, has the potential to reduce land and water use. Our results also reveal that the reduction in demand for livestock feed can have a positive impact both on the domestic use of natural resources and on that displaced by international trade. The application of FFPs as feed ingredients for the diet of post-weaning piglets resulted in no negative alterations in the plasma metabolome, thus confirming the potential of the inclusion of FFPs in pig diets on the environment and on animals. The US and EU27 have shown that significant results can be attained, however similar environmental benefits could be achieved in other parts of the world, where the use of ex-foods is currently uncommon or not properly regulated. Far higher benefits than those shown in this study could be achieved if similar strategies were implemented in China, as the largest pigmeat producer and consumer.

#### Code availability

The algorithm used for the environmental analysis is available in the Methods. The Arcgis Pro and MATLAB codes, as well as Excel files, however, are available from the authors upon reasonable request. Concerning the in vivo trial and the metabolomics investigation, the Excel files, as well as the SPSS, MS-DIAL, and MetaboAnalyst codes are available from the authors upon reasonable request.

#### CRediT authorship contribution statement

**Camilla Govoni:** Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization. **Matteo Ottoboni:** Writing – original draft, Methodology, Formal analysis. **Michele Manoni:** Writing – original draft, Visualization, Methodology, Formal analysis. **Luciano Pinotti:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization. **Maria Cristina Rulli:** Writing –

review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Data availability

All data inputs for the environmental analysis in this study were retrieved from publicly available sources that are cited in the manuscript (e.g., FAOSTAT, GLEAM, Chiarelli et al. 2020) and which are described in the main text and/or Methods section. Results that are additional to those provided in the main text, figures, and tables are available from the authors upon reasonable request. Similarly, the raw data collected during the in vivo trial are available from the authors upon reasonable request.

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