Reducing freshwater use in pork production
the case of Ireland

Shilpi Misra

Propositions

1. Providing enrichment is essential to improve animal welfare as well as water use in pork production.
   (this thesis)

2. The justification for detailed water monitoring on farms can be given once the monitoring is completed.
   (this thesis)

3. Generating carbon credits by planting trees is greenwashing.

4. Technological innovations create more problems than they solve.

5. Use of social media fuels depression.

6. Teams meetings can never replace real-life meetings.

Propositions belonging to the thesis, entitled

Reducing freshwater use in pork production – the case of Ireland

Shilpi Misra

Wageningen, 6 June 2023

Reducing freshwater use in pork production
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Shilpi Misra

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Abstract

Freshwater is an important resource which is under threat due to overuse. It is used in pork production for a range of processes from cradle-to-slaughterhouse-gate. Therefore, this thesis aimed to identify farming strategies to reduce freshwater use from on- and off-farm processes along the pork production chain, Ireland was used as a case study. Freshwater use (green and blue) from cradle-to-farm gate was studied using the water footprint (WFP) method. Detailed farm data (e.g. diet composition, production data) were combined with data collected using on-farm water meters to explore variation among farms. The overall WFP was at the low end of previously published studies. Variation between farms was small, and a weak negative correlation between WFP and farm size, and WFP and meat produced was found. We, however, found that using by-products in pig diets had beneficial effects for WFP and also lowered feed-food competition. In terms of reducing freshwater use and lowering feed-food competition, beet pulp, bakery by-products and rapeseed meal were the most promising ingredients. Avoiding feed ingredients that are human edible is considered an important topic for future studies. In this thesis, we also studied how changes in farm management strategies can influence the on-farm blue water use for cleaning and drinking, and their links with pig welfare and behaviour. Different cleaning and disinfection methods for weaner pig pens were tested to determine which methods use least water while reducing bacterial levels. The washing treatments used were power washing and disinfection, pre-soaking followed by power washing and disinfection, and pre-soaking followed by detergent, power washing and disinfection. We found no differences in either water use or bacterial load between treatments. From the producers perspective, however, pre-soaking and detergent use are the preferred options as they save washing time and labour costs. Drinking water use is one of the major freshwater uses on-farm. The influence of providing grower-finisher pigs with additional enrichment and more shared space on drinking and foraging behaviour was also assessed. Pigs with high enrichment used less water than pigs provided with low enrichment, with water wastage lower in pens with high rather than low enrichment. Aggressive and harmful behaviour were performed less in large groups and pens with high enrichment. Thus, improved enrichment provision may have benefits for both the environment and animal welfare. In conclusion, from this thesis we can see that a collaborative framework of integrative solutions is required to make pork production more sustainable.

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Chapter 1

General Introduction

1. Background

The planetary boundaries aim to define the safe operating space for humanity in order to avoid unacceptable global environmental changes, and are currently acknowledged as the ultimate boundaries of sustainability (Steffen et al., 2015). If human societies wish to continue to develop and thrive, we have to remain within these planetary boundaries; at present, however, this is posing a challenge. Sustainability is also the central theme of the United Nations 2030 Sustainable development goals (SDGs). The 17 SDGs require all stakeholders to form collaborative partnerships and protect the planet through sustainable production and consumption. Likewise, the new modernised common agricultural policy in the EU (2023-27) places strong emphasis on the sustainability of agricultural and rural areas. Reforms under the common agricultural policy support the transition towards sustainable agriculture and align with the aims of the European Green Deal to increase sustainability from farm to fork (European Commission, 2019).

Production of animal-source food (ASF) has received major attention due to its environmental impacts, even though it plays a crucial role as a significant source of protein and micronutrients. On a global scale, the livestock sector uses around 40% of the world's arable land (Mottet et al., 2017), one third of the cereals produced, and one third of fresh water withdrawals (Poore and Nemecek, 2018; FAO, 2018). Being furthermore an important contributor to emissions of pollutants, such as eutrophication compounds and greenhouse gases, the sector is held responsible for irreversible environmental changes, and harmful human health effects (Ridoutt et al., 2012). To feed a growing population a healthy diet while respecting the planetary boundaries, therefore, we are in need of more environmentally friendly and responsibly produced products (Noya et. al., 2016).

There are nine planetary boundaries to human pressures on biophysical systems and processes. The planetary boundaries climate change, land system change, biodiversity loss and extinctions and biogeochemical flows are already at risk due to human pressures. Earlier, the freshwater boundary was not thought to be at risk (Steffen et al., 2015) but a recent study indicated that the freshwater boundary is already transgressed (Wang-Erlandsson et al., 2022). This study focuses on the freshwater boundary. Since freshwater use plays an important role in livestock farming there is a need of strategies to reduce this freshwater use.

1.2 Understanding freshwater use

Livestock production is putting pressure on already water stressed areas, contributing to water scarcity. Freshwater water use in agriculture can be differentiated into consumptive and non-consumptive water use. Consumptive water use (CWU) refers to water that does not return to the same watershed (drainage basin or catchment) and, therefore, is not available for re-use (e.g. water that is evapotranspired during crop cultivation). Non-consumptive water use refers to water that is withdrawn and discharged into the same watershed (Ran et al., 2016). In this study we will focus on CWU, which can be differentiated into green and blue water.

Green water refers to rain water that is stored in the upper part of the soil (soil moisture) or temporarily stays at the top of vegetation, and can be used by plants. Green water, therefore, is directly coupled with land use. Blue water refers to the water withdrawn from water bodies (surface and underground), such as rivers, lakes and aquifers. Both green and blue water resources are interconnected; a change in green water availability also affects blue water availability and vice versa. Besides green and blue water, literature also refers to grey water use (Ercin et al., 2012). Grey water is defined as a virtual amount of freshwater that is required to assimilate the pollution load of the product system based on the existing water quality standards (Ercin et al., 2012). Grey water, therefore, is a proxy for water pollution and does not represent actual water use. In this study I will not consider grey water use.

Although the existing planetary boundaries of freshwater use (Steffen et al., 2015) are solely defined by consumptive blue water use, the importance of also considering green water use has been addressed (Ran et al., 2017). Main reasons are the significant human pressure on green water resources, and the interconnection between green and blue water use (Wang-Erlandsson et al., 2022), in this research I will therefore consider both.

1.3 Methods of assessing freshwater use

Freshwater use for livestock production can be quantified using various methods, such as a water productivity assessment (WP), life cycle assessment (LCA) and water footprint assessment (WFP) (Ran et al., 2016). Water productivity assesses the ratio of the net benefit from the different production systems (cropland, livestock) to the amount of water depleted due to that benefit. A net benefit can be defined as an economic or a physical output. Generally WP studies determine one value for water use and do not provide any separate values for green and blue water. Water productivity can be calculated for a product, an entire production system or a specific area, such as a river basin. Moreover, studies focussed on the farm-level mostly. On the other hand, LCA assesses the environmental impact related to freshwater use along the entire value chain of a product, based on location specific water stress indices. Mostly, LCA studies only quantify blue water use and excludes green water use, it also relates blue water use to local stress indices and water scarcity. Finally, the WFP also considers the whole product life cycle and quantifies the total amount of blue, green and grey water but generally does not relate it to a local environmental impact (Ran et al., 2016). Besides these, another method was proposed (Ran et al., 2017), defined as water use ratio (WUR). LCAs and WFP studies do account for the water use for cultivation of animal feed, but it does not explain the effect of redirecting this water, and the associated land, to cultivate crops for human consumption. The water use ratio is a measure that is developed to gain insight into the competition for water and land resources between crop and livestock production. It is defined as the maximum amount of human digestible protein (HDP) that could be derived from food crops, from all water used to produce one kg of ASF over the amount of HDP in that kg ASF. Hence, WUR determines the efficiency of different production systems to use water resources to produce human digestible food protein (HDP) compared to livestock protein. For this PhD project, I will be quantify the water use an LCA/WFP approach (i.e. WFP equals an LCA if you only consider blue and green water use) to assess green and blue water use along the pork chain and WUR to determine the competition for water resources between food-feed production.

1.4 Freshwater use along the pork production chain

This PhD project focuses on factors affecting freshwater use in livestock production, and more particularly on that in pork production. Pork is the second most widely eaten meat in the world (Lin-Schilstra et al., 2022). In order to respect the planetary boundaries for freshwater use, we need to understand how pork production contributes to freshwater use, and provide pig farmers with strategies to improve their green and blue water footprint. This PhD project will use Irish pork production as a case study.

In Ireland, the pig industry is the 3rd most important agricultural enterprise, after dairy and beef, and it contributes up to 8% to the gross agricultural output. Just like in other European countries, in Ireland pigs are kept in intensive indoor production systems which are highly dependent upon purchased feed (Meul et al., 2012). The pork production chain is a complex value chain, including feed production, gestation and farrowing of the breeding animals, and fattening and slaughtering of the meat producing pigs. The vast majority of the pigs in Ireland are reared in large commercial units with farrowing, rearing and fattening units all on one farm. According to the most recent national pig census (2021), the total number of pigs in Ireland is estimated at 1.8 million, out of which 92% are fattening pigs and 8.0% are breeding pigs (gilts and sows). Commercial pig farms in Ireland have an average herd size of 790 sows (range from less than 100 sows to over 2,500 sows; Teagasc, 2021), and are generally structured by production stage, including gestation (115 days), farrowing (28 days), weaners (6-8 weeks) and grower-finishers (12 weeks).

In the pork production chain, freshwater plays a crucial role. Freshwater is used for feed production, for drinking, and for cleaning purposes, both on the farm and in the slaughterhouse (Figure 1). Feed crop production can be either rain-fed or irrigated, which means both green and blue water can be used. Blue water is used for fertilizer and pesticide production, as well as being crucial to support growth and wellbeing of the pigs on-farm. On-farm services, such as feed delivery, drinking and cleaning also use blue water. Finally, for the slaughtering phase and for meat processing blue water is utilized as well.

So far, little research has been performed that focuses on identifying strategies for individual livestock farmers to reduce their freshwater use. In pig farming systems, farmers are the main stakeholders that can influence the different components of the pork production chain, from feed ingredients used, to management practices on the farm that can help reduce freshwater use. Therefore, focus is needed on both on- and off-farm processes where farmers can take ownership and help to reduce the overall burden on water use of the pork production chain. When we consider off-farm processes that contribute to water use, feed production is the main component which contributes to both green and blue water use. Farmers could consider that using more environmentally sustainable feed ingredients can help reduce the freshwater use of pork production. From the perspective of entire food-systems, competition of pig feed with human edible food crops is another aspect that needs attention in freshwater use assessments. Most of the ingredients used in pig feed are also human edible and use a significant amount of arable land and associated green water. Thus, from a food security perspective, using these land and water resources to produce food that can be consumed by humans directly is much more efficient than using it to produce feed (Foley et al., 2011; McAuliffe et al., 2017; Mottet et al. 2017).

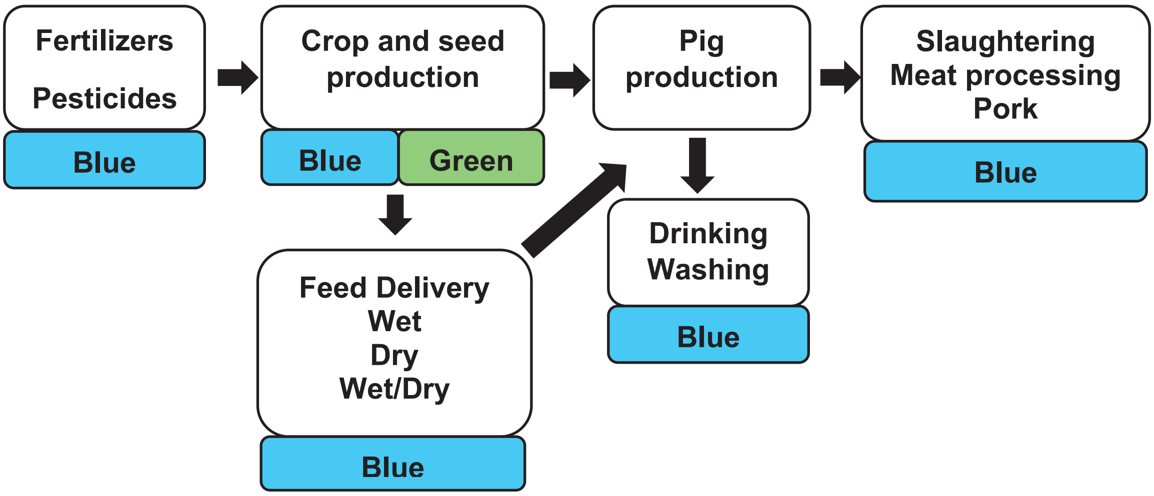

Figure 1: Pork production chain and types of freshwater used at the various stages

In terms of on-farm water use, farmers' attitudes and selection of management strategies on the farm can directly help in influencing the volume of drinking and cleaning water used. Stressful conditions in intensive pig production systems are linked to reduced animal welfare and health of pigs (Albernaz-Gonçalves et al., 2021). For instance both enrichment and space allowance greatly impact animal behaviour (Velarde et al. 2015), which could potentially influence drinker related behaviour, and water use. Improper cleaning on farm, and not following strict hygiene rules can lead to increased disease risk (Halpin et al., 2022). Therefore, focusing on farm management practices to promote good health and reduce stress could help improve the overall wellbeing of the pigs, as well as influence the freshwater use.

1.5 Knowledge gaps

In the pork production cycle freshwater is used in different processes from cradle-to-farm gate, including off-farm (feed production) and on-farm (drinking, feed mixing, washing) processes. However, little research has been performed that focuses on identifying strategies for individual pig farmers to reduce their on-farm and off-farm freshwater use of pork production.

1.5.1 Farm data collection

The foundation of any life cycle approach is to collect data for all steps and processes from starting until the end of the process or product is reached. Collection of farm level data is thus essential in order to fully understand variations in water consumption between different pig farms, and how different farm management practices could affect water consumption. This will enable the identification of farm specific improvement options to reduce the freshwater use of pork production. While previous researchers (Wiedemann et al., 2010; Mekonnen and Hoekstra, 2012; de Miguel et al., 2015; Gonzalez Garcia et al., 2015; Noya et al., 2016) looked at the water footprint (WFP) of different pig production systems, most of them did not collect on-farm data, nor did they collect farm specific water use data for each production stage to understand the variation between different farms based on feeding systems, herd size etc. Moreover, there is a lack of knowledge about linkages between the various factors, which can influence blue and green water usage in pork production such as herd size, feeding system, water flow rates, meat production, feed ingredients etc.

1.5.2 Feeding strategies to reduce water use and food-feed competition

Off-farm, production of feed is considered the main contributor to freshwater use with green water being most important (approx. 79%), and blue water comprising approx. 21% of the total freshwater use (Noya et al., 2016).

Pigs currently consume high quality feed and most of these feed ingredients are human edible. Although, pigs are efficient feed convertors, they often consume more human edible protein than they produce (Mottet et al., 2017, van Zanten et al., 2018). The major feed ingredients fed to pigs include human edible wheat, soyabean, barley and maize. It requires significant amount of water and land resources to grow these ingredients, and since these ingredients are human edible they also contribute to food-feed competition. To improve the sustainability of pig production, it is crucial to account for food-feed competition. In this regard, knowledge about freshwater use of pig diets based on local feed ingredients, or by-products unsuitable for human consumption, is lacking. Locally sourced ingredients could help reduce the external water stress caused due to importing pig feed from water stressed areas and by-products are a side stream of crop production or food industry. Moreover, research is also needed to investigate the use of alternative feed ingredients or waste streams as pig feed, which can replace human edible pig feed, and thus reduce food-feed competition. Therefore, in this PhD I will also focus on an alternative method to WFP, called the water use ratio (WUR). Until now, there are no studies that looked into the WUR of pork production systems.

1.5.3 Farm management other than feeding

On-farm processes such as drinking and cleaning also contribute to the blue water use of pork production. There are several improvement options on-farm which have not been explored in terms of improving the water use of pork production systems.

Cleaning of pig pens between batches is very important, particularly for younger pigs, and especially those newly weaned, to avoid infectious diseases (Fairbrother and Gyles, 2012). However, there is very no literature available about the freshwater use and efficacy of different cleaning and disinfection treatments in reducing bacterial load for younger age categories of pigs. Further knowledge on the effect of cleaning and disinfection strategies on both freshwater use and bacterial load would be useful to determine an optimal strategy for both.

Another aspect of on-farm water management is drinking. Provision of sufficient water for drinking is considered fundamental in animal agriculture to ensure good welfare. Grower-finisher pigs consume majority of the freshwater used on pig farms, but this comprises of both water that is consumed and wasted, as pigs do not use the drinker only for drinking. It is possible that this can be directly influenced by the farmers if certain environmental or management factors on farm are modified. Increasing resource allowance, such as shared space and functionally effective enrichment, are some factors that have potential to affect the drinking behaviour of pigs, and therefore warrant investigation.

2. Aim

The aim of this thesis is to identify farming strategies to reduce green and blue water use from on- and off-farm processes along the pork production chain. To this end, we used Ireland as a case study.

3. Outline of the thesis

Figure 2 presents the outline of the thesis. **Chapter 2** quantified the on-farm and off-farm freshwater use of Irish pork production based on pig farm water data collection and pig diets. In Ireland, 12 pig farms were selected based on having all pig production stages. The water used for feed production, drinking, cleaning and feed mixing was quantified. **Chapters 3, 4 and 5** identify both on- and off-farm strategies that can help reduce green and blue water use in pig farming systems. **Chapter 3** focuses on off-farm feed water use, and shows how alternative feed ingredients and modified pig diets using locally grown ingredients or crop by-products compare with standard Irish pig diets, based on their WFP, and while accounting for food-feed competition. **Chapters 4 and 5** focuses on how changes in farm management strategies can influence the on-farm blue water use for cleaning and drinking, and their links with pig welfare and behaviour. In **Chapter 4** different cleaning and disinfection methods for weaner pig pens were tested to determine which methods use least water

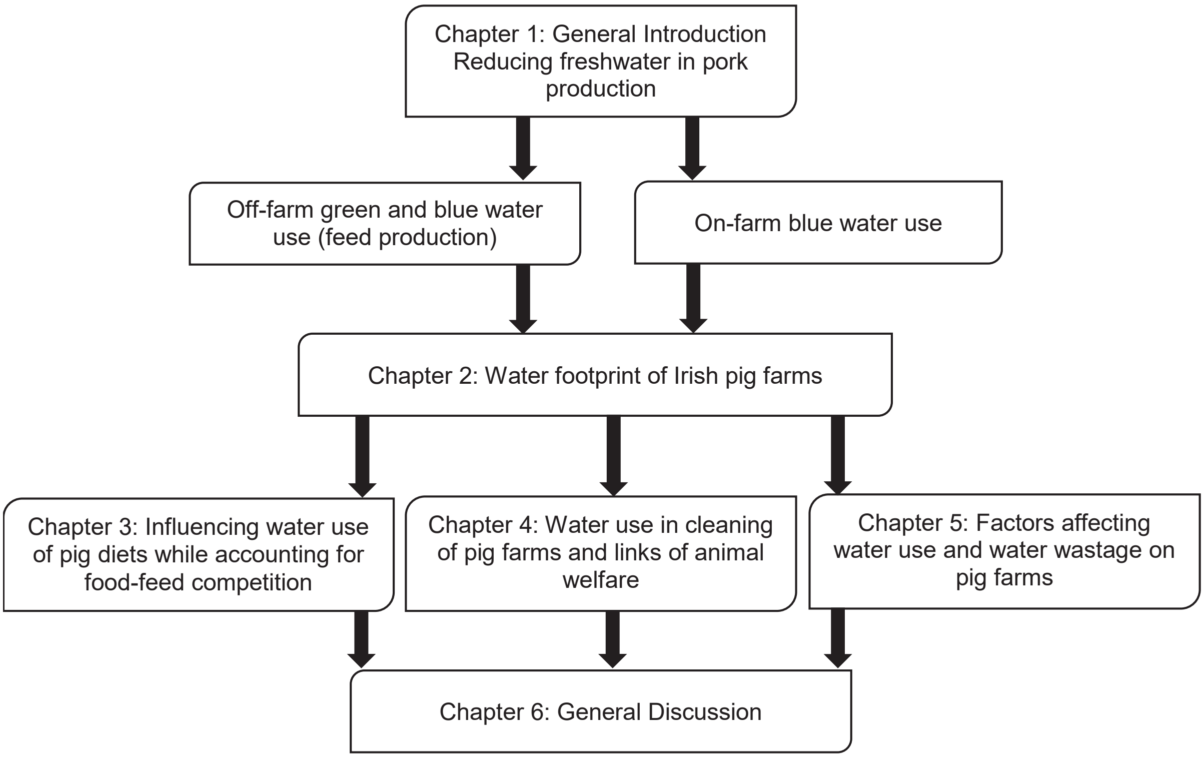

Figure 2: Schematic overview of chapters in this thesis

while reducing bacterial levels (thus maintaining conditions to not inhibit good pig health and welfare). **Chapter 5** focused on influencing drinking and foraging behaviour of grower-finisher pigs by providing them with additional enrichment and more shared space. **Chapter 6** discusses the different aspects of how freshwater use in the pork production chain can be influenced by adopting strategies to make it environmentally sustainable while keeping within the planetary boundaries.

Chapter 2

Water footprint of pig farms in Ireland based on commercial farm data

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Imke J.M. de Boer, John Upton

Abstract

Livestock production is getting increased attention due to its impact on natural resources, and freshwater is one such limited resource. To reduce the pressure on freshwater use and develop sustainable livestock systems from farm-to-fork we need to study the whole production cycle, and look for hotspots of major freshwater use. Considering this, we chose intensive pork production as our focal livestock system, since it is one the most eaten meats globally. We focused on pork production in Ireland and studied the freshwater use (green and blue) from cradle-to-farm gate using the water footprint (WFP) method. Detailed farm data (e.g. diet composition, production data) were combined with on-farm water meters to explore variation among farms and potential explanatory variables. So far, there have been no WFP studies in pork production that explored this, while insight into variation could help to identify options for improvement. We analysed on-farm and off-farm green and blue water use of 10 Irish pig farms. Our results show that the average total WFP, including on-farm and off-farm water use, was 2,537 L/kg pork which was at the low end of previously published studies. Green water use during the production of purchased feed was responsible for the largest share (99%) of the total WFP. On-farm blue water use formed only a minor component of the total WFP (14 L/kg pork), with drinking water playing the major role. We can conclude from this study that variation in WFP between least and most efficient farms was small (181 L/kg pork) indicating that efficiencies of around 7% could be gained by the least efficient cohort of farms by adjusting on-farm management practices. We also found a weak negative correlation between WFP and farm size, and WFP and meat produced. Nevertheless, this study also indicates an opportunity for present and future pork production systems to source feed ingredients from non-water stressed areas to further reduce the burden on freshwater resources.

1. Introduction

The reformed common agricultural policy (2023-27) (European Commission, 2021) focuses on a sustainable food future and targets reduced pressure on global and local water resources while considering local needs. The objective of the new CAP is also aligned with the aims of the European Green Deal to reduce the environmental footprint of EU food systems and increase sustainability from farm-to-fork. In recent years, livestock production has seen increased attention due to its environmental impacts, but it also plays an important role as a source of human food, employment and other income sources (Herrero et al., 2011; González Garcia et al., 2015). Livestock systems use about 40 percent of global arable land (Mottet et al., 2017), one third of the cereals produced globally, and one third of fresh water withdrawals (Poore and Nemecek, 2018; FAO, 2018). However, these resources are limited, and therefore we need more efficient and sustainable livestock production systems. Freshwater is one such resource which plays a crucial role in livestock production. The majority of freshwater use in livestock production is attributed to evapotranspiration from plants grown to produce feed, with a lesser, but yet significant role played by livestock drinking, cleaning and feed-mixing water (Ran et al. 2017).

Freshwater is used in pork production for a range of processes from cradle-to-slaughterhouse-gate. Pork production systems in Europe are generally classified as intensive industrial systems and are structured by production stage, including gestation (115 days), lactation (28 days), weaning (6-8 weeks) and growing-finishing (12 weeks). In Ireland, the pig industry is the 3rd most important agricultural enterprise after dairy and beef, and contributes up to 8% of the gross agricultural output (Boyle et al., 2022). The vast majority of the pigs in Ireland are reared in large commercial units with breeding, rearing and fattening units all on one farm. There are 292 commercial pig farms in Ireland with an average herd size of 790 sows (range from less than 100 sows to over 2,500 sows; Teagasc, 2021).

Freshwater use of pork production can be quantified by calculating its water footprint (WFP), i.e., the volume of freshwater used per unit of product produced (usually m^3/ton). The WFP is divided into green (i.e. rain water evapotranspired during crop cultivation or embedded in crops), blue (e.g. irrigation water or stock drinking water) and grey water (i.e. virtual freshwater used to assimilate pollution) (Ercin et al., 2012). Grey water is better represented in other impact categories of a life cycle assessment, as it is not a direct water consumption. In this study, therefore, we focus on the use of green and blue water only.

Among all the livestock production systems, pork production contributes 19% to the global WFP (Mekonnen and Hoekstra, 2012). However, the environmental impact of freshwater use in pork production has not been fully addressed by many researchers. For example, Mekonnen and Hoekstra (2012) estimated the weighted global average green and blue WFP for industrial pork production to be 4,537 L/kg of carcass weight. This estimate was based mainly on data from secondary sources, such as FAOSTAT and global average data from other researchers. A Spanish study by Miguel et al. (2015) estimated the WFP of different types of pig farming systems (intensive and extensive, i.e. outdoor) also using data from secondary sources and concluded that the average WFP of pig production in Spain was 3,428 L/kg carcass weight. Some researchers used a combination of primary (animal husbandry and slaughter house) and secondary (crop water requirements) data sources to estimate the WFP in the range of 2,800 to 7,200 L/kg pork (Wiedemann et al., 2010; Gonzalez Garcia et al., 2015; Noya et al., 2016).

While these studies looked at the WFP of pork production systems in different countries and from different sources, most of the studies did not collect all primary farm data from cradle to farm gate, nor did they collect farm specific water use data for each production stage to understand the variation between farms. In particular when concerning the WFP for feed production, the studies cited earlier used WFP values from secondary sources. Similarly, these previously cited studies did not take into consideration variation in management factors such as herd size, type of feeding systems (in terms of wet or dry feeding), age of facility, feed origin, or the amount of meat production among farms when calculating the WFP of the systems. In order to accurately compute the WFP of a product and to fully understand variation in water consumption among farms as well as how different farm management practices affect water consumption, collection of farm level data is essential. The objective of this study therefore, was to calculate the direct on-farm and off-farm green and blue water use of Irish pork production systems, and to study variation among farms. This will enable the identification of farm specific improvement options to reduce the freshwater use of pork production.

2. Material and methods

2.1 System boundaries

Twelve commercial pig farms in Ireland were selected with the support of the Specialised Advisors from the Teagasc Pig Development Department. These study farms were located in north, north-west, south, south-east, south-west and mid-east of the country. The selection criteria of the farms included availability of farm production data, that farms operated a farrow to finish unit with all pig production stages on one site, and that the farmer was willing to participate in water meter installation and water data collection. For all the farms we collected water and production data between 2019 and 2021. We used data representing one full year from each farm in our analysis. Pig production takes place indoors, therefore, unlike other production systems (dairy and beef) there is no seasonal variation due to weather conditions. The system boundary was cradle-to-farm gate (Figure 1). Within the system boundaries the freshwater use that was quantified included water required for cultivation of crops for pig feed, and water required for animal husbandry (drinking, feed mixing) and farm maintenance (washing etc.). Water use related to the production of energy and fertilizer, and slaughtering was not included. These aspects will not influence the variation between farms because most of the crops used as feed were similar and the farm sizes were not drastically different from each other.

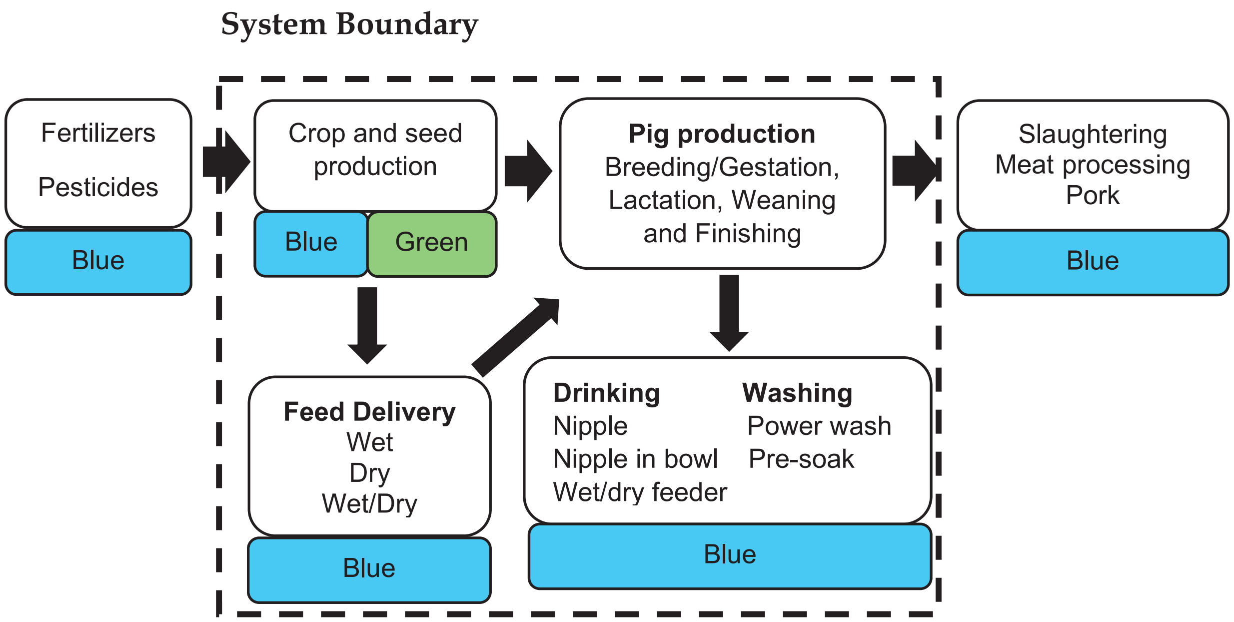

Figure 1: Processes along the pig production chain contributing to blue and green water use. The dotted line presents the system boundary of this study

2.2 Data collection

The type of data collected in this study included data of pig production, pig diets, feed usage, farm infrastructure, and water meter data to record blue water usage on each farm.

2.2.1 *Pig diets, feed usage and production data*

The pig diets for each production stage for each farm, i.e. type of feed ingredients in the pig diets and share of each feed ingredient in the diets, were obtained from the farmer (in the case where they milled their own feed) or feed mills (in the case where they purchased feed) for the year in question. The detailed average pig diets per production stage are given in Appendix C. The amount of feed used (tonnes/year) per production stage was obtained from the Teagasc E-Profit Monitor system, which is an online financial analysis tool to assess farm profitability.

The national feed import data, i.e. country of origin of each feed ingredient between the years 2019 and 2021, was obtained from the Feedingstuffs, Fertilizer, Grain and Poultry Division (FFGPD) of the Department of Agriculture, Food and the Marine (DAFM) of Ireland (personal communication). The weighted average of all the feed imports was used to identify the country from which the maximum tonnage of each feed ingredient was imported into Ireland. Table 1 shows the country of origin of each feed ingredient used on the farms. The production data of each farm (herd size, number of pigs produced, and meat production) was obtained from the Teagasc E-Profit Monitor system.

Table 1: List of feed ingredients used in the pig diets and the country of origin of each ingredient

Feed ingredient	Country of Origin
Barley	United Kingdom
Wheat	United Kingdom
Maize grain/flaked maize/cooked maize	Ukraine
Soyabean and by-products	Argentina
Wheat feed/wheat pollard	Netherlands
Rapeseed meal	France
Field beans	Ireland
Pot ale syrup	Ireland
Sunflower seed meal	Portugal
Beet pulp	Ireland
Sugarcane molasses	Guatemala
Rape oil	Ireland
Palm oil	Indonesia
Delactosed permeate (DLP) whey curd	Ireland
Whey permeate	Ireland
Maize gluten	United States

2.2.2 Farm infrastructure and water use data

Farm infrastructure data including feed delivery system (wet, dry or wet and dry), feed usage, on-farm water sources (well/local/government supply), water flow rates from drinkers, types of heating system, and washing procedures etc. were collected using a farm survey (Appendix A). Water meters were also installed on each farm to record water volumes (m^3) used throughout the farm, including water used for animal drinking, farm washing and feed mixing, with separate meters for each pig production stage i.e. gestation, lactation, weaners and finishers. Water use was recorded and monitored on a monthly basis via an automated online water monitoring system (Carlo Gavazzi Automation, Italy). These water meter recordings were used to calculate the on-farm blue water use for each individual farm.

2.3 Water footprint of the farm

The total WFP of each farm is the sum of the on-farm water use and the off-farm water use i.e. water used for crop cultivation.

2.3.1 Water footprint of on-farm water use

Total monthly blue water use on each farm was computed by adding the volume of water used (m^3) from every meter on each farm. Only 10 farms were used for the analysis, due to technical issues with the water meters we were not able to collect the on-farm water use from two farms. In one case (farm 9) we could only get the total on-farm water use. To calculate the monthly blue WFP (L/kg pork) of the metered water we divided the total monthly water use (L) by the amount of meat (carcass weight) produced per month, including meat from sows (kg). All the monthly data were then averaged to get the yearly average total blue WFP (L/kg pork).

2.3.2 Water footprint of feed ingredients

Freshwater required to grow feed ingredients can be differentiated into green (rainwater and soil moisture) water and blue (irrigation) water. To compute the green and blue water used for each feed ingredient the method described by de Boer et al. (2013) was used, containing the following steps.

As described above, first the country of origin of each feed ingredient was obtained from DAFM, Ireland. In each country, the International Food Policy Research Institute (IFPRI) grid data (IFPRI, 2019) were used to identify the regions/locations (coordinates) that are responsible for the highest national production. For the selected region, the predominant soil type was identified from the Harmonized World Soil

Database v 1.2 (FAO/IIASA/ISRIC/ISS-CAS/JRC, 2012). The sowing dates and length of growing period of Irish crops were either obtained from Teagasc Crop Science Department (Teagasc, 2021 (personal communication) or from global database (USDA, 2020) and for rest of the crops only global database (USDA, 2020) were used. The actual yield of the crop in the region with the highest production was obtained using the IFPRI grid data (IFPRI, 2019), and where not available data from FAO (2020) was used.

Second, the AQUASTAT climate information tool (AgERA5 dataset; Boogaard et al., 2020) was used to retrieve the climate data (mean temperature, mean sunshine etc.) and calculate the ET_o (evapotranspiration of the reference crop, millimeter/growing period) for the specific location based on the classic Penman-Monteith equation (Allen et al. 1998). These climate inputs and ET_o values were added to the CROPWAT-online tool, (on AQUASTAT) along with the actual crop type, sowing dates, cropping days and soil type to calculate the soil water balance and crop water requirements. Subsequently, the crop specific evapotranspiration (ET_p, millimeter) over the entire growing period was calculated, assuming maximum soil water availability. This was calculated by multiplying the crop coefficient (K_c) for the respective growth period with the reference crop evaporation (ET_o) per day, and summing these daily values for the entire crop growing period from sowing to harvest (Eq. 1).

$$ET_p = \sum K_c \times ET_o \qquad (1)$$

Rain-fed evapotranspiration (ET_{rf}, millimeter), i.e. the volume of the evapotranspired precipitation (green water) of a crop over its growth period, was derived from AQUASTAT. ET_{rf} for the crop growing period was calculated using Eq. (2) using values from AQUASTAT

$$ET_{rf} = \sum K_s \times ET_p \qquad (2)$$

Where Ks, the transpiration reduction factor, necessary to consider water stress, was calculated as a function of maximum and actual available soil moisture in the rooting zone derived from AQUASTAT. Also the values for effective root depth and soil water depletion fraction were taken from AQUASTAT.

Third, actual evapotranspiration (ET_a; millimetres/year) was computed as follows (3):

$$ET_a = -\left((1-Y_a/Y_{mp}) \,/\, k_y - 1\right) \times ET_p \qquad (3)$$

where Y_a is the actual crop yield per hectare; Y_{mp} is the maximum potential crop yield per hectare; k_y is the yield response factor, which is crop specific and describes the relationship between ET deficit and yield reduction, and ET_p is the crop specific potential evapotranspiration (millimetres) as described above. The potential crop yield Y_{mp} was calculated by multiplying the national average yield for the region with a factor of 1.2 (Reynolds et al., 2000).

If $ET_a \leq ET_{rf}$ then irrigation was assumed to be absent. If $ET_a > ET_{rf}$, irrigation volume was computed as follows (4):

$$\text{Irrigation volume} = (ET_a - ET_{rf}) \ / \ Ir_{eff} \qquad (4)$$

Where Ir_{eff} is the irrigation efficiency, which was assumed to be 0.7 for all crops, implying that per unit of irrigation water, 70% was taken up by the crop and 30% was lost (Allen et al., 1998). The water footprint of all ingredients are mentioned in Appendix B (Table B.1).

Fourth, to compute the green and blue water use of each crop the following method was used. Under rain-fed conditions, blue crop water use was zero, whereas green water use of the crop was calculated as follows (5):

$$\text{Green water use} = (ET_a \times 10) \ / \ \text{crop yield} \qquad (5)$$

where green water use was expressed in m^3 per tonnes, ET_a was expressed in millimeters per year, and the factor 10 was used to convert mm per year to m^3/ha, and crop yield was expressed in tonnes/ha.

Blue water use of the crop during crop production was estimated by the irrigation volume for a specific crop grown in specific region, as follows (6):

$$\text{Blue water use} = (\text{Irrigation volume} \times 10) \ / \ \text{crop yield} \qquad (6)$$

where blue water use was expressed in m^3 per tonnes, irrigation was expressed in millimeters per year, and the factor 10 was used to convert mm per year to m^3/ha and, crop yield was expressed in tonnes/ha.

Based on the consumptive green and blue water use per crop we computed the green and blue WFP (m^3/t) of each feed ingredient. This was done by multiplying the green and blue water use with the economic allocation factor of each crop/feed ingredient, divided by the amount of ingredient produced per unit of crop (tonne/tonne). The economic allocation factor for each feed ingredient was derived from previous literature or databases (van Middelaar et al., 2011; Vellinga et al., 2013; Colomb et al., 2015; Wernet et al., 2016).

2.3.3 Water footprint of diets and per kg of pork

The total input of each diet (tonnes/year) (gestation, lactation, weaner, and finisher) and the relative share of each feed ingredient in the diet (%) was used to calculate the amount of each feed ingredient in the diet (tonnes/year). These values were then multiplied with the green and blue water use (m^3/tonnes) to compute total green and blue water use of each crop ingredient per farm per year. The WFP of all ingredients was summed up to get the total green and blue WFP of each diet and converted to L/year.

We then divided the total feed production green and blue water use (L) by the total amount of pork (kg) i.e. carcass weight, produced on the farm during the year to yield the feed relater WFP.

The total WFP of each farm was calculated by adding the total feed water use (L/year) to the metered on-farm blue water use (L/year) and dividing by the total amount of pork produced (kg) (i.e. carcass weight) on the farm during the year.

2.4 Data analysis

We performed a correlation analysis (PROC CORR) to study the strength of the relationship between total WFP and different farm variables (e.g., herd size, meat produced), and an univariate analysis (PROC UNIVARIATE) to calculate the inter quartile range of the total WFP using SAS version 9.4 (SAS Institute Inc., Cary, NC, USA).

3. Results and discussion

3.1 General farm characteristics

Table 2 shows the production details of the study farms in terms of the number of sows, type of feed delivery system (wet, dry or wet and dry), feed usage and meat produced. The average number of sows on the study farms was 567 (range 283 – 900). The average meat (carcass weight) produced from the farms was 1,396 tonnes/year, which equalled approximately 2.45 tonnes/sow/year.

Table 2: Production parameters of study farms

Farm	Sows	Feed type	Meat produced* (tonnes/year)	Meat produced (tonnes/sow/year)	Feed used (tonnes/year)
1	818	Wet	2,038	2.49	6,755
2	617	Wet and Dry	1,457	2.36	5,032
3	540	Wet and Dry	1,517	2.81	5,230
4	900	Wet and Dry	2,187	2.43	6,838
5	475	Wet and Dry	1,384	2.91	4,575
6	376	Dry	999	2.66	3,234
7	743	Dry	1,661	2.24	5,417
8	381	Dry	972	2.55	3,375
9	283	Dry	488	1.72	2,052
10	540	Wet	1,254	2.32	4,490
Min	283		488	1.72	2,052
Mean	567		1,396	2.45	4,700
Max	900		2,187	2.91	6,838
SD	202		506	0.33	1,516

*Includes meat of culled sows

The average herd size of Irish pig farms was 790 sows in 2021 (Teagasc, 2021). Therefore the study farms had an average farm size which was 28% lower than the national average.

3.2 Green and blue water footprint of farms

3.2.1 On-farm blue water footprint

The on-farm WFP consisted of blue water only, and was sourced from on-farm wells. Table 3 presents the breakdown of the on-farm blue WFP (BWFP) for each farm, including drinking water (for each production stage), feed-mixing water and washing water. The on-farm blue WFP ranged from 8.0 to 29.4 L/kg pork with a mean value of 14.1 L/kg pork (SD 5.8 L/kg pork) and was 70% of the total blue WFP. The remaining BWFP was off-farm and used for the production of pig feed. Mostly the wet feed farms (10.5 L/kg pork) had average BWFP towards the lower side compared to dry feed farms (12.7 L/kg pork). The wet feed farms had an average BWFP 23% lower than the mean, the dry feed farms average BWFP was 6% lower than the mean while the wet and dry feed farms had an average BWFP 29% greater than the mean. Among all the production stages the finisher stage (65%) contributed most to the drinking water use, followed by the weaner (19%), gestation (10%) and lactation (7%) stages. Overall, the major contribution towards on-farm BWFP was from drinking followed by feed mixing and washing water. However, considering the dry feed and wet feed farms separately, we can distinguish that for dry feed farms drinking is the main component and for wet and wet and dry feed farms feed mixing is the major part of on-farm blue water use.

3.2.2 Off-farm green and blue water footprint

The off-farm WFP consisted of both green and blue water use for the production of pig feed. Table 4 shows the details of the green and blue water used to produce pig feed and the total WFP (on and off-farm) of each farm. The average WFP for feed production was 2,523 L/kg pork (SD 233 L/kg pork) with a range of 2,006 to 2,894 L/kg pork. The total feed WFP included mainly green water use and small amount of blue water use.

3.2.3 Comparison of WFP of different farms

The average total WFP, including both on-farm and off-farm water use, was 2,537 L/kg pork (SD 234 L/kg pork), with a range of 2,017 to 2,910 L/kg pork (Table 4). In the total WFP of farms, feed production (off-farm water use) had the largest contribution (99.4%), whereas a minor quantity (0.6%) was due to on-farm water use.

When we compared the total WFPs over the 10 farms, the interquartile range was 2,478 to 2,659 L/kg pork. Therefore the difference between the most efficient quartile (Q1) and the least efficient quartile (Q3) was only 181 L/kg pork (7% of the total WFP). Correlation analysis showed a weak negative correlation between total WFP and farm size ($r = -0.50$; $P = 0.143$) and meat produced ($r = -0.46$; $P=0.177$). We did not find any clear indication of the effect of feed type (dry, wet or wet and dry) on the total WFP of the farms.

The large ratio of green to blue water use in this study indicates that most of the feed for the pig diets was imported from rain-fed regions with the exception of one farm which had a small blue water contribution. This was due to the use of field beans from Ireland. The average volume of water consumed on the pig farms was 1.6 million L/month (range from 0.7-3.4 million L/month), equating to a blue WFP of 14.1 L/kg pork (range from 8.0 - 29.4 L/kg pork). There is no water shortage in Ireland on an annual basis, although availability of freshwater can be limited during summer months due to there being less infiltration of rainwater to the well supply (Murphy et al., 2017). On-farm blue water use in this study only contributed to 0.6% of the total WFP.

Table 3: On-farm blue water use of study farms

Farm	Gestation* (m^3/month)	Lactation (m^3/month)	Weaning (m^3/month)	Finishing (m^3/month)	Feed mixing (m^3/month)	Washing (m^3/month)	Total on-farm blue water use (m^3/month)	On-farm blue WFP L/kg pork
1	18.2	111.8	183.7	228.7	795.3	25.9	1363.6	8.0
2	60.6	17.3	363.5	698.1	358.2	38.7	1536.4	12.7
3	108.4	237.0	70.8	116.4	1190.2	86.2	1808.9	14.3
4	165.0	50.6	244.5	115.3	1528.2	282.9	2386.5	13.1
5	141.7	52.4	371.1	1544.5	744.6	535.1	3389.5	29.4
6	147.7	365.1	273.1	152.1	NA	81.6	1019.7	12.2
7	252.4	142.8	348.9	653.3	NA	144.8	1542.2	11.1
8	205.6	87.1	99.0	170.1	NA	329.2	890.9	11.0
9	NA	NA	NA	NA	NA	NA	673.1	16.6
10	18.7	25.3	116.8	86.5	1045.8	56.8	1349.8	12.9
Min	18.2	17.3	70.8	86.5	358.2	25.9	673.1	8.0
Mean	124.2	121.1	230.1	418.3	943.7	175.7	1596.1	14.1
Max	252.4	365.1	371.1	1544.5	1528.2	535.1	3389.5	29.4
SD	80.8	114.2	118.0	482.6	404.3	172.3	795.0	5.8

*Gilts are included in gestation stage

Table 4: Breakdown of Total WFP for pork production

	Off-farm water					On-farm water	Total water
Farm	Green water use/year (10^6L)	Blue water use/year (10^6L)	Green WFP L/kg pork	Blue WFP L/kg pork	Total feed WFP L/kg pork	Blue WFP L/kg pork	Total WFP L/kg pork
1	5,477	0.0	2,688	0.0	2,688	8.0	2,696
2	3,848	8.87	2,641	6.09	2,647	12.7	2,659
3	3,862	0.0	2,545	0.0	2,545	14.3	2,560
4	5,151	0.0	2,355	0.0	2,355	13.1	2,369
5	3,543	0.0	2,561	0.0	2,561	29.4	2,590
6	2,464	0.0	2,466	0.0	2,466	12.2	2,478
7	3,331	0.0	2,006	0.0	2,006	11.1	2,017
8	2,516	0.0	2,589	0.0	2,589	11.0	2,600
9	1,411	0.0	2,894	0.0	2,894	16.6	2,910
10	3,104	0.0	2,475	0.0	2,475	12.9	2,488
Min	1,411	0.0	2,006	0.0	2,006	8.0	2,017
Avg	3,471	0.89	2,522	0.61	2,523	14.1	2,537
Max	5,477	8.87	2,894	6.09	2,894	29.4	2,910
SD	1,223	2.81	232	1.92	233	5.8	234

4. General discussion

This study aimed to investigate the direct on-farm and off-farm green and blue water use of Irish pork production systems, and to establish links between water consumption and management practices. We found only a weak negative correlation between total WFP and farm size and meat produced. Moreover, there was only small variation between the least and most efficient farms. The water used for feed production was the main contributor to total WFP and green water use constituted the main component. Blue water formed only a minor component of the WFP of farms, and feed WFP.

4.1 WFP of Irish pork production

4.1.1 Comparison of WFP of Irish pork production with other countries

Ireland exports approximately 62% of its pork to different countries, with the largest export to UK followed by continental Europe and China. Therefore, comparison of the WFP of Irish pork production to that of pork produced in other regions is useful, even though there are few studies from other countries that have estimated the WFP of the pig sector considering the whole production cycle. Our findings are in line with those of the majority of other studies, which in the main found a WFP ranging from about 2,800 to 4,500 L/kg pork (Wiedemann et al., 2010 (Australia); Mekonnen and Hoekstra, 2012 (Global average); de Miguel et al., 2015 (Spain); Gonzalez-García et al., 2015 (Portugal)) with green water making up 80 to 99% of the total WFP. We are aware of only one study which found a significantly higher WFP value of 7,200 L/kg pork (Noya et al., 2016), which can be largely explained by the no allocation approach used in the study and 98% of the WFP was due to feed production of which 9% was grey water use, resulting in high green and blue water use. Compared to those other studies the total WFP of Irish pork was at the low end (2,537 L), and with the majority due to the green water footprint (99%) rather than blue. This could be due to the improvement in pig performance over the past 20 years. Some of the improvements in performance in Irish pork production systems between 2000-2020 include a 30% increase in piglets born alive per litter, an increase in deadweight (carcass weight) of 20.1 kg per pig, improved average daily gain (ADG) from weaning to sale of 150 g per day and a decrease in the amount of feed required from 3.66 to 3.50 kg of feed to produce a kilogram of pork (Boyle et al., 2022).

4.1.2 Off-farm WFP

Our results also indicated that off-farm water used for feed production (99.4%) was the major contributor to the total WFP, and of this, green water was by far the most important contributor. With regard to the importance of feed production, our results are similar to the global estimates of WFP for pig meat production by Mekonnen and Hoekstra (2012); in that study the feed WFP was 98% of the total WFP, and the remaining water use was for on-farm activities (cleaning, drinking, feed mixing). With feed production being the single most important contributor to the water use of pork production, factors such as feed efficiency, feed composition and the country of origin have a major influence on water use. Moreover, choosing sustainable feed ingredients such as inedible by-products or locally sourced feed to reduce pressure on the water resources of other countries producing the feed is a management decision which many pig farmers in Ireland could take, since about 43% of the Irish pig farmers are home millers (Calderon Diaz et al., 2019; Misra et al., 2023). Thus detailed and high quality data collection on feed production, feed usage and feed imports is important, as these can influence the calculation of the overall WFP. Although the majority of the water used in Irish pig production was green for feed production, very few studies focus on the importance of green water use in livestock production systems (Mekonnen and Hoekstra 2012; Ran et al., 2017). It is important to remember that green water use is a significant component of freshwater use assessment.

Another aspect to be discussed in regard to feed WFP is food-feed competition, which considers whether we should use our diminishing freshwater resources for animals feed production or for food crops for humans; it is generally considered preferable to redirect the freshwater used for feed production to produce food for humans (Muscat et al., 2021). Therefore, future research should focus on investigating methods of feeding human inedible crop by-products to livestock. We should also look for alternative diets which could further reduce food-feed competition and at the same time have lower WFP.

Blue water forms a very small component of feed WFP. Our results show that the small amount of blue water used in feed production was due to use of field beans grown in Ireland, even though in Ireland beans are not irrigated. This can be explained by a divergence between the yield data and the climate data (temperature, precipitation etc.). As field beans are only recently grown in Ireland, yield data was derived from FAO (2020) and based on the years 2018-2019 for beans, while the climate dataset (AgERA5) we used for the WFP calculations was from 1979 to present.

4.1.3 On-farm WFP

In our study drinking water played a major role in the on-farm WFP, followed very closely by feed mixing, and lastly by the water used for cleaning. However, when we consider only dry feed farms, drinking is the major component, whereas for wet and wet and dry feed farms, feed mixing had the most influence on on-farm blue water use. This difference could be because in wet feeding systems pigs are consuming water via the wet feed. This indicates that installation of water meters for different sections of the farm is useful where targeted interventions to particular areas are of interest.

The drinking water use on the study farms was dominated by the finishing stage followed by weaning, gestation and lactation. Our results show close similarities to Muhlbauer et al. (2010), who likewise concluded that the largest amount of blue water was used in the finishing (64%) followed by gestation (16%), weaning (11%), and lactation (9%). This implies that to minimize the blue water use on the farm, the finishing stage can act as a crucial starting point with focus on strategies to reduce water usage and wastage. For example, Misra et al. (2021) provided pigs with supplementary environmental enrichment in the finishing stage (a rack of cut grass), with the aim of distracting pigs' attention away from the drinkers. They found that indeed pigs with additional enrichment spent less time interacting with the drinker, wasted less water overall, and the proportion of water wasted relative to water used, was also less. Thus, management strategies as well as dietary options could have a part to play in minimizing water use.

4.2 Limitations of the study

Although all the farm data for the study has been collected accurately we still faced some issues when we had to draw comparisons between farms. One limitation of this study was the number of study farms. We had in total 12 Irish pig farms involved in the project out of which we were able to obtain pig diets for all farms. However, due to technical issues with the on-farm water data collection we could only obtain on-farm blue water data for 10 farms. These results did not affect the overall results of individual farms or the WFP results of all farms, yet it limited us from making direct comparisons between farms and studying the effect of different management factors. Future data collection should therefore include more farms in order to reach sufficient data for analysis and comparison of the impact of factors that could affect water use (e.g. cleaning protocols, feed delivery system etc.).

5. Conclusions

This study presents the first WFP assessment of Irish pig farming using farm specific data, which does not currently exist in the literature. The overall WFP of Irish pig farms was at the low end of previously published studies (2,537 L/kg pork). Thus, with regard to pork production, Irish systems appear to perform well when it comes to minimizing use of freshwater resources. Nevertheless, this study also indicates an opportunity for present and future pork production systems to source feed ingredients from non-water stressed areas to further reduce the burden on freshwater resources. When we take into consideration farm to farm variation, we found a small difference in WFP (181 L/kg pork) between the most and least efficient farms, indicating that efficiencies of around 7% could be gained by the least efficient cohort of farms by adjusting on-farm management practices.

6. Acknowledgements

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Appendix A: Farm Survey

Name of Farmer							
Address							
Telephone/Email							
Age of the facility							
Contained unit/ Multiple unit							
Gestating Sows							
Number of sows							
Number of pens in dry sow house							
Number of sows per pen							
After how many days post-service are sows moved to dry sow house?							
When are sows moved to farrowing house?							
Are sows washed before being moved to the farrowing unit?							
Lactating sows							
Number of farrowing pens							
Average weaning age (days)							
Weaners							
Length of weaner 1st stage (days/weeks)?							
Length of weaner 2nd stage (days/weeks)?							
Finishers							
Length of finisher stage (days/weeks)?							
Feeding Practices	Gestation	Lactation	Piglet	Weaner 1	Weaner 2	Finisher	Gilts
Feed Type							
Feed Form							
Feed Delivery							
Feed Frequency							
Water:feed ratio (if wet feed)							
Heating and water	Gestation	Lactation	Piglet	Weaner 1	Weaner 2	Finisher	Gilts
Method of heating the room							
Water Source							
Do you have sprinklers?							
Do you have any domestic houses attached to the water supply?							
Do you have any other enterprise (dairy, sheep) using water?							
New Buildings							
Any planned renovations in the next 2 years?							
Any planned new builds?							
If yes, what building?							

Cleaning Practices	Gestation	Lactation	Piglet	Weaner 1	Weaner 2	Finisher	Gilts
Do you remove the heavy organic matter before washing?							
Do you scrape the corridors (external passages) before washing?							
How frequently do you wash the pens?							
How frequently do you wash the corridors (external passages)?							
Is pre-soaking done before cleaning of pens?							
Is pre-soaking done before cleaning of corridors (external passages)?							
Methods of cleaning the pens							
Methods of cleaning the corridors							
Do you use a detergent for cleaning?							
How frequently do you use detergent?							
Which disinfectant do you use?							
Self-Observations	Gestation	Lactation	Piglet	Weaner 1	Weaner 2	Finisher	Gilts
Quantity of ration used							
Number of Pens							
Average piglet born alive							
Number of piglets per pen							
Number of finishers per pen							
Pen size, cm							
Floor Type							
Type and number of drinkers							
Feeder type							
No. feeder spaces available per pen (cm)							
Drinker flow rate (litres/min)							

Appendix B: Allocation factors and WFP of feed ingredients

Feed ingredients	Economic allocation	GreenWFP (m^3/ton)	BlueWFP (m^3/ton)
Wheat	0.78	451	0
Barley	0.75	479	0
Maize/flaked/ cooked	1	977	0
Full fat soya	1	1898	0
Soyabean meal	0.556	1498	0
Soya hulls	0.031	779	0
Soya oil	0.341	4621	0
Field beans	1	895	55
Rapeseed oil	0.756	1780	0
Whey permeate	0	0	0
Beet pulp	0	0	0
Rapeseed meal	0.234	507	0
Sunflower seed meal	0.203	7971	0
Wheat feed	0.066	330	0
Sugarcane molasses	0.046	215	0
Palm oil	0.863	2586	
Maize gluten	0.051	700	0
DLP whey curd	0	0	0
Pot ale syrup		0.4	0

Appendix C: Average ingredient composition of each diet (%)

	Gestation	Gilts	Lactation	Creep	Link	Weaner	Finisher
Barley	42.1	44.6	29.9	17.5	20.9	25.5	28.8
Wheat	21.8	23.7	33.2	28.4	31.5	34.5	26.7
Maize	4.85	6.23	7.26		1.33	8.35	17.7
Flaked maize					2.49		
Cooked maize				5.00	2.49		
Maize gluten	0.27						0.15
Full fat soya					4.27		
Soyabean hulls	8.21	4.18	1.54			0.38	1.13
Soyabean meal	9.09	11.7	17.7	1.17	9.71	20.6	14.7
Soyabean oil	0.41	1.64	2.43	2.02	2.21	3.41	1.05
Wheat feed	4.67	1.72	1.23			0.44	1.95
Rapeseed meal	2.82	0.72	0.92			0.82	1.66
Field beans							0.38
Sugarbeet pulp	2.51	1.57	1.67	0.75	0.60	0.64	0.32
Lactoflo- whey permeate						0.23	
Pot ale syrup						0.73	2.34
DLP Whey Curd							0.09
Miscl.	3.33	3.96	4.12	45.2	25.2	4.47	3.08

Chapter 3

Re-thinking water use in pig diets while accounting for food-feed competition

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Abstract

Livestock feed production is one of the primary users of freshwater and arable land, and it is also in competition with human food production. Therefore, we require reconsideration of the way we use freshwater in livestock feed production. The objective of this study is to assess the impact on freshwater use of pork production by using alternative pig diets based on local feed ingredients, or by-products. We used a lifecycle approach to analyse the freshwater use associated with feed production to produce one kg of pork. We explored three feeding scenarios (STANDARD: diets commercially used in Ireland; LOCAL: diets based on ingredients grown in Ireland; and BY-PRODUCT: diets based on by-products only). We calculated the freshwater use, using the water footprint (WFP) method, and the competition for water use between food and feed production using the water use ratio (WUR) for each scenario. The WUR quantifies the maximum amount of human digestible protein (HDP) derived from food crops that could be produced on the same land, and using the same water resources, that were used to grow the feed ingredients needed to produce 1 kg of pork.

The WFP of the scenarios was 2,470 L/kg pork for STANDARD, 2,492 L/kg pork for LOCAL, and 2,205 L/kg pork for BY-PRODUCT. When we considered the WUR, none of the scenarios had a value < 1 (i.e. in all scenarios, more HDP can be produced from direct cultivation of food crops rather than pork). However, the BY-PRODUCT scenario (1.4) performed better than STANDARD (1.9) and LOCAL (2.9). Beet pulp and bakery by-products had zero WFP and no edibility and were thus considered promising ingredients. Moreover, rapeseed meal had a low WFP and rapeseed meal and sunflower seed meal are not considered human edible and were considered fit for future inclusion in diets. We also concluded that both the WFP and WUR methods have separate strengths and limitations, and should thus be used in conjunction; the ideal diet is one with the minimum WFP and WUR. Consideration of human edibility of feed ingredients is an important approach which should be included in future studies. Moreover, the entire food system including dairy, beef, poultry and other competitive uses should be taken into account when considering which feed ingredients to use in pig diets.

Highlights

- Freshwater use of Irish pork production was studied focusing on different pig diets.
- Freshwater use was assessed using the water footprint and water use ratio.
- Based on both methods, a diet formulated using by-products used the least water.
- Freshwater use assessment should consider human edibility of feed ingredients.

1. Introduction

Livestock production is responsible for about one third of global freshwater withdrawals (i.e. blue water use), primarily for the irrigation of feed crops (Poore and Nemecek, 2018). Furthermore, almost 40% of global arable land, and hence the coupled green water withdrawal (i.e. rainwater that is taken up by plants or evaporates), is used for animal feed production (Mottet et al., 2017). From a food security perspective, using these land and water resources to produce food that can be consumed by humans directly is much more efficient than using it to produce feed (Schlink et al., 2010; Foley et al., 2011). As global population is still rising, the pressure on land and water resources is expected to increase further. We, therefore, need to optimize the utilization of our natural resources to produce food, which implies, among others, rethinking freshwater use in animal production systems.

The pig sector is one of the largest livestock sectors globally (Bellini, 2021). Pig production in Europe is currently primarily carried out under intensive industrial land-less systems. As a result, it hugely depends on the import of feed from outside the farm (Meul et al., 2012). In pig production chain, feed production is the main contributor to freshwater use (70%), with green water being most important (79%), followed by blue water (21%) (Noya et al., 2016). On-farm processes contribute about 24% (González-García et al., 2015). One method to estimate the green and blue water use of food products (either plant or animal based) is ‘water foot-printing (WFP)’, which is defined as the volume of freshwater that is used directly or indirectly to produce the product, e.g. a unit (kg) of pork (Ercin et al., 2012).

Water foot-printing does account for the water use for cultivation of animal feed, but it does not explain the effect of redirecting this water, and the associated land, to cultivate crops for human consumption. Thus, although WFP helps us to understand the water resource competition from a blue water use perspective, since green water use is directly connected to land use, competition over the latter remains unclear. Thus, the question arises whether to use our current diminishing resources for production of animal feed (which can be either human edible or inedible) or for production of crops that are to be consumed by humans directly. The tension or trade-offs between uses of edible crops for animal feed or human consumption is defined as food-feed competition (van Zanten et al., 2018).

While pigs are efficient feed convertors, they currently consume high quality feed, and often consume more human edible protein than they produce (Mottet et al., 2017; van Zanten et al., 2018). Major ingredients fed to pigs that could also be used for human consumption include, among others, wheat, soybean, barley, and maize. To improve the sustainability of pig production, it is crucial to account for food-feed competition. To account for food-feed competition and to address the interlinkages between land and water resources, an alternative to the WFP method has been proposed, called the water use ratio (WUR; Ran et al., 2017). The WUR allows us to account for this competition by calculating the ratio between the maximum amount of human digestible protein (HDP) that could have been produced from food crops from all water used to produce one kg of animal product (e.g., pork), and the amount of HDP in that kg of animal product. If the WUR exceeds 1, then it means more HDP can be produced from food crops.

To improve the environmental sustainability of pig diets several researchers have studied the use of alternative feed ingredients to those with a high environmental footprint, such as imported soybeans and soybean meal (Meul et al., 2012). With regard to food-feed competition, there is growing interest in use of feed ingredients that are unsuitable for human consumption. These potentially viable by-products mainly come from grain fermentation, grain milling, bakeries, milk processing, meat processing, vegetable losses, sugar and starch production (Thaler and Holden, 2010). Inclusion of by-products (wheat bran, wheat middlings, dried citrus pulp, potato peels) in pig diets has been studied in relation to their nutritive value as pig feed (Kyriazakis and Emmans, 1995; Rosenfelder et al., 2013; Ncobela et al., 2017), and in relation to various environmental impacts, but not in relation to freshwater use. The environmental impact (i.e., acidification potential, eutrophication potential, global warming potential, nonrenewable energy use and nonrenewable resource use) of including co-products (meat meal, bakery meal, corn DDGS and wheat shorts) in grower/finisher diets, for example, was studied by Mackenzie et al. (2016) and it was found that increased inclusion of bakery meal and wheat shorts reduced all the studied impact categories.

Although by-products and locally grown ingredients have been included in pig diets previously to investigate whether they improve measures of sustainability, no detailed studies exist that calculated the WFP, or the WUR of diets based on locally grown ingredients or a diet completely based on by-products compared to that of a conventional diet. Thus, we hypothesize that alterations in feed composition (e.g., locally grown crops, other crops, residues or food waste) could reduce the freshwater use of pig farms while also reducing food-feed competition and make pig production systems more sustainable.

The objective of this study is to assess the impact on freshwater use of pork production when using alternative pig diets based on local feed ingredients, or by-products unsuitable for human consumption, based on a life cycle approach. To account for food-feed competition, the WUR was calculated in addition to the WFP. We have explored which feeding strategies (scenarios) can reduce the green and blue water use of pig diets including all production phases (gestation, lactation, weaners and finishers) and help in avoiding feed-food competition. For this study the conventional pig diets used in Ireland were used as the benchmark.

2. Material and Methods

Our study focused on the Irish pig production chain, so we formulated scenarios representing plausible diets with feed ingredients used in Ireland, including the ones that are imported into the country. We compared the freshwater use, expressed per kg pork, of three scenarios that differed in the types of ingredients used during gestation, lactation, the weaner and the finisher stage. This resulted in 12 diets in total, i.e., three potential scenarios in each of the four production stages (3x4). All the diets were applied to a standard Irish pig farm, which was simulated using the Teagasc Pig Production Model (TPPM; Calderón Díaz et al., 2019). This standard Irish pig farm was based on the performance figures from the National Pig Herd Performance Report for 2020 (Teagasc, 2020), and was defined as a farrow-to-finish system with an average herd size of 799 sows, weekly farrowing batches with a mean of 2.3 litters per sow per year, 14.3 piglets born alive per litter, a piglet mortality rate of 11.1%, a weaner mortality rate of 2.8%, a finisher mortality of 2.7%, and a resulting 27.5 pigs produced per sow per year. Pigs were sent to slaughter once they reach 115.3 kg.

2.1 Considered scenarios

The diets explored represent three scenarios: standard scenario (STANDARD) representing those diets typically and currently used commercially in Ireland; local scenario (LOCAL) considering diets based on ingredients grown in Ireland; and by-product scenario (BY-PRODUCT) consisting of diets formulated using entirely by-products. Diets were composed based on nutritional requirements without considering dietary costs. This allowed us to explore opportunities for reducing freshwater use without economic constraints. Table 1 shows the summary of diet composition with percentage of each feed ingredient used in all scenarios and production stages. The production stages considered in the study are gestation, lactation, weaners and finishers. Gilts are included in the gestation stage and they are fed the gestation sow diet. Grower-finisher stages are considered together in this study because in Ireland, these two stages are normally not separated, producers keep pigs in the same group from when they are about 35 kg to slaughter age. The detailed ingredients and diet composition of the studied pig diets can be found in Appendix A (Table A1). Nutritional needs for pigs (FEDNA, 2013) and the nutritional values for all the feed ingredients were taken from Fundación Española para el Desarrollo de la Nutrición Animal (FEDNA, 2019) and NRC feed ingredient tables (NRC, 2012). All the diets were formulated on dry-fed basis and as per the energy and nutritional requirements of the different stages, so animal performance was assumed to remain unchanged. A detailed description of the diets is given below.

Scenario 1: STANDARD

The standard scenario was based on the pig diets typically used in Ireland with the main ingredients being wheat, barley, maize, soyabean meal, full fat soya, soya hulls and soya oil. These diets were based on the reference diets used in Teagasc pig research facility (a 200 sow farrow to finish farm).

Scenario 2: LOCAL

The locally grown diets included ingredients which are commonly grown within Ireland and could be used in Irish pig diets instead of sourcing imported feed. The ingredients used were wheat, barley, field peas, rye, faba beans and rapeseed oil. Field peas and faba beans were mainly used to replace the protein rich imported soyabean used in the standard diets, and rapeseed oil was used to replace soya oil.

Scenario 3: BY-PRODUCT

The by-product diets were formulated using by-products that are commonly produced in or imported to Ireland, and frequently used in pig diets because of their nutritional value. The by-products included were wheat middling, rapeseed meal (RSM), bakery by-product, whey powder, sunflower seed meal (SSM), beet pulp, maize DDGS (distiller's dried grains with solubles) and soyabean meal (SBM).

2.2 Simulated farm data using TPPM

The Teagasc Pig Production Model (TPPM) is a stochastic model that simulates the annual production of a farm using biological (e.g. herd size, number of litters/sow/year, mortality %), physical (e.g. infrastructure) and technical (e.g. feeding practices) inputs to calculate physical (e.g. feed usage and number of pigs slaughtered) and financial outputs. The detailed feed usage and performance parameters of simulated pig farms, generated using the TPPM when provided with each of the three scenario diets for each production stage, are presented in Table 2.

Table 1: Diet composition per scenario and production stage

	Gestation	Lactation	Weaners	Finishers
STANDARD diet				
Barley	40%	30%	19%	11%
Wheat	30%	40%	33%	43%
Maize			13%	23%
Soyabean meal	11%	21%	21%	18%
Soya hulls	11%			1.8%
Full fat soya			6.2%	
Soya oil	1.0%	3.0%	4.0%	0.4%
LOCAL diet				
Barley	34%	20%	10%	7.9%
Wheat	33%	33%	20%	31%
Field peas	8.0%	19%	31%	21%
Faba beans	18%	23%	30%	25%
Rye				11%
Rapeseed oil		0.4%	4.5%	0.5%
BY-PRODUCT diet				
Wheat middlings	15%	34%	20%	31%
Rapeseed meal	7.5%			
Bakery by-product	30%	30%	45%	32%
Maize DDGS		6.0%		12%
Soyabean meal		10%	19%	8.5%
Whey powder	12%	15%	13%	13%
Sunflower seed meal	14%			
Beet pulp	16%	1.0%		

* Diet details in Appendix A (Table A.1)

2.3 Water footprint assessment

2.3.1 Freshwater use for crop cultivation

The WFP of a diet was calculated by weighing the WFP of each feed ingredient by its relative share in the diet. Data on the WFP of added minerals and vitamins are scarce, and as the share of these additives was almost comparable in all diets, we neglected to include the water use of these additives. We used the method described by De Boer et al. (2013) to calculate the green and blue water used for each feed ingredient.

To determine the country of origin of each feed ingredient, we first obtained the national feed import data for ingredients included in the standard and the by-products diet from the Feedingstuffs, Fertilizer, Grain and Poultry Division (FFGPD)

Table 2: Details of the simulated farm (using Teagasc Pig Production Model) for each scenario

	Scenarios		
	STANDARD	LOCAL	BY-PRODUCT
Feed usage, t/year			
Gestation	670	654	675
Lactation	430	448	436
Weaner	1270	1292	1346
Finisher	3762	3977	4773
Sales/year			
Culled sows and finisher pigs, #	21372	21372	21372
Meat sold, t/year#	1856	1856	1856
ADG* wean-to-sale, g	775	809	775
ADFI** wean-to-sale, g	1705	1783	2060
FCR*** wean-to-sale	2.20	2.20	2.66

*Average daily gain, **Average daily feed intake, ***Feed conversion ratio #Carcass weight including weight of culled sows and finisher pigs

Table 3: List of feed ingredients in STANDARD and BY-PRODUCT diets and country of origin

Feed ingredient	Country of Origin
Barley	United Kingdom
Wheat	United Kingdom
Maize	Ukraine, Canada
Soyabean and by-products	Argentina
Wheat middling	United Kingdom
Rapeseed meal	France
Bakery by-product	United Kingdom
Whey powder	Ireland
Sunflower seed meal	Portugal
Beet pulp	Ireland
Maize DDGS	Canada

of the Department of Agriculture, Food and the Marine (DAFM) of Ireland (Table 3). All ingredients in the LOCAL diet were grown in Ireland.

In each country, the International Food Policy Research Institute (IFPRI) grid data (IFPRI, 2019) were used to identify the regions/locations (coordinates) that are responsible for the highest national production. For the selected region, the predominant soil type was identified from the Harmonized World Soil Database v 1.2 (FAO/IIASA/ISRIC/ISS-CAS/JRC, 2012). The sowing dates of each crop and length of the growing period were either obtained from national databases (Teagasc, 2021 (personal communication) or, when not available, from global databases (USDA, 2020). The actual yield of the crop in the region with the highest production was calculated using the IFPRI grid data (IFPRI, 2019), and where not available data from FAO (2020) was used.

Second, the AQUASTAT climate information tool (AgERA5 dataset; Boogaard et al., 2020) was used to retrieve the climate data (mean temperature, mean sunshine etc.) and calculate the ET_o (reference evapotranspiration, millimeter/growing period) for the specific location based on the classic Penman-Monteith equation (Allen et al. 1998). These climate inputs and ET_o values were added to the CROPWAT-online, (on AQUASTAT) along with the crop type, sowing dates, cropping days and soil type to calculate the soil water balance and crop water requirements. Subsequently, the crop specific evapotranspiration (ET_p, millimeter) over the entire growing period was calculated, assuming maximum soil water availability. This was calculated by multiplying the crop coefficient (K_c) for the respective growth period with the reference crop evaporation (ET_o) per day, and summing these daily values for the entire crop growing period from sowing to harvest (Eq. 1).

$$ET_p = \sum Kc \times ET_o \qquad (1)$$

Rain-fed evapotranspiration (ET_{rf}, millimeter), i.e. the volume of the evapotranspired precipitation (green water) of a crop over its growth period, was derived from AQUASTAT. ET_{rf} for the crop growing period was calculated using Eq. (2)

$$ET_{rf} = \sum K_s \times ET_p \qquad (2)$$

Where Ks, the transpiration reduction factor, necessary to consider water stress, was calculated as a function of maximum and actual available soil moisture in the rooting zone derived from AQUASTAT. Also the values for effective root depth and soil water depletion fraction were taken from AQUASTAT. The consumption of rainwater (green) and irrigation (blue) water per kg of crop dry matter was calculated using the actual crop yields. To determine blue water use during crop cultivation, ET_{rf} was compared with the actual evapotranspiration of a crop (ET_a) based on actual yields. Evapotranspiration related to the actual yield (ET_a) (millimeters/year) was computed as follows (3):

$$ET_a = -\left((1-Y_a/Y_{mp}) \,/\, k_y - 1\right) \times ET_p \qquad (3)$$

where Y_a is the actual crop yield per hectare; Y_{mp} is the maximum potential crop yield per hectare; k_y is the yield response factor, which is crop specific and describes the relationship between ET deficit and yield reduction, and ET_p is the crop specific potential evapotranspiration (millimetres) as described above. The potential crop yield Y_{mp} was derived by multiplying the national average yield for the region with a factor of 1.2 (Reynolds et al., 2000).

If $ET_a \leq ET_{rf}$ then irrigation is assumed to be absent. If $ET_a > ET_{rf}$, irrigation volume was computed as follows (4):

$$\text{Irrigation volume} = (ET_a - ET_{rf}) \ / \ Ir_{eff} \qquad (4)$$

Where Ir_{eff} is the irrigation efficiency, which was assumed to be 0.7 for all crops, implying that per unit of irrigation water, 70% was taken up by the crop and 30% was lost (Allen et al., 1998). The waterfootprint of all ingredients are mentioned in Appendix B (Table B.1)

2.3.2 Water footprint of diets and per kg of pork

To compute the green and blue water use of each crop/ingredient the following method was used. Under rain-fed conditions, blue crop water use was zero, whereas green water use of the crop was calculated as follows (5):

$$\text{Green water use} = (Et_a \times 10) \ / \ \text{crop yield} \qquad (5)$$

where green water use is expressed in m^3 per tonnes, Et_a is expressed in millimeters per year, and the factor 10 is used to convert mm per year to m^3/ha, and crop yield is expressed in t/ha.

Blue water use of the crop during crop production is estimated by the irrigation volume for a specific crop grown in specific region, as follows (6):

$$\text{Blue water use} = (\text{Irrigation volume} \times 10) \ / \ \text{crop yield} \qquad (6)$$

where blue water use is expressed in m^3 per tonnes, irrigation is expressed in millimeters per year, and the factor 10 is used to convert mm per year to m^3/ha and, crop yield is expressed in t/ha.

Based on the consumptive green and blue water use per crop calculated above we computed the green and blue WFP (m^3/t) of each feed ingredient. This was done by multiplying the green and blue water use with the economic allocation factor of each crop/feed ingredient, divided by the amount of ingredient produced per unit of crop (t/t). The economic allocation factor for each feed ingredient was derived from databases (van Middelaar et al., 2011;Vellinga et al., 2013; Colomb et al., 2015; Wernet et al., 2016).

The total input of each diet (t/year) (gestation, lactation, weaner, and finisher) and the relative share of each feed ingredient in the diet (%) was used to calculate the amount of each feed ingredient in the diet (t/year). These values were then multiplied with the green and blue water use (m^3/t) to compute total green and blue water use of each crop ingredient per farm per year.

The WFP of all ingredients was summed up to get the total green and blue WFP of each diet.

To determine the amount of water used per kg of pork produced (associated with feed production) on the farm for each diet (gestation, lactation, weaners and finisher) under the three scenarios (STANDARD, LOCAL and BY-PRODUCT) we divided the green/blue water use (L) by the total amount of pork (kg) i.e. carcass weight, produced on the farm during the year.

2.4 Water use ratio

Water use ratio represents the maximum amount of human digestible protein (HDP) derived from food crops that could be produced on the same land and using the same water resources that were used to grow the feed ingredients to produce 1 kg of pig-meat. To determine food-feed competition and water use efficiency of the pig diets in the different scenarios we calculated the WUR according to Eq (7), as described by Ran et al. (2017):

$$\text{WUR} = \frac{\sum_{i=1}^{n}\sum_{j=1}^{m}\left(CWU_{ij} \times HDP_j\right)}{HDP\ of\ one\ kg\ pork} \qquad (7)$$

where CWU_{ij} is the consumptive water use in m^3, evapotranspired over a land area used to cultivate the amount of feed ingredient i (i=1,n) in country j (j=1,m) used to produce 1 kg of pork. HDP_j is the maximum amount of human digestible protein (HDP) that can be produced using the same water resources, by direct cultivation of food crops in country j. HDP values were corrected for protein quality by multiplying the crude protein values with the digestible indispensable amino acid score (DIAAS), which is a measure of protein quality of a food product. It is based on the lowest score of the true ileal digestibility of the indispensable amino acids that are present in product (Rutherfurd et al., 2015). The denominator is the amount of HDP in 1 kg of pork. To determine the direct value of protein in animal feed that is human edible we modified the methodology to include human edible portion (HEP) of feed ingredients and protein quality based on Hennessy et al. (2021).

Table 4: Crude protein (CP) values, Human Digestible Protein (HEP) and protein digestibility scores (DIAAS) of pork and food crops and by-products.

	kg DM/kg product	g CP/kg DM	Estimated HEP %	DIAAS %
Pork	0.50[a]	139[a]	78[g]	114[c]
Wheat	0.90[a]	125[a]	66[b]	40[c]
Barley	0.90[a]	110[a]	61[b]	47[c]
Maize	0.90[a]	105[a]	15[b]	42[c]
Soybean	0.99[a]	399[a]	61[b]	100[c]
Oats	0.92[a]	184[a]	80[e]	57[e]
Peas	0.21[a]	54[a]	74[b]	65[c]
Faba beans	0.89[a]	261[a]	92[b]	57e
Rye	0.89[a]	116[a]	72[b]	48[c]
Wheat middlings	0.88[f]	143[f]	90[b]	70[f]
Whey powder	0.96[f]	110[f]	80[b]	90[f]
Soyabean meal	0.90[f]	470[f]	60[b]	86[f]

[a] USDA, 2015; [b] Lassie et al., 2019; [c] Ertl et al., 2016; [d] Wilkinson 2011; [e] Hennessy et al., 2021; [f] Fedna 2013; [g] Ockerman and Hansen, 1988

2.4.1 Human digestible protein in food crops and pork

To determine the HDP in food crops, we first quantified the amount of consumptive water resources (CWU_{ij}) required to grow each feed ingredient (i=1, n) in the different countries of origin (j=1, m), used to produce 1 kg of pork. This was done by calculating the WFP of each feed ingredient as explained in section 2.3.2. Second, the suitability of the same land area to cultivate food crops using the crop suitability index defined by Global Agro-Ecological Zones (GAEZ) database (IIASA and FAO, 2012). Crop suitability in this database is defined by eight groups (not suitable to very high), depending on the crop requirements, climatic conditions, soil properties and management practices. We evaluated the crop suitability for the current cultivated land based on high input levels, optimal water supply and baseline climatic conditions (1961-1990). Crops falling within the suitability index >55 (i.e. good, high or very high) were considered suitable for cultivation on that land.

Based on the suitability of the crops, we selected the crop which had the highest yield and protein content. Then, we determined which crop had the highest HDP by multiplying the amount of food crop produced per hectare for each suitable crop with its dry matter content, HEP, crude protein content and DIAAS (Table 4).

Once the most suitable crop (i.e. the one with the highest HDP) was selected, we determined the WFP of cultivating that food crop in the same region, replacing the feed ingredient. Next, we assessed how much of this food crop (kg) could be produced using the same water resources used to produce the amount of that feed ingredient needed to produce 1 kg of pork. Then we calculated the HDP_j in the selected food crop that replaced the feed ingredient. The sum of all the HDP in all the feeds per scenario form the numerator of the WUR equation. To assess the denominator, i.e., the amount of HDP in 1 kg edible pork, we multiplied the crude protein content and DIAAS (Table 4).

A ratio larger than 1 indicates that a larger amount of HDP can be produced from food crops rather than pork and a ratio below 1 means that through livestock production we can produce more HDP rather than direct food crop cultivation.

2.4.2 Water use ratio of the three scenarios

In the case of the main feed crops which are human edible such as wheat, barley, peas, faba beans etc. we calculated the WUR by directly calculating the HDP of these crops or by replacing them with another crop as described in section 2.4.1. Unlike other (van Zanten et al., 2016; Ran et al., 2017) studies that calculated the land use ratio (LUR) or WUR of animal-sourced food products, we also accounted for food-feed competition in the case of the by-products which was not considered in these studies. To do so, we followed two approaches. In the first approach, for by-products that are human edible or have a human edible portion (e.g., wheat middlings, whey powder and soybean meal), we calculated the HDP, as if humans could have consumed these by-products directly. By-products that do not have a human edible portion were assigned a value of zero. In the second approach, we used economic allocation, to calculate how much HDP could have been produced by cultivating food crops based on the same procedure as for the main ingredients.

Sugar beet pulp and bakery by-products do not have a human edible portion so have a HDP of zero, and they also have an economic value close to zero. Rapeseed meal, sunflower seed meal and maize DDGS also do not have any human edible portion (i.e. HEP = 0), but because of their economic value they were replaced by another food crop with higher HDP. In the case of whey powder, the maximum HDP was based on the HEP of whey powder (so no alternative application of water resources). Economic allocation factors of all ingredients are listed in Appendix B (Table B.2) (van Middelaar et al., 2011; Vellinga et al., 2013; Colomb et al., 2015; Wernet et al., 2016).

3. Results

3.1 Water footprint of the three scenarios

Table 5 shows the WFP of pork associated with feed production (i.e. partial WFP) in each of the three scenarios, broken down into green and blue water, and the contribution per production stage, expressed in liters per kg of pork. The total WFP was 2470 L/kg pork for STANDARD, 2492 L/kg pork for LOCAL, and 2205 L/kg pork for BY-PRODUCT. The WFP for the STANDARD scenario consisted entirely of green water, whereas that of LOCAL and BY-PRODUCT included blue water (227 L/kg pork in case of LOCAL and 5.0 L/kg pork in case of BY-PRODUCT) arising from the peas, faba beans and whey powder added to the diets.

Table 5: The water footprint of pork associated with feed production, divided between green and blue water, and the contribution per production stage (L/kg pork) per scenario.

Stage/Diet	STANDARD	LOCAL		BY-PRODUCT	
	Green WFP (L/kg pork)	Green WFP (L/kg pork)	Blue WFP (L/kg pork)	Green WFP (L/kg pork)	Blue WFP (L/kg pork)
Gestation	226	198	10	463	0.41
Lactation	181	149	14	112	0.35
Weaner	640	512	64	342	0.92
Finisher	1424	1403	138	1284	3.3
Total	2470	2265	227	2200	5.0

Among all the scenarios and production stages, the finisher stage (58-66%) contributed most to the WFP (green and blue water), followed by weaners (16-28%), gestation (5-21%) and lactation stages (5-7%). The diet composition and distribution of water use per feed ingredient per kg pork is presented in Figure 1 (Appendix B; Table B.3 also provides a list of diet composition and water use per feed ingredient). In the STANDARD scenario the highest contribution to the WFP of pork was from soyabean meal followed by wheat, maize and barley. In the LOCAL scenario, the highest contribution was from peas and faba beans. These crops also contributed to the blue

WFP for the LOCAL scenario. In the BY-PRODUCT scenario, almost half of the WFP of pork was related to water use for the production of whey powder and soyabean meal, being by-products from cheese and soyabean production, although they only constituted 14% and 16% of the diet on a dry matter basis (Table 1). Beet pulp and bakery by-products are wastes arising from human food industry and are commonly used in the manufacture of compound feeds. They have no economic value so all of the water used is allocated to production of the main product and the respective products have a WFP of zero when using economic allocation.

3.2 Water use ratio

The water use ratios (WUR) of pork for the three scenarios are presented in Fig. 2. The WUR accounts for food-feed competition and the fact that water resources used for animal feed production can potentially support food crops for humans. The BY-PRODUCT scenario resulted in the lowest WUR, followed by the STANDARD and LOCAL scenarios. In the STANDARD and LOCAL scenarios, the two approaches used to calculate the WUR resulted in similar values. The WUR values show that per kg HDP in pork, we could potentially produce approximately 2 kg HDP (STANDARD) and approximately 3 kg HDP (LOCAL) from food crops directly, using the same water resources. In the BY-PRODUCT scenario, the two approaches to calculate WUR did result in slightly different outcomes. The first approach (only edible by-products contribute to food-feed competition) resulted in a WUR of 1.3, while the second approach (all by-products with an economic value contribute to food-feed competition) resulted in a WUR of 1.6. The second approach results in a slightly higher WUR as this approach accounts for the potential alternative use of water resources in case human inedible by-products do have an economic value, while the first approach does not include an alternative water use if the byproduct is human inedible. For example, rapeseed meal and sunflower seed meal have no human edible portion but an economic value of 23% and 20% respectively. Thus, using the second approach, the water use allocated to those products could potentially be used to produce a food crop. The fact that even the first approach results in a WUR > 1 shows that even though by-products were the only ingredients, the proportion of human edible products used in the BY-PRODUCT scenario is still high. Because the results were so similar, the different WUR approaches did not affect the comparison between scenarios.

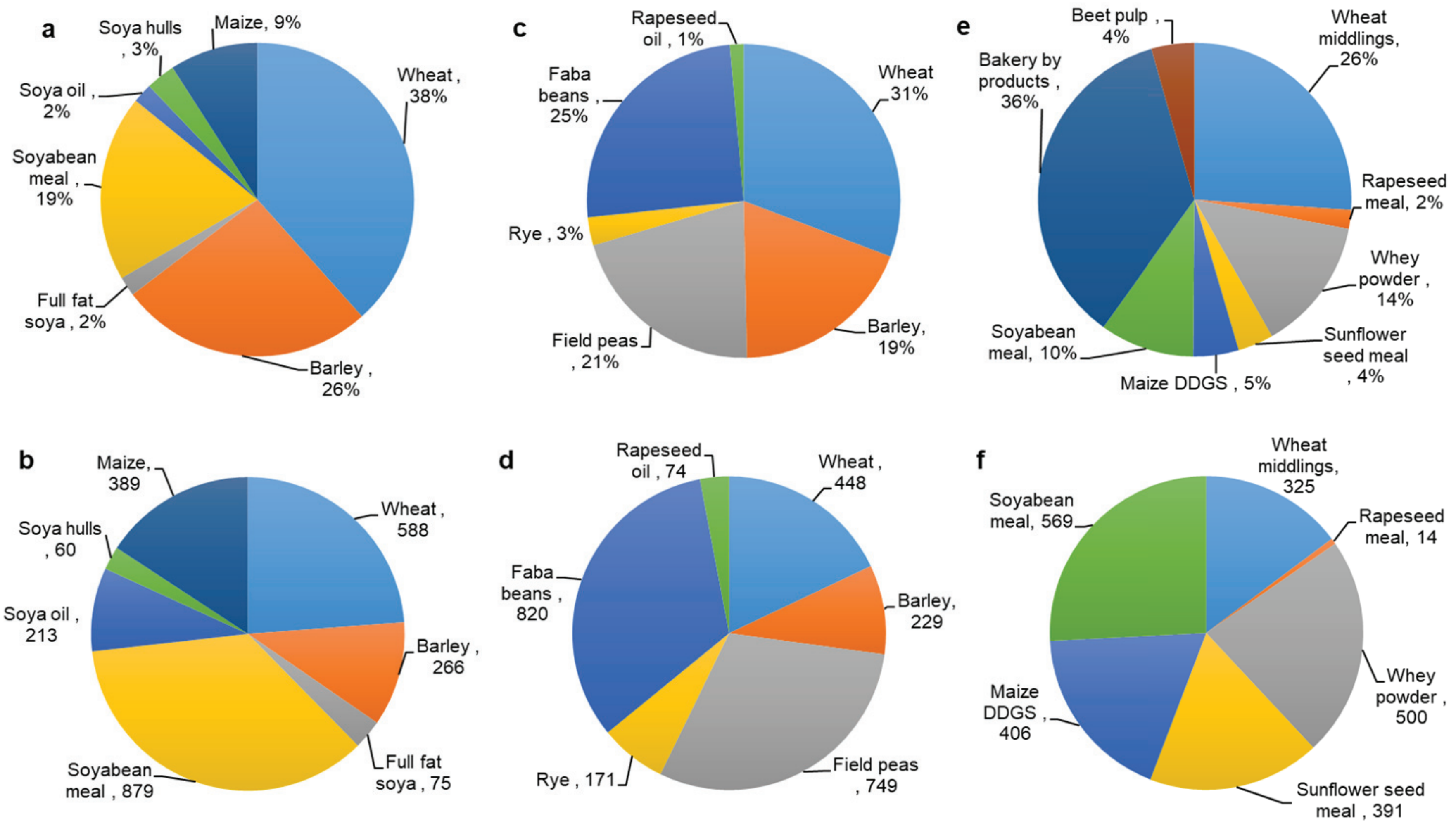

Figure 1: Diet composition (% of ingredients per kg DM) by scenario: STANDARD (a), LOCAL (c) and BY-PRODUCT (e) and consumptive water use (CWU in liters/kg pork) per ingredient by scenario: STANDARD (b), LOCAL (d) and BY-PRODUCT (f) (Appendix B; Table B.3 provides the tabulated data for the diet composition and consumptive water use)

When we compare the results of WFP and WUR (Fig. 2), it is evident that while for the WFP method results for the STANDARD and LOCAL scenarios are comparable, the WUR of the STANDARD scenario is lower than that of the LOCAL scenario. Regardless of the method used, the BY-PRODUCT scenario has the lowest water use.

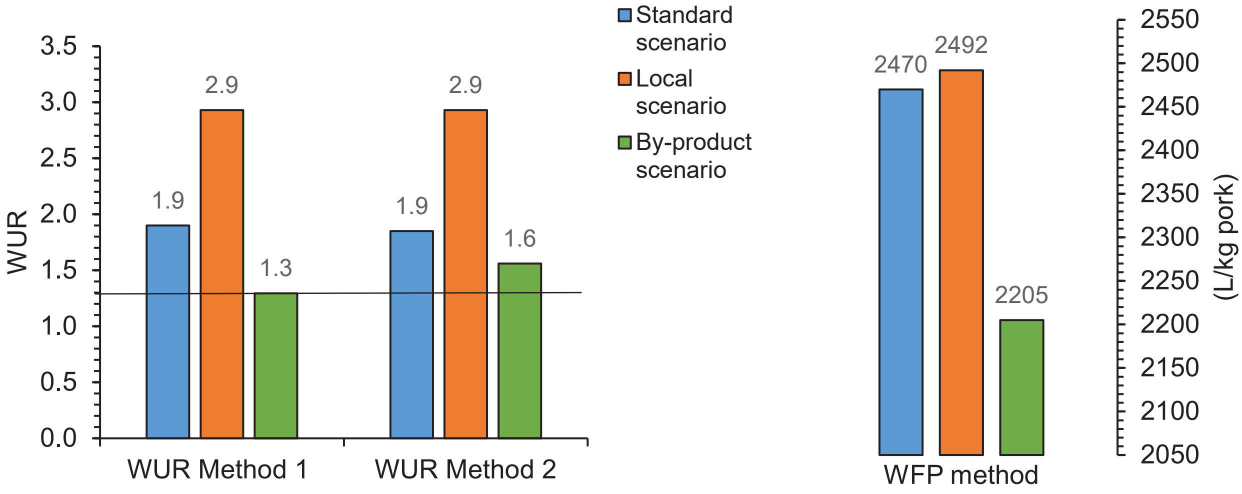

Figure 2: Water use ratio (WUR) and the WFP (associated with feed production) L per kg pork of the three scenarios.

4. Discussion

This study aimed to investigate the impact of alternative pig diets based either on locally grown feed ingredients, or food crop by-products, on the freshwater use of pork production. We used a life cycle approach to calculate the WFP of pork, focusing on freshwater use related to feed production only. The Irish pig production system was taken as a starting point and feed ingredients grown in Ireland and imported into Ireland were included. This study also considered competition for water resources between food and feed production for both the local and by-product scenarios relative to a typical commercially used pig diet by calculating the WUR of pork for each scenario. Below, we will discuss the results from both analyses (WFP and WUR), and suggest options for altering feed composition to shift to a more sustainable use of water resources.

4.1 Significance of WFP and WUR results

4.1.1 WFP of the three scenarios

The WFP calculations showed that the STANDARD and LOCAL scenario result in similar WFP values (liters per kg pork), while in case of the BY-PRODUCT scenario, the WFP was about 12% lower. The factors that influence this partial WFP of pork are the composition of the diet (i.e., the share of each ingredients in the diet), the feed requirements per kg pork produced, and the WFP of each feed ingredient. In practice, diet composition is affected by the price, the availability, and the nutritional value of the single ingredients.

In the STANDARD scenario three ingredients contributed 75% of the total WFP of pork; soyabean meal (1498 m^3/t meal), maize (977 m^3/t maize from Ukraine; 520 m^3/t maize from Canada) and wheat (451 m^3/t wheat). Previous researchers (Mekonnen and Hoekstra, 2010) have also concluded that, wheat, maize and soyabean have the largest share in the total WFP. The high WFP of the LOCAL diet is mainly driven by field peas (green WFP 777 m^3/t peas; blue WFP 245 m^3/t peas) and faba beans (green WFP 895 m^3/t beans; blue WFP 55 m^3/t), as they explain 63% of the WFP of pork and constitute 46% of the dry matter of the diet. Beans and peas have a high WFP due to their lower yield, which means that more water is used per kg of beans and peas (Mekonnen and Hoekstra, 2010). Although in Ireland peas and beans are not irrigated, our results show a small blue WFP for both products. This can be explained by a divergence between the yield data and the climate data in case of those two crops. As field peas and beans are only recently grown in Ireland, yield data was derived from FAO (2020) and based on the years 2016-2019 for peas and 2018-2019 for beans, while the climate dataset (AgERA5) we used for the WFP calculations was from 1979 to present. For all other crops, yield data was based on IFPRI (2019) and therefore in line with the climate data. Conversely, although wheat constitutes 31% of the dry matter of diets used in the LOCAL scenario, it has a lower contribution to the total WFP of pork due to its lower WFP (448 m^3/t wheat).

In the BY-PRODUCT scenario, soyabean meal contributes 26% to the WFP but constitutes only 10% of the dry matter of the diet. Another by-product, whey powder, a by-product of cheese production from milk, contributes 23% to the WFP even though it forms only 14% of the dry matter of the diet. Similarly, maize DDGS and sunflower seed meal in the BY-PRODUCT scenario is only 5% of the dry matter, but the WFP contribution is 18%. Thus, the high WFPs of each of the four diets in this scenario can be attributed to the input of these four ingredients. Sunflower seed meal contributes most to green water use (7971 m^3/t meal) followed by soyabean meal (1498 m^3/t

meal), maize DDGS (1258 m^3/t DDGS) and whey powder (983 m^3/t powder). Moreover, whey powder is the only ingredient in the BY-PRODUCT scenario with a small proportion of blue water use (9.9 m^3/t powder), in addition to the green water use. In case of the BY-PRODUCT scenario, by-products used in the diet such as whey powder, maize DDGS and wheat middlings, all have a high WFP mainly because of the high ratio between inputs- and outputs (i.e. to produce small quantities of whey powder, relatively large volumes of milk are required), and therefore these ingredients have an important influence on the WFP of pork. To reduce the contribution to the WFP by soyabean meal and sunflower seed meal, we considered replacing it with alternatives such as rapeseed meal (507 m^3/t meal), which is produced in Europe and has a lower WFP. Indeed, a recent review by Lannuzel et al. (2021), concluded that rapeseed meal is a promising ingredients in terms of reducing reliance on imported soya and have competitive prices. However, the protein and lysine contents are lower and fiber contents are higher than soyabean meal which limits its inclusion in monogastric diets. The finisher stage is the main contributor to the total WFP. So that our results would be commercially relevant we formulated all three scenario diets so that the animals would have similar growth-rates, consistent with those typically found on Irish pig farms. As such, the inclusion of these identified alternatives to soyabean meal was not feasible.

Nevertheless, the WFP results show that by-products with a WFP of zero (in this case bakery by-products and beet pulp) or low WFP rapeseed meal (507 m^3/t) hold promise as ingredients that can reduce the total diet WFP. Reconsidering current growth rates might be required to enable the inclusion of ingredients of lower qualities, contributing to lowering the WFP of pork.

4.1.2 WUR results

Comparison of the WUR of the various diets allows us to compare how the competition between food and feed production varies across the scenarios. Our findings that the WUR of the BY-PRODUCT scenario was lower than both the standard and local ones clearly demonstrated the benefits of this diet over the others, using this metric. For both the LOCAL and STANDARD scenarios most of the ingredients used in the diets were human edible, and the WURs were the same whether the edibility or economic value of the ingredients was used in the calculations. However, in the BY-PRODUCT scenario there was a slight difference in the WUR, whereby WUR based on edibility was lower than when based on the economic value of ingredients.

According to a recent study on LUR (Hennessy et al., 2021), all the feed used in standard pig diets originates from arable crop production, therefore resulting in food-feed competition. However, in our study we formulated diets including crop by-products or waste, considered feasible based on expert judgement. We used the optimum growth performance approach for pigs, which meant that diets needed to meet the required energy demand. Thus, we ended up including some energy and nutrient rich human edible by-products in the diets such as whey powder, wheat middlings and soyabean meal. From the perspective of food-feed competition inedible by-products like bakery by-products, beet pulp, rapeseed meal and sunflower seed meal are preferred. Consequently, if we allow for a lower growth performance, the selection of by-products could shift to those not edible and with less energy and protein, potentially resulting in lower WUR.

Apart from the WFP approach that was used in this study, literature also categorizes other methods commonly used to quantify freshwater use in livestock production (Ran et al., 2016). These methods include water productivity assessment and other LCA based methods. While water productivity assessment doesn’t differentiate between green and blue water use, LCA methods normally only focus on blue water use. Thus, for our study we chose to use the WFP assessment to quantify both green and blue water use of pig feeding scenarios and to combine this assessment with a WUR method to determine the impact on food-feed competition.

4.2 Water use assessment methods

Green water constitutes a major part of pig diets (Mekonnen and Hoekstra, 2012), and indeed in the current study STANDARD scenario has 100% green water use. Even though the LOCAL and BY-PRODUCT scenarios incorporated some blue water use, the vast majority was green water use (91% and 99.8%). Inclusion of green water in water use assessment studies has historically been controversial since it is not associated with water stress; nevertheless, its inclusion can help in reducing the total water use of food production (Ran et al., 2017). Moreover, green water also plays a crucial role in food-feed competition since most of the feed ingredients used in the pig diets are human edible. Green water use is associated with arable land and therefore, human edible feed crops grown on this land are in direct competition with human food and by-products have an indirect competition for resources.

The benefit of using both the WFP and WUR methods is that they provide insights that are complementary to each other: while WFP accounts only for the water use for cultivation of animal feed, the WUR explains the effect of redirecting this water and the connected land use to cultivate crops for human consumption. Both methods are needed and should be used in conjunction because WFP helps us to identify the crops which are not water intensive and therefore more suited for animal feed, but it does not show alternatives where this water can be diverted and it does not reflect the increased pressure on arable land use. On the other hand, the WUR helps us to compare livestock systems and food crop production, and determine which systems use water most efficiently to produce human edible protein while accounting for food-feed competition. The WUR shows us that by using crop residues/by-products it is possible to convert human non-edible feed products into food (pork).

When calculating food-feed competition based on the WUR we used two methods, edibility and economic value of the product. Previous studies that calculated food-feed competition using either or both LUR or WUR assumed the economic value of by-products to be zero and did not consider their edibility. This approach does not reflect the true competition for resources and overestimates the resource use of the entire system (van Zanten et al., 2018). Therefore, economic value and human edibility are additional criteria which should be used when calculating the WUR. However, in our study we saw that economic allocation alone did not make any difference to the WUR, because most of the feed ingredients were human edible. Thus, using more inedible by-products in the diets might lead to less arable land use for animal feed production, and the unused land can be used for growing food crops. However, selecting by-products should be done carefully based on their palatability and nutritional profiles as both can impact on overall pig performance. Moreover, to optimize the use of by-products in the diets and lower the overall WFP, we should follow an entire food system approach, thus considering other production systems like dairy, beef and poultry which pose competitive uses.

To verify our results, a sensitivity analysis was carried out to assess the impact of changing some of the main parameters to calculate the WFP and WUR values. For the WFP values, we changed the evapotranspiration values and maximum potential yields of crops by 10%. These changes did not alter the conclusion that the WFPs of pork were similar for the STANDARD and LOCAL scenarios, while that for the BY-PRODUCT scenario was lower. For the WUR values, we adapted the HEP values based on the *potential* human edible protein values reported by Lassie et al. (2019). The final conclusion of our study did not change and the WUR of pork was lower for the BY-PRODUCT scenario than for the other two scenarios. The final graphs of the sensitivity analysis are added to Appendix C.

4.3 Future research and feeding systems

Future water use assessments should focus on valorizing only the inedible food wastes and crop by-products for inclusion in pig diets. A wide range of by-products are available from the grain milling, baking, brewing, fruit and vegetable processing and other industries, some of which are already used in the present system. A recent study (van Hal et al., 2019) also concluded that feeding livestock only with low-opportunity cost feed such as food waste and food processing by-products can provide some nutritious animal source food while reducing competition for land resources. Future feeding systems should consider the exact inclusion levels of different by-products so that they have minimal impact on growth performance. It is also important to consider that by-product-based diets could be cheaper than traditional diets, and the savings could offset costs associated with reduced growth rates. Detailed cost: benefit analysis should be carried out in tandem with investigation of water use assessment. Apart from use in animal feed, there are many other competitive uses of by-products such as for fuel and fibre production. Thus, availability of by-products should also be considered and making all conclusions based on WFP and WUR is not entirely correct.

Our data demonstrate that based upon both WFP and WUR calculations, by-product-based diets hold promise to promote sustainable water use. However, increasing the proportion of by-products used in pig diets will require a change in farming practices and moving from a more profit based to a more circular and sustainable approach. Crop by-products generally have large variability in nutritional value and physical characteristics and thus more knowledge is required about the best handling and processing methods to include these as feed ingredients (Boumans et al., 2022). To include crop by-products in pig diets we need more insight into their nutritional value, palatability, intake and digestibility, as well as into the impact on pig performance and well-being. Indeed, future research should also focus on understanding consumer perception of diverting from the current consumption pattern of a high animal source food diet to a moderate animal source food diet. Therefore, feedback from livestock producers and consumers is critical if we want to move towards a circular livestock production system.

5. Conclusion

When we compared three scenarios STANDARD, LOCAL and BY-PRODUCT based on the WFP and WUR methods, the BY-PRODUCT scenario used the least water and had the lowest impact on food-feed competition. The results of the WFP assessment show that the most promising ingredients are rapeseed meal, bakery by-products and beet pulp as they have a lower or no water use. The results of the WUR assessment suggest that all the human inedible by-products i.e. bakery by-products, rape seed meal, beet pulp and sunflower seed meal are best suited for reducing food-feed competition. In conclusion, water use assessment should focus on both WFP and WUR in conjunction, and human edibility of the feed ingredients is an important criteria to determine which ingredients will reduce the competition over water resources between food and feed production in the future.

6. Acknowledgements

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Appendix A

Table A.1: Composition of all the diets belonging to the three scenarios

Ingredients and nutritional composition of the three scenarios for all the production stages. All ingredient inclusions shown in g/kg as fed, all nutrient levels shown as % as fed unless otherwise stated.

	Standard				Local				By-product			
	Gestation	Lactation	Weaners	Finishers	Gestation	Lactation	Weaners	Finishers	Gestation	Lactation	Weaners	Finishers
Barley	400.0	300.0	188.5	105.0	340.0	200.00	100.0	79.1				
Wheat	300.0	400.0	327.3	433.5	330.0	325.00	200.0	310.0				
Maize	0.00	0.00	132.0	225.3								
Soyabean meal (SBM)	110.0	214.0	206.0	176.0					0.00	100.0	190.0	85.0
Full fat soya	0.00	0.00	61.6	0.0								
Soya hulls	110.9	0.00	0.00	18.0								
Soya oil	10.0	30.0	40.0	4.00	0.00	3.50	45.0	4.50				
Field peas					80.0	190.00	310.0	207.1				
Faba beans					180.0	230.00	300.0	250.0				
Rye					0.00	0.00	0.00	110.0				
Wheat middlings									150.0	340.0	200.0	305.0
Bakery byproduct									300.0	300.0	450.0	319.0
Rapeseed meal (RSM)									75.0	0.00	0.00	0.00
Wheypowder									115.0	150.0	128.0	130.0
Sunflower seed meal (SSM)									135.0	0.00	0.00	0.00
Beet pulp									160.0	10.0	0.00	0.00
Maize DDGS									0.00	60.0	0.00	120.0
CaCO3	13.0	14.0	6.00	11.0	14.2	11.0	5.00	9.50	12.5	18.0	10.1	10.6
Di calcium phosphate	16.8	15.5	15.7	10.0	15.8	20.0	18.5	12.0	2.00	2.50	3.90	0.00
HCl Lys	0.00	0.70	5.80	2.60	0.00	0.70	4.40	0.45	0.00	1.60	5.90	2.98

Table A.1 Continued

DL-Methionine	0.00	0.00	1.40	0.40	0.10	0.90	3.60	1.29	0.00	0.01	1.70	0.20
L-Threonine	0.00	0.00	2.30	0.30	0.00	0.60	3.00	0.50	0.00	0.00	1.90	0.00
L-Tryptophan	0.00	0.00	0.40	0.00	0.00	0.20	1.10	0.30	0.00	0.00	0.40	0.00
Salt	3.94	4.50	4.00	3.80	4.00	4.00	4.00	4.00				
Vit/Min	35.4	21.3	9.00	10.1	35.9	14.1	5.40	11.4	50.5	17.9	8.10	27.2
Nutrients												
ME (MJ/kg)	12.2	13.5	14.3	13.3	12.5	12.9	14.0	13.1	12.1	13.2	13.9	13.1
NE (MJ/kg)	8.92	10.1	10.7	9.94	9.35	9.56	10.4	9.71	8.55	9.60	10.2	9.61
Dig Lys	0.53	0.81	1.29	0.85	0.55	0.77	1.24	0.79	0.51	0.79	1.27	0.83
Trp min	0.17	0.23	0.28	0.20	0.15	0.18	0.28	0.19	0.19	0.20	0.27	0.19
Met total min	0.22	0.27	0.42	0.29	0.19	0.27	0.54	0.31	0.29	0.27	0.44	0.29
Thr total min	0.49	0.63	0.91	0.59	0.46	0.60	0.92	0.61	0.59	0.64	0.88	0.61
Crude protein	14.2	18.0	19.6	16.4	14.2	16.4	19.1	16.8	15.3	17.1	19.2	16.9
Ca	1.04	1.02	0.73	0.77	1.00	0.98	0.73	0.73	1.00	0.99	0.72	0.71
P	0.60	0.63	0.64	0.52	0.60	0.69	0.67	0.55	0.63	0.70	0.62	0.67
Dig P	0.32	0.32	0.33	0.24	0.31	0.38	0.37	0.28	0.26	0.33	0.30	0.32

Appendix B

Table B.1: Water footprint of all feed ingredients

Feed ingredients (Origin)	Green WFP (m^3/ton)	Blue WFP (m^3/ton)
Wheat (UK)	451	0
Wheat (Ireland)	448	0
Barley (UK)	479	0
Barley (Ireland)	563	0
Maize (Ukraine)	977	0
Maize (Canada)	520	0
Soyabean meal (Argentina)	1498	0
Full fat soya (Argentina)	1898	0
Soya hulls (Argentina)	779	0
Soya oil (Argentina)	4621	0
Faba beans (Ireland)	895	55
Peas (Ireland)	777	245
Rye (Ireland)	726	0
Rapeseed oil (Ireland)	1780	0
Wheat middlings (UK)	306	0
Bakery by-products (UK)	0	0
Whey powder (Ireland)	983	9.93
Beet pulp (Ireland)	0	0
Rapeseed meal (France)	507	0
Sunflower seed meal (Portugal)	7971	0
Maize DDGS (Canada)	1258	0

Table B.2: Economic allocation factors of all feed ingredients

Feed ingredients	Economic allocation factor
Wheat	0.78
Barley	0.75
Maize	1
Soyabean meal	0.556
Soya hulls	0.031
Soya oil	0.341
Faba beans	1
Peas	1
Rye	0.70
Rapeseed oil	0.756
Wheat middlings	0.066
Bakery by-products	0
Whey powder	0.079
Beet pulp	0
Rapeseed meal	0.234
Sunflower seed meal	0.203
Maize DDGS	0.1935

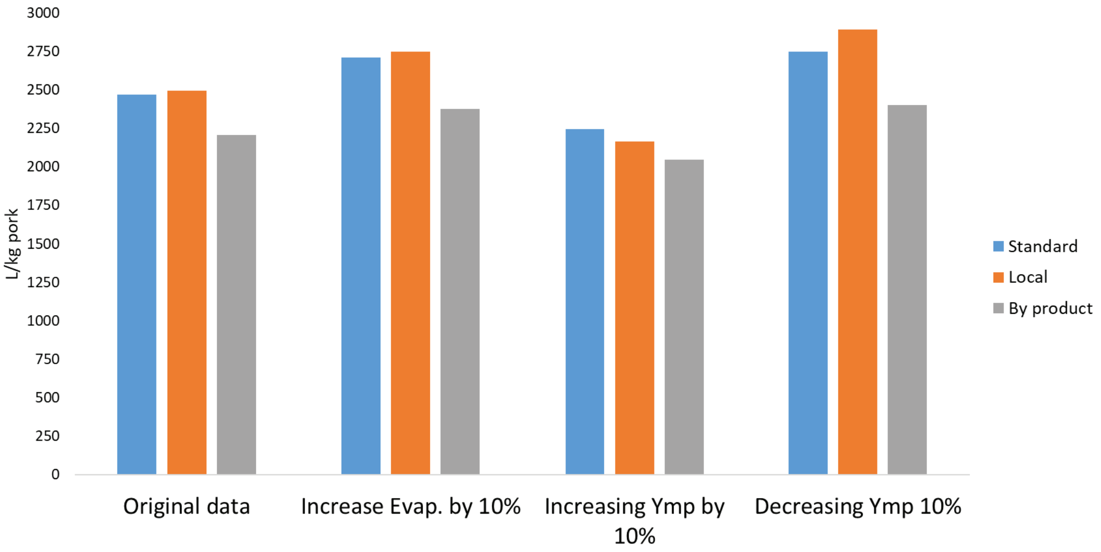
Table B.3: Dry matter (%) and Consumptive water use (CWU in liters/kg pork) of ingredients by scenario: STANDARD, LOCAL and BY-PRODUCT

Feed ingredients	STANDARD		LOCAL		BY-PRODUCT	
	Dry matter %	CWU L/kg pork	Dry matter %	CWU L/kg pork	Dry matter %	CWU L/kg pork
Wheat	38%	588				
Barley	26%	266				
Full fat soya	2%	75				
Soyabean meal	19%	879				
Soya oil	2%	213				
Soya hulls	3%	60				
Maize	9%	389				
Wheat			31%	448		
Barley			19%	229		
Field peas			21%	749		
Rye			3%	171		
Faba beans			25%	820		
Rapeseed oil			1%	74		
Wheat middlings					26%	325
Rapeseed meal					2%	14
Whey powder					14%	500
Sunflower seed meal					4%	391
Maize DDGS					5%	406
Soyabean meal					10%	569
Bakery by products					36%	0
Beet pulp					4%	0

Appendix C: Sensitivity analysis of HEP and WFP values. Results of WUR and WFP are presented in the graphs below.

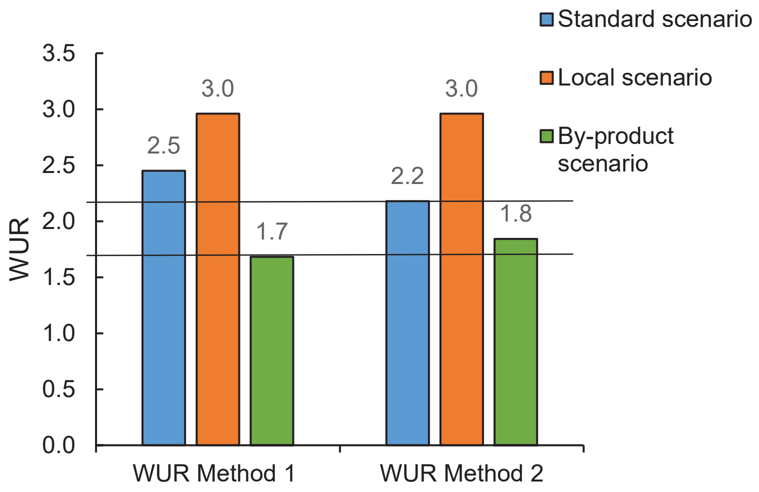
STANDARD scenario- Reference pig diets from Ireland, LOCAL scenario-all feed ingredients grown in Ireland, BY-PRODUCT scenario-only by-product based diet

WFP results



Original data are our main results presented in the paper, Increase Evapotranspiration values 10% -we increased all the Eto, Etp and Etrf values by 10%, Increased and decreased the maximum potential yields (Ymp) by 10%

WUR ratio results



Chapter 4

Effect of different cleaning procedures on water use and bacterial levels in weaner pig pens

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Abstract

Pork is one of the most globally eaten meats and the pig production chain contributes significantly to the water footprint of livestock production. However, very little knowledge is available about the on-farm factors that influence freshwater use in the pig production chain. An experiment was conducted to quantify the effect of three different washing treatments on freshwater use, bacterial levels [(total bacterial counts; TBC), *Enterobacteriaceae* and *Staphylococcus*] and cleaning time in washing of pens for weaning pigs. Three weaner rooms were selected with each room having 10 pens and a capacity to hold up to 14 pigs each. Pigs were weaned and kept in the pens for 7 weeks. Finally, the pens were cleaned before the next batch of pigs moved in. The washing treatments used were power washing and disinfection (WASH), pre-soaking followed by power washing and disinfection (SOAK), and pre-soaking followed by detergent, power washing and disinfection (SOAK + DETER). A water meter was used to collect water use data and swab samples were taken to determine the bacterial levels. The results showed that there was no overall effect of washing treatments on water use. However, there was an effect of treatment on the washing time (p<0.01) with SOAK and SOAK+DETER reducing the washing time per pen by 2.3 minutes (14%) and 4.2 minutes (27%) compared to WASH. Nonetheless, there was an effect of sampling time (before or after washing) (p<0.001) on the levels of TBC and *Staphylococcus*, but no effect was seen on *Enterobacteriaceae* levels. Thus, the washing treatments used in this study had no effect on the water use of the pork production chain. Although there was no difference in both water use and bacterial load, from a producer perspective, presoaking and detergent use can save time and labour costs, so this would be the preferred option.

1. Introduction

Depletion of freshwater resources is an important environmental issue, with the livestock sector being responsible for 33% of global water withdrawals (Poore and Nemecek, 2018). Freshwater use in livestock production is often quantified using “water footprinting” (Mekonnen and Hoekstra, 2012), which can be defined as the volume of freshwater used per unit of product produced (usually m^3/ton). It is divided into green (rain water evapotranspired during crop cultivation or embedded in crops), blue (irrigation water) and grey (virtual freshwater used to assimilate pollution (Ercin et al., 2012)) water. Pork is one of the most globally eaten meat products and its consumption is projected to increase further (Henchion et al., 2014). Detailed knowledge of blue water use in pig production and the on-farm factors that influence it is missing from the literature; the weighted global average blue water footprint for pork is 459 m^3/ton (cradle-to-farm gate), which is approx. 9% of the estimated water footprint including green and blue water, and the environmental consequences can be significant (Mekonnen and Hoekstra, 2012; Ran et al., 2016). Insight into reduction options, therefore, is essential (Ran et al., 2016).

Several studies concluded that in the pig production chain, on-farm activities are the second largest contributor to blue water after feed production (de Miguel et al. 2015; González-García et al. 2015; Noya et al., 2016). In US pork production systems, on-farm water use consisted of 87% for drinking, 5% for washing, 6% for cooling and 2% for other uses (Matlock et al., 2014). So far, there is very little literature available on water use for washing on pig farms; a conference article (Hurnik, 2005) compared different washing techniques and concluded that hot water reduced washing times by an average of 22%, presoaking by 50% and cleaning agents (soap) by an average of 12%, and that disinfectants reduced bacterial load. However, there was no information provided on the volume of water used. The cleaning process, as described by Sinner’s circle, is a combination of four factors; temperature, mechanical action, cleaning time and chemical action. These factors determine the efficiency of cleaning along with the properties of the surface to be cleaned (Rodgers et al., 2019). Thus, changing the washing protocol, furthermore, can impact the hygiene on pig farms. In intensive pig production systems in Europe, strict biosecurity protocols and good hygiene are essential to reduce the risk of disease outbreaks, which can cause significant economic losses and have an important impact on animal welfare (Rodrigues et al., 2019).

Pigs in intensive systems are transferred to different accommodation types during the production cycle and the washing of pens between batches of pigs is important, particularly for the younger pigs, including newly weaned pigs, which are more vulnerable to infectious diseases (Fairbrother and Gyles, 2012). However, there is not much literature available about the efficacy of different cleaning and disinfection treatments in reducing bacterial load for younger age categories of pigs; most cleaning and disinfection studies focus on efficacy of washing procedures in finisher sections of the pig facilities, or lairage pens in slaughterhouses. Mannion et al. (2007) studied the efficacy of washing and disinfecting finisher units of different pig farms in reducing or eliminating levels of *Enterobacteriaceae*, and found a significant reduction in levels of *Enterobacteriaceae* on the pen floors, but no significant reduction was seen for feeder/drinker surfaces. Indeed, there was a significant increase in *Enterobacteriaceae* levels detected in the feeders following washing and disinfection. A study by Arguello et al. (2011), evaluated the effectiveness of cleaning and disinfection treatments against *Salmonella* on finishing farms, transport and lairage, and found that *Salmonella* persisted on 22.2% of the finisher farms, even after washing and disinfection procedures. Moreover, neither of these studies included measurement of water use. For newly weaned pigs, it would be useful to determine the levels of *Enterobacteriaceae* in the pens after cleaning because it is an important cause of a wide range of diseases especially post weaning diarrhoea, and this can cause significant economic losses (Fairbrother and Gyles, 2012). *Staphylococcus* spp. (species) should also be determined as they are responsible for exudative epidermidis, abscesses and other conditions (Frana, 2012). Therefore, thorough cleaning and disinfection of facilities are essential, and further knowledge on the effect of cleaning and disinfection on freshwater use and bacterial load is required.

Thus, the aim of this study was to quantify the effect of three different washing treatments on water use, bacterial levels and cleaning time in washing of weaner pig pens.

2. Material and methods

2.1 Experimental facilities

The study was conducted in the Teagasc Moorepark Pig Research Facility, which is a farrow to finish experimental pig unit with a 200 sow herd. Three rooms appropriate for housing newly weaned pigs were used for the experiment. Each room had 10 pens (2.4 m × 2.6 m) with a capacity to hold up to 14 pigs each. All the pens had fully slatted plastic floors with a single space wet-dry feeder in each pen, as well as a separate nipple drinker. The room temperature was maintained between 22-28°C. All the pigs received Moorepark standard weaner diet (15% barley, 23% wheat, 20% soya and 33% maize). On this farm, pigs remain in the weaner stage for 7 weeks, and then are moved to the finisher house. The pens are then cleaned before the next batch of pigs move in. The experiment was carried out over 3 replicates, every 7 weeks from April to August 2019.

2.2 Washing and disinfection treatments

Three washing treatments were evaluated: 1) power washing and disinfection (WASH), 2) presoaking followed by power washing and disinfection (SOAK), and 3) presoaking followed by detergent, power washing and disinfection (SOAK+DETER). Within each replicate one of the three treatments was randomly assigned to each experimental room, so that by the end of the experiment each room had each treatment applied once. No mechanical pre-treatment was done before the washing treatments and all the washing procedures were done by the same person. All the pens were washed from top to bottom i.e. first the feeders and walls were washed then the floor. It was only possible to apply treatments at room level, as the sprinklers covered the entire area, and thus it was not possible to separate the treatments within a room. Within each room and replicate, three pens were randomly selected for use in the experiment. Thus, by the end of all three replicates, 9 out of the 10 pens within each room had been used, as no pen was ever used twice.

For WASH, the treatment consisted of cold water (10-15°C, pH-7.53, conductivity-896µs/cm) washing using the power hose. For SOAK and SOAK+DETER treatments, the cold water (supply water at 10-15°C) sprinklers in each room were turned on for approximately 1h 40 minutes, and the detergent was applied for approximately 1h 35 minutes. At that point in the SOAK treatment the pens were washed as before, but for the SOAK+DETER treatment, detergent was applied with the cold water. The detergent used was Kenosan (CID lines, Belgium) used at 0.5% recommended dilution rate. All pens were disinfected after washing using Hyperox (Virkon, LANXESS Deutschland GmbH, Germany), a colourless aqueous formulation of peracetic acid, hydrogen peroxide, acetic acid and surfactant used at 1% recommended dilution rate. After the power washing, rooms were left to dry for 24h before applying disinfectant and after application of disinfectant, the rooms were left to dry for 48h.

2.3 Water data collection

A calibrated water meter (Shanxi Solid Industrial Co., Ltd., China) was installed on the power washing line (3000 psi and 14 L/min) and the volume of water used and the time taken to power wash each of the experimental pens was recorded. The time for which sprinklers were operating for the presoaking was also recorded. In total, there were 9 water recordings per room and per cleaning treatment.

2.4 Swab sample collection

To determine the efficacy of the different cleaning treatments, swab samples were collected from the floor, feeder and wall of each experimental pen. Sponge swabs (1.5 x 3-inch biocide-free cellulose sponge, pre-hydrated with a Neutralizing Buffer diluent; 3M Health Care, Minneapolis, USA) were used. In each pen, after it was emptied of pigs and before the implementation of the cleaning treatment, two floor swabs, one wall and one feeder swab, were collected. The feeder was made of metallic material and the swabs were collected from inside the feeders. The material of the walls and floor were plastic, floor samples were collected from the middle and side of the pen to get a representative sample. The floor of the pen was plastic slats so the surface area swabbed was 23cm x 23 cm (approx.). The swabs used for wall sampling covered an area of 30cm x 30cm and the swab used for the feeder covered 10cm x 10cm.

After washing and drying, swab samples were collected from the three rooms in the same way as before washing. Controls and blanks were used for the microbiological methods. All the swab samples were collected aseptically between 1600-1700h and stored overnight at 4°C and processed within 24h.

2.5 Microbiological analysis

Each swab was suspended in 90ml Maximum Recovery Diluent (MRD; Oxoid, Basingstoke, UK), homogenized in a Seward stomacher 400 (West Sussex, UK) for 1min and a ten-fold dilution series was performed in MRD. Relevant dilutions were plated in duplicate as follows (1) plated on 3M Petrifilm Aerobic count plates (3M Health Care, Minneapolis, USA), incubated at 30°C for 48h for total bacterial count (TBC); (2) pour-plated with Violet Red Bile Glucose (VRBG; Oxoid) agar which was overlaid and incubated at 37°C for 24h for *Enterobacteriaceae*; (3) spread plated on Baird Parker agar (Merck, Damstadt, Germany) mixed with Egg Yolk Tellurite Emulsion (VWR, Dublin, Ireland), incubated at 37°C for 48 h for *Staphylococcus*. For

Enterobacteriaceace, the limit of detection was 10 CFU/cm^2 for floor and wall swabs, and 100 CFU/cm^{2}for feeder swabs. For *Staphylococci,* the limit of detection was 100 CFU/cm^2 for floor and wall swabs, and 1000 CFU/cm^2 for feeder swabs. For TBC, the limit of detection was 10 CFU/cm^2 for floor and wall swabs, and 100 CFU/cm^2 for feeder swabs.

2.6 Statistical analysis

All data were analysed using SAS version 9.4 (SAS Institute Inc., Cary, NC, USA). Prior to analysis the data were examined to visualize the distribution (PROC UNIVARIATE). The water use data were analyzed using linear mixed models (PROC MIXED). The model included washing treatment, replicate and room, as fixed effects, the number of pigs in the pen (11.6 ± 1.4) as a covariate, and pen nested within room as a random effect.

The TBC, *Enterobacteriaceae*, and *Staphylococcus* data were log transformed and analyzed using a linear mixed model (PROC MIXED). Our model included treatment, timing (i.e. before or after the treatment was applied), swab location, replicate and relevant interactions (treatment*timing and timing*location) as fixed effects, the number of pigs in the pen as a covariate, and the pen nested within room as a random effect. Time of sampling (i.e. before or after cleaning) was included as a repeated effect. The water use data and bacterial count data has been added as Supplementary Material S1 and S2. Residuals were checked graphically to ensure that the assumptions of the analyses were met. For all analyses, statistical significance was established at $\alpha \leq 0.05$. In all cases, the Tukey-Kramer least squares means adjustment for multiple comparisons was used to separate the treatment means.

3. Results

3.1 Water use

The effect of treatment on the time taken for washing each pen and the water used for washing are presented in (Table 1). There were no overall effects of treatment, or pair-wise differences, with regard to any measure of water use. There was an overall effect of treatment on the time taken to wash a pen ($p < 0.01$), with differences between all pairs of treatments. The WASH treatment took longer than both SOAK ($p < 0.01$) and SOAK+DETER ($p < 0.001$), whereas SOAK took longer than SOAK+DETER ($p < 0.05$). Thus, both presoaking and use of detergent reduced the time taken for pen washing. Detailed water use data is mentioned in S1 Dataset.

Table 1: Effect of cleaning and disinfection treatments on time taken for washing and the total water used (LSmeans±SE)

	WASH	SOAK	SOAK+DETER	P-value
Time/pen (min)	15.7 ± 0.5[a]	13.4 ± 0.5[b]	11.5 ± 0.5[c]	0.001
Water use/wash/pen (L)[1]	196.9 ± 18.2	191.1 ±17.7	179.1 ± 27.1	ns
Water use/pig (L)	16.5 ± 1.6	19.2± 1.5	18.3 ± 2.3	ns
Water use/pigspace/year (L)[3,4]	99.0 ± 9.5	114.2 ± 9.2	108.6 ± 14.0	ns
Total water use/pen (L)[2]	196.4 ± 18.8	226.6 ± 18.2	215.4 ± 27.9	ns

Treatments: WASH: cold water power washing, SOAK: presoaking using sprinkler followed by power washing, SOAK+DETER: presoaking using sprinkler followed by detergent application then power washing

[1] Water use per wash is the water used while power-hosing the pens

[2] Total water use/pen includes both water use per wash, and the volume of water used through the sprinklers

[3] Pigspace - 0.42m^2 per pig (represents the average floor space used by each pig/pen)

[4] Values multiplied by 6 washes/year

a,b,c Values within a row with different superscripts differ significantly at $p<0.05$

ns – not significant

3.2 Effect of treatment on bacterial counts

None of the treatments, nor the interaction between treatment and time (before or after washing), had any effect on any of the bacterial count measurements (Figure 1). Overall, the time of sampling (before or after wash) had an effect on both TBC and *Staphylococcus* counts ($p < 0.001$ for both), and within each treatment there was also an effect of time (before or after washing) ($p < 0.001$). However, there was no overall effect of time, or effect of time within treatment, on *Enterobacteriaceae* counts. Detailed bacterial count data is mentioned in S2 Dataset.

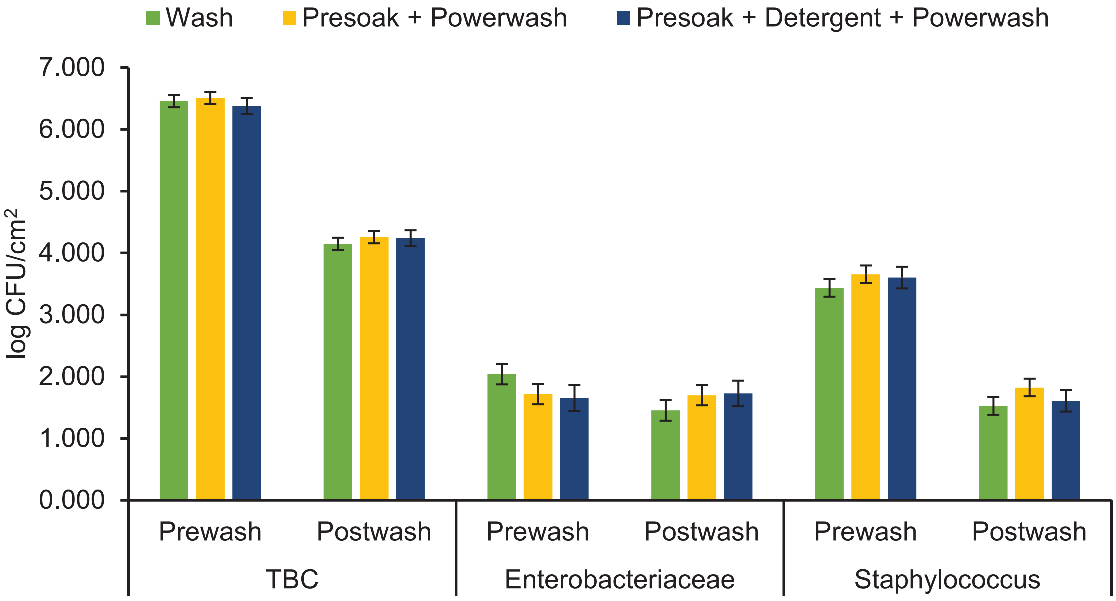

Figure 1: Effect of the different cleaning treatments on TBC (total bacterial count), *Enterobacteriaceae* counts and *Staphylococcus* counts in empty weaner pens before and after the treatments were applied (LSmeans±SE).

There was no effect of treatment or interaction between treatment and sampling time for any measure.

Treatments: WASH: cold water power washing, SOAK: presoaking using sprinkler followed by power washing, SOAK+DETER: presoaking using sprinkler followed by detergent application then power washing

3.3 Effect of sampling location on bacterial counts

The effect of sampling location and sampling time (before or after washing) on the bacterial counts is presented in (Table 2). After washing, there was a difference between counts at all locations ($p < 0.001$), indicating that washing of the walls had more of an effect in reducing bacterial load than washing of floors, regardless of the washing routine used. Again, for both TBC and *Staphylococcus*, the bacterial count was lower after washing than prior to washing, regardless of the location in the pen ($p < 0.001$ for all comparisons). However, the pattern for *Enterobacteriaceae* was different. There was no difference in *Enterobacteriaceae* count in any of the three locations before and after washing. Fig 2 shows the results of the bacterial counts based on the location of sampling before and after the cleaning treatments were applied.

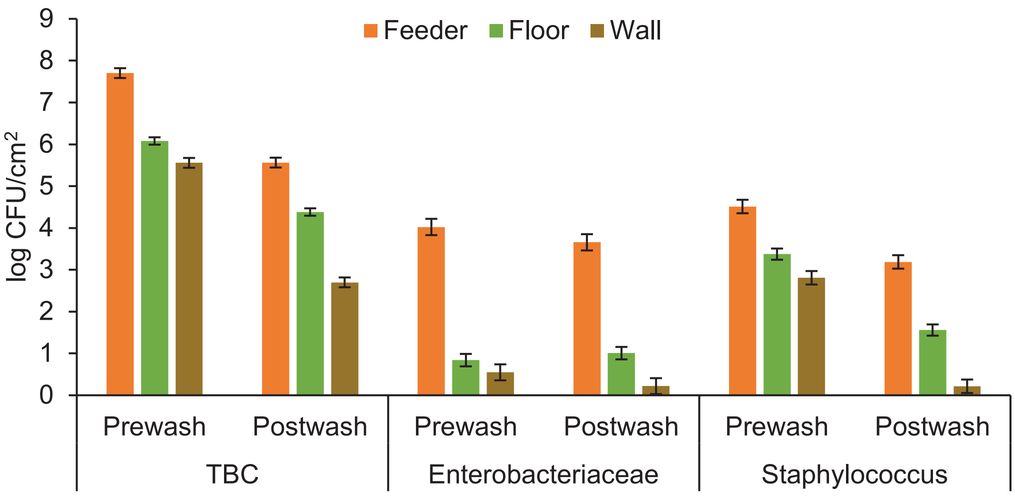

Figure 2: Effect of the different cleaning treatments on TBC (Total bacterial counts), *Enterobacteriaceae* counts and *Staphylococcus* counts in various locations in empty weaner pens before and after cleaning treatments were applied (LSmeans±SE).

There was no effect of treatment or interaction between treatment and sampling time for any measure. Treatments: WASH: cold water power washing, SOAK: pre-soaking using sprinkler followed by power washing, SOAK+DETER: pre-soaking using sprinkler followed by detergent application then power washing

Table 2: Significance of the effect of sampling location and timing (before or after washing) on the bacterial counts of weaner pig pens.

	Total bacterial count	***Enterobacteriaceae***	***Staphylococcus***
Location of sampling	$P<0.001$	$P<0.001$	$P<0.001$
Timing	$P<0.001$	ns	$P<0.001$
Location*Timing	$P<0.001$	ns	$P<0.001$

ns – not significant

4. Discussion

In this study three washing treatments for weaner pig pens, with regard to the amount of water used, time taken for washing, and to their ability to reduce levels of TBC, *Enterobacteriaceae* and *Staphylococcus* were evaluated. Overall, it was shown that all three strategies were equally effective with regard to reducing bacterial load, and that they used the same volume of water. However, pre-soaking either alone or with a detergent significantly reduced the amount of time needed to clean the pens, and as such this strategy may have labor saving advantages for pig producers.

There is very little literature available about water use for washing in the pig industry, most of the research being focused on drinking water usage and water wastage for finishing houses. However, there are some studies that mention different cleaning methods and their effect on water use and cleaning efficiency. For example, Froese and Small (2001) surveyed nine pig facilities in Manitoba and Saskatchewan, Canada, and found that the average daily washing water usage per pig for the nursery stage was 0.38 (L/day). A study done by a Swine Technical Group (Willson and Whittington, 2000), reported that washing water usage for nursery stage was 10 L per piglet, 12 L/pigspace/wash, and that the time taken to wash a nursery pen was 1 minute per pigspace, which are lower than the values obtained in this study. They concluded that procedures such as use of detergent did not have a significant impact on wash timing, which is contradictory to the results of this study, where pre-soaking and use of detergent decreased washing time by 27% and pre-soaking decreased washing time by 14%, compared to only power-washing. The reason why there was no difference in time taken for washing even after use of detergent could be due to the lower concentration of the detergent used or less time given for pre-soaking. Moreover, washing treatments had no impact on the water use, which is similar to the results of this study.

In the current study even though the pre-soaking treatments (with or without detergent) used more water numerically, this was not detected as statistically significant. This could be a limitation of our study design. Based on the differences found, a larger scale study with 76 pens per treatment would be required to detect the differences in water use as statistically significant. The inclusion of sprinkler water in total water use, increased the water use for the SOAK and SOAK+DETER treatments. Thus, reducing the time for which sprinklers were running could reduce the water use while reducing washing time, but this needs to be studied further. However, when it came to water used purely for power-washing, the overall water use in these pens was lower than the WASH treatment, and the time it took to wash the pens was lower. Thus, when it comes to the reasons why producers may select various techniques, the benefits of reduced labor and time spent washing might outweigh any benefits of reduced water use.

The study by Hurnik, compared the effect of hot water to cold water washing, pre-soaking the pens, and the use of soap for washing pig pens in a finishing house in Canada (Hurnik, 2005). In that study, it was found that when compared to only cold water pressure washing, use of hot water, along with pre-soaking and soap reduced the washing time by 31.2 minute or 45.9% per pen. Pre-soaking reduced the wash time by 26.6 minutes or 39.1% per pen and the use of soap with pre-soaking reduced the wash time by 31.7 minutes or 46.5% per pen (Hurnik, 2005). In the current study, pre-soaking reduced the washing time by approximately 2.3 minutes or 14% per pen and use of detergent with pre-soaking reduced the washing time by approximately 4.2 minutes or 27% per pen. The time reduction was probably because pre-soaking helps to loosen the manure making it easier to clean. Pre-soaking also helps to break the biofilm and remove waxy residues which water alone cannot do, thus reducing the power washing time.

The efficacy of washing and disinfection strategies on bacterial reduction on pig farms has not been studied to a great extent and most of the studies focus on *Salmonella* prevalence in finishing houses or lairage pens. A study by (Mannion et al., 2007) reported the efficacy of cleaning and disinfection in reducing or eliminating the levels of *Enterobacteriaceae* in finisher units on Irish pig farms. All the farms studied used cold high pressure washing with or without disinfectant. As in the current study, swab samples were collected before and after cleaning from the pen floors and feeder/drinkers. Although *Enterobacteriaceae* levels decreased moderately on the floors after cleaning, significant residual contamination remained on the surface of the feeder/drinker. Moreover, farms that washed without disinfection had little or no reduction in *Enterobacteriaceae* levels and a common trend among all farms was an increase in *Enterobacteriaceae* levels following cleaning and disinfection. These results are similar to those found in the current study. Cleaning and disinfection procedures were generally effective for TBC and *Staphylococcus* on pen floors and walls but contamination of feeder/drinkers is still of concern, probably due to difficulty in accessing all the crevices of feeders/drinkers. Indeed, the levels of *Enterobacteriaceae* did not decline from pre to post washing and disinfection. This could be due to the resistance of *Enterobacteriaceae* to the disinfectant used, or to the concentration of disinfectant being too low, or to the growth phase (log, lag or stationary phase) of the bacteria, which can influence bacterial reduction (Cherchi and Gu, 2011). Cherci and Gu (2011) used chlorine based disinfection although, Gosling recommends aldehyde-based disinfectants to be most effective in reducing bacterial counts (Gosling, 2018).

Additionally, a recent study (Heinemann et al., 2020) about hygiene in pig fattening pens showed that even after the cleaning and disinfection procedures, the TVC was higher in drinkers/feeding areas compared to floors and walls. In general, it appeared that the feeders were the primary harborage site for *Enterobacteriaceae* which could be due to feed residues left in the feeders post cleaning, because of difficulty in cleaning the crevices of feeders. Other reasons as mentioned in the study (Mannion et al., 2007) include water splashing when pen floors are washed or generation of aerosol droplets due to high water pressure, thus reducing water pressure was recommended by them. Another factor as mentioned in a study (Hancox et al., 2013) is use of detergent in the cleaning regime. They concluded that detergents have their own bactericidal properties thus, soaking with detergent significantly reduced the total aerobic count and *Enterobacteriaceae,* depending on the target surface material.

Similar studies about the effectiveness of cleaning and disinfection procedures on farms have been done on other animal species. Martelli et al., (2016) studied the effect of cleaning and disinfection on *Salmonella* in duck farms and found detergent and formaldehyde are very effective against *Salmonella*. However, they also observed residual contamination on feeders/ drinkers after the cleaning procedures. Luyckx et al., (2015) evaluated the cleaning and disinfection procedures in broiler houses and found overnight soaking to be effective in reducing the total aerobic counts. The drain holes and the floor cracks were still infected with *E. coli* even after disinfection. Washing and disinfection procedures might help to remove the residual matter and bacteria from the pens but in most cases residual contamination remains in the inaccessible areas, which is a reason for concern. Moreover, water use in cleaning is still an area which needs further research. Use of detergent for cleaning might be of potential environmental concern if slurry containing detergent enters sewers or public waters. However, studying the environmental impact of detergents was not a part of this study.

5. Conclusions

The three washing treatments used in this study had no significant effect on water use but there was a significant difference in washing time. The cleaning treatments reduced the levels of *Staphyloccocus* and TBC from pre to post wash, even though no significant difference between the treatments was observed. On the other hand, the levels of *Enterobacteriaceae* did not decline post washing. Since there was no difference in both water use and bacterial load, power-washing without pre-soaking or detergent seems to be the simplest method, and thus perhaps the preferred option. However, if a view from the producer perspective is taken, pre-soaking and detergent use saves time and labour cost, so this would be the preferred option.

The information gathered in this study is useful for future research. Future research in this area should test different concentrations of detergent and disinfectant, a large scale study with more pens might show different results. However, increasing the concentrations of disinfectant and detergent might have some environmental consequences which need to be studied for optimizing the cleaning protocols.

6. Acknowledgements

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Supporting Information

S1 Dataset. **This contains the water use data.**

https://doi.org/10.1371/journal.pone.0242495.s001

S2 Dataset. **This contains the bacterial count data.**

https://doi.org/10.1371/journal.pone.0242495.s002

Chapter 5

Effect of environmental enrichment and group size on the water use and waste in grower-finisher pigs

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Abstract

The grower-finisher stage accounts for 64% of the total on-farm herd water use. Part of this is consumed by the pigs, but a part is also wasted. Drinking water usage and wastage is affected by different factors. We investigated how different group sizes and different levels of enrichment affect water usage (ingested plus wasted), water wastage, behavior and performance in grower-finisher pigs. Pigs (n=672), 11 weeks of age (77 ± 2 days) were used for the experiment. The effect of group size: SMALL (12 pigs), MEDIUM (24 pigs), and LARGE (48 pigs) was assessed across two levels of enrichment (LOW - wooden post, hanging rubber toy, HIGH - Same as LOW + fresh grass). There was no effect of group size on water use or wastage. Pigs with HIGH enrichment (10.4 ± 0.4 L/pig/day) used less water than LOW enrichment (11.0 ± 0.4 L/pig/day; $p<0.001$). The water wastage/drinker/hour was lower in pens with HIGH enrichment than LOW ($p=0.003$). The drinking bout number ($p=0.037$) and total occupancy/hour ($p=0.048$) was also higher for pens with LOW than HIGH enrichment. Aggressive and harmful behaviour were performed less in LARGE groups and pens with HIGH enrichment. Thus, HIGH enrichment allowance reduced water usage and wastage so may have benefits for the environment, as well as animal welfare.

1. Introduction

Global demand for meat products is likely to increase as both world population and incomes grow (Wiedemann et al., 2018). This might lead to a surge in the demand for pork, one of the most globally eaten meats (Henchion et al., 2014). Pig production already contributes 19% to the global water footprint of farm animal production (Mekonnen and Hoekstra, 2012). This means about 6000 m^3 of water per ton of pigmeat[3] of which 70% is used off-farm for the production of feed, 24% is used on-farm for drinking, cleaning and feed mixing, and 6% for slaughtering (González-García et al., 2015). As global freshwater supplies are limited, it is of major importance that water use in the pig production chain is optimized.

Provision of sufficient water for drinking is considered fundamental in animal agriculture to ensure good welfare. In pig production, drinking water accounts for 80-87% of the total on-farm water use (Froese and Small, 2001; Matlock et al., 2014) and the grower-finisher stage accounts for 64% of the total herd water use (Froese and Small, 2001). During this stage, drinking water use ranges from 1.9 to 6.8 L/pig/day (Li et al., 2005). Part of this water is indeed consumed by the pigs, but a part is also wasted. Besides impacting on fresh water resources, water wastage increases the volume of the slurry which dilutes the nutrient content. This increases the operating costs (i.e. cost for manure processing and disposal), and is therefore another reason for minimising water wastage.

Drinking water usage and wastage, and the ratio between the two, is affected by a complex interaction of both pig (e.g. body weight, social competition, feed intake) (Turner et al., 2000; Godyn et al., 2019), environmental (e.g. temperature, humidity) (Muhlbauer et al., 2010) and management factors (e.g. drinker type, pen design) (Turner et al., 2000; Li et al., 2005; Chimainski et al., 2019). An important factor which affects drinking behavior is resource allowance. Researchers found that over a period of 24 h groups of 10 growing pigs had more visits to the single nipple drinker at night than groups of 3 (Andersen et al., 2014). This was hypothesized to result from a higher proportion of interrupted visits during the day, as there was likely more competition for access to the drinker in the larger groups during periods when pigs are normally active. Group size appears to affect both water use and drinking behavior; this was also found in a study where pigs in groups of 20 engaged more with the drinker (more visits to the drinker, and spent more time drinking) but used less drinking water than pigs in groups of 60 (Turner et al., 1999; Turner et al., 2000). When stocking density is kept constant, pigs in larger groups have more shared space per pig, which could provide a more complex and engaging environment for them. The impact of this on drinking behavior has not been fully explored, but it could be that more shared space leads to less engagement with the drinker resulting in less wastage, as pigs have a greater area for exploration.

These results also indicate that pigs do not seem to use drinkers purely for drinking (Turner et al., 1999; Turner et al., 2000). The barren environment in which pigs typically live could also promote the performance of redirected (foraging) behavior. This can manifest itself in the form of playing with drinkers (Patience, 2012; Godyn et al., 2019), which leads to water wastage. Providing appropriate environmental enrichment can reduce the occurrence of these kinds of negative behaviors (Chou et al., 2019) and thereby has the potential to reduce water wastage. The use of a range of enrichment materials suitable for slatted systems has been compared, and it was found that loose material provided in a rack was preferred by pigs over point source items such as wooden chew bars, rubber toys etc.(Chou et al., 2020). With regard to the type of material to provide in a rack, either fresh grass, or grass silage seems favored by pigs over straw; silage keeps pigs occupied for longer (Holinger et al., 2018), and more grams of fresh grass are used per day than straw (Chou et al., 2019).

To reduce water wastage it is essential to understand drinking behavior, and water wastage in relation to this. Although we know that across all the production stages, grower-finisher pigs consume most of the total water used on a farm and several studies have focused on water use of grower/finisher pigs (Li et al., 2005; Li and Gonyou, 2001; Turner et al., 2000; Turner et al., 1999; Andersen et al., 2014; Tavares et al., 2014; Chimainski et al., 2019) no study has focused on the impact of group size and the effect of enrichment on both drinking behavior and water wasted from drinkers. Therefore, the objective of this study was to investigate how different group sizes and different levels of enrichment affect water usage (ingested plus wasted), water wastage, behavior and performance in grower-finisher pigs. We hypothesized that a larger group size and provision of a favored enrichment material will optimize water use by reducing waste.

2. Methods

2.1 Experimental Facilities

The study was conducted in the Teagasc Pig Research Facility in Ireland, a farrow to finish experimental pig unit with a 200 sow herd. The experiment was carried out from July 2019 to April 2020. Ethical approval was obtained from the Teagasc Animal Ethics Committee (TAEC233-2019); all procedures were carried out in accordance with the

Irish legislation (SI no. 543/2012) and the EU Directive 2010/63/EU for animal experiments.

2.2 Animals, housing, diet and husbandry

A total of 672 pigs [Danish Duroc × (Large White × Landrace)] were included in the experiment. Between weaning (4 weeks of age) and the start of the experiment (11 weeks of age; 77 ± 2 days) pigs were managed in weaner pens (2.4 m × 2.6 m) of 12 pigs. The experiment was carried out over three replicates in a single room. The room contained 4 pens for each experimental group size: SMALL (4.2 m × 2.5 m; 12 pigs), MEDIUM (5.0 m × 4.2 m; 24 pigs), and LARGE (8.2 m × 5.0 m; 48 pigs), providing a space allowance of 0.86 m^2 per pig in all treatments (Room layout in Supplementary material S1). The room also contained two hospital pens which were of the same size as the pens of the SMALL treatment.

The pigs were fed *ad-libitum* with a standard pelleted diet (43.5% wheat, 30% maize, 17.1% soya-HIpro, 7.1% soya hulls) through single space wet/dry feeders with a built-in nipple. Pigs could mix the water and feed in the trough as required. The feed intake per feeder was recorded through a computerized feeding system (BigFarmNet Manager, Big Dutchman Ltd. v3.1.5.51039, Calveslage, Vechta, Germany). Each pen also had a separate nipple in a bowl drinker mounted 35 cm above ground level and 30 cm from the wet/dry feeder. SMALL pens had 1 feeder and 1 separate drinker, MEDIUM pens had 2 feeders and 2 separate drinkers and LARGE pens had 4 feeders and 4 separate drinkers to ensure the same number of pigs per drinker and feeder in each pen. All pens were fully slatted concrete flooring, the room had mechanical ventilation with a roof fan at the center of the room and artificial light was provided 8 h/day. The average room temperature was maintained at 20ºC.

2.3 Treatments and experimental design

The experiment was carried out by using a 3 × 2 factorial design. The effect of group size (SMALL, MEDIUM, LARGE) was assessed across two levels of enrichment (HIGH, LOW). Pigs on the LOW enrichment received one wooden post and one hanging rubber toy/12 pigs. Pigs on the HIGH enrichment received the same, with the addition of one rack/12 pigs containing fresh grass, which was attached to the wall of the pen. All pens were equipped with enrichment materials prior to entry of the pigs.

The day before the commencement of the experiment pigs were weighed individually, then the individual weights within each weaner pen summed. For the SMALL treatment, 6 pigs from two separate weaner pens were mixed. For the MEDIUM treatment two weaner pens of pigs were mixed, and for the LARGE treatment 4 weaner pens were mixed. The final overall average pen weight was 33.8 ± 3.6 kg. There were an equal number of male and female pigs in each of the final groups. Males and female pigs are kept in the same pen in Ireland and this is a common practice in Irish commercial farms. In Ireland, entire males are produced so the slaughter weights are lower to avoid the boar taint problems.

A total of 24 pens were used in the whole experiment, 12 pens in the first replicate and 6 pens each in second and third replicate. The first replicate had 2 pens for each group size and enrichment combination (e.g. 2 SMALL pens with LOW enrichment, 2 MEDIUM pens with LOW enrichment, 2 SMALL pens with HIGH enrichment, 2 MEDIUM pens with HIGH enrichment etc.). In the second and third replicate, we included 1 pen for each group size and enrichment combination (e.g. 1 SMALL pen with LOW enrichment, 1 MEDIUM pen with LOW enrichment, 1 SMALL pen with HIGH enrichment, 1 MEDIUM pen with HIGH enrichment etc.) due to a scarcity of pigs available for enrolment in the study. For replicates 2 and 3 separate halves of the room were used, so that all pens were used twice over the entire experiment.

2.4 Environmental measurements

Daily measurements (logging interval every 15 mins) of temperature and humidity were recorded using data loggers (Tinytag, Sussex, UK) set up in the room at 2 m above floor height. All the data loggers were installed in the passages of the room with each passage having 2 data loggers. For the first replicate 6 data loggers were installed in the room, for the second and third replicate 4 data loggers were installed. Before starting the experiment light intensity in each pen (in front of the drinker) was measured using a luxmeter (ISO-TECH, ILM 1337 Light Meter, UK).

2.5 Enrichment measurements

The wood and hanging rubber toy were weighed at the beginning and at the end of the experiment to estimate the rate of wear by the pigs. Loose fresh cut grass (10-20 cm length) was added to the rack at 90 g/pig and was replenished whenever the quantity dropped to below half of the total allowance per rack as described previously (Chou et al., 2020).

2.6 Recording and sampling of water usage and wastage

At the beginning of the experiment, water flow rate from each nipple drinker was measured. Water was collected for 30 seconds in a plastic bag and the volume measured using a 1000 ml graduated cylinder. The average water flow rate was 1.47 ± 0.14 L/30 sec (mean ± s.d.). Water meters were installed in all pens, and each one covered one wet/dry feeder and the bowl drinker next to it. Water use was monitored via an automated online water monitoring system (Carlo Gavazzi Automation, Italy). Data was recorded every 15 minutes.

To record water wasted from each drinker, a wooden box (0.9 × 0.43 × 0.22 m) was designed (Supplementary material S2, S3). The box surrounded the drinker on all sides, with an opening (0.25 m wide × 0.35 m high) through which the pigs could access the drinker. The opening was positioned 0.35 m above floor level, and there was unrestricted access to the drinker. Water overflow from each drinker was collected using a container (3.6 L capacity) placed inside the box and underneath the drinker, which fitted comfortably to the sides of the box; thus any waste water could not escape between the side of the container and the box. The amount of wasted water was measured one day per week for six weeks, starting 5 days after the pigs were moved into the pens (i.e. 82 ± 2 days old). Once a week (on Monday), between 0930h and 1600h the amount of water in the container was measured using a 1000 ml graduated cylinder at least once per hour, and more often if necessary.

2.7 Direct behaviour observations

Pig behaviour was directly observed once per week (on Wednesday) starting a week after the pigs were moved into the pens (84 ± 2 days old). For the first two replicates observations were carried out for the entire 9 weeks of the fattening period, but for the third replicate observations were only carried out for the first 5 weeks (interrupted due to COVID-19). Five minutes of continuous all occurrence observation were conducted 4 times a day for each pen at approximately 1000h, 1100h, 1400h and 1500h. The order of observations for the pens was randomised across each observation time, so that the average time of observation was similar for all treatments. We were primarily interested in performance of damaging behaviours and enrichment use so these behaviours were recorded using the ethogram in Table 1.

2.8 Video recordings

Video cameras (2.0MP fixed wide angle bullet cameras with 40 m infrared night vision (HIKVision, China) were installed directly over the drinkers on day 25 of the experiment, when pigs were approximately 102 ± 2 days old.

Table 1: Ethogram of pig behaviour

	Behaviour	Description
Aggression	Fight	Mutual pushing parallel or perpendicular, ramming or pushing of the opponent with the head, with or without biting in rapid succession and/or head thrusting. Lifting the opponent by pushing the snout under its body (Stewart et al., 2008)
	Bite	Pig bites another pig with a vigorous movement of the head: mouth open, contact made with body
	Head knock	As for threat but makes contact with head against recipient pigs body
Harmful	Tail bite	Pig forcefully bites down on another pigs tail – often reflected in reaction (vocalisation, fast movement away) by the recipient pig
	Ear bite	Pig takes another pigs ear in its mouth and closes jaws around it – often associated with vocalisation or swift head movement to extract its ear by recipient pig
	Belly nosing	Vigorous nosing of another pigs belly when lying
	Bite other	Biting aimed at another part of the body e.g. leg. Not to be confused with aggression
Enrichment	Interacts with wood	Pig bites or touches the wood or its holder with its mouth
	Interacts with hanging toy or chain	Pig bites or touches the hanging toy or chain with its mouth
	Interacts with grass rack	Pig bites or touches the grass or its holder with its mouth

All the cameras were directed towards the drinkers and each drinker had a separate camera which continuously recorded for a 24h period. Data were downloaded onto a 1 TB Hard drive (PC PRO Computers Ltd., Ireland). Preliminary analysis of the water use data (from the water meters) indicated that the drinkers were most in use between 0800 and 2000h. An hour of video footage was extracted for each drinker (1000h – 1100h) for observation and the time taken start to end of visit was also noted. Occupancy of the drinkers and bouts were determined by recording every time a pigs head entered the box around the drinker (snout disappeared within the opening of the box), and the time that the head was removed. From these data the number of bouts, the duration of each bout, and the duration of occupancy per hour were calculated. The identity or sex of the pigs was not recorded.

2.9 Animal performance

Pigs were weighed individually using a digital scale (R323, Rinstrum, Langenfeld, Germany) the day before the trial started, and at the end of the trial period (147 days), and from these weights the average daily gain (ADG) was calculated. From the computer records of feed delivered to each feeder, the total amount of feed delivered to each pen on each day of the trial was calculated so that the average daily feed intake (ADFI) of pigs in the pen could be calculated. From this the average feed conversion ratio (FCR) per pen was calculated. Records were kept of pigs removed from the trial due to injury, illness or death.

2.10 Statistical analysis

All data were analyzed using SAS version 9.4 (SAS Institute Inc., Cary, NC, USA). Prior to analysis the data were examined to visualize the distribution (PROC UNIVARIATE). The water use (ingested plus wasted), water wastage, animal behavior, drinking behavior and performance data were analyzed using linear mixed models (PROC MIXED). All the models included group size (i.e. SMALL, MEDIUM and LARGE), enrichment level (i.e. HIGH and LOW), day and replicate and relevant interactions (group size*enrichment) as fixed effects and pen was included as a random effect.

2.11 Water use and waste

Several different measures of water use were analyzed. First, the total amount of water delivered through each meter was summed to provide a total amount of water delivered per day to each pen. These data were then used in analysis to compare water use over the entire experimental period across treatments. Day was included as a repeated effect.

Following this, a second analysis was carried out which considered only measurements taken between 0930h and 1600h on the days which waste water was measured. In addition to water wasted, the total water usage and the water ingested (total less waste) were compared during this period. For some of the drinkers, the daily waste water measurements were unavailable due to water overflow from the container. Therefore, the unit for analysis was the drinker, rather than the pen. The model included group size (i.e. SMALL, MEDIUM and LARGE), enrichment level (i.e. HIGH and LOW), drinker, week, replicate and relevant interactions (group size*enrichment) as fixed effects and drinker with pen was included as a random effect. Week within replicate was included as a repeated effect.

The performance of aggressive, harmful, and enrichment directed behaviour summed up for each pen during each recording session, then divided by number of pigs to calculate the rate of performance/pig/session. The average of all sessions within each recording day was then calculated for analysis. As before, the model included group size, enrichment level, week, replicate and relevant interactions (group size*enrichment) as fixed effects and pen was included as a random effect. Week within replicate was included as a repeated effect.

Three parameters were measured for drinking behavior; the number of bouts, the duration of each bout, and the duration of drinker occupancy per hour. The model for number of bouts and the duration of occupancy per hour included drinker within pen as a repeated effect. The model for the duration of each bout included each pig visit to the drinker as a repeated effect.

The model for animal performance (ADG, ADFI and FCR) included group size (i.e. SMALL, MEDIUM and LARGE), enrichment level (i.e. HIGH and LOW), replicate and relevant interactions (group size*enrichment) as fixed effects and pen was chosen as a random effect.

Interactive effects are reported where they occur. Residuals were checked graphically to ensure that the assumptions of the analyses were met. For all analyses, statistical significance was established at $\alpha \leq 0.05$. In all cases, the Tukey-Kramer least squares means adjustment for multiple comparisons was used to separate the treatment means.

3. Results

3.1 Ambient temperature and humidity

The temperature ranged from 18.3-24.5ºC for replicate 1, 15.2-26.0ºC for replicate 2 and 15.8-24.4ºC for replicate 3. The relative humidity ranged from 52.6-97.3%% for replicate 1, 51.8-94.2% for replicate 2, 46.3-91.5% for replicate 3. The light intensity ranged from 43 to 201±39.7 (lux).

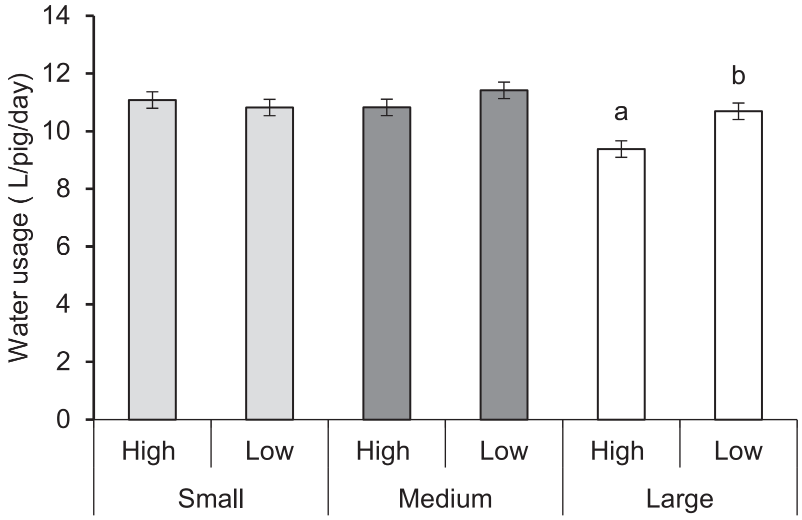

Figure 1: Effect of group size and enrichment on the water usage (ingested + wasted) L/pig/day (LSmeans±SE).

Group size: Large (48 pigs/pen), Medium (24 pigs/pen), Small (12 pigs/pen), Enrichment: Low (Wood + Hanging toy), High (Wood + Hanging toy + Grass). ^{abc}Different letters denote significant differences picked up by Tukey–Kramer test ($p<0.05$).

3.2 Overall water usage (ingested plus wasted)

Pens with HIGH enrichment used less water (10.4 ± 0.4 L/pig/day) than pens with LOW enrichment (11.0 ± 0.4 L/pig/day). There was also an interaction between group size and enrichment ($F_{1, 138}= 18.78$, $p<0.001$; Figure 1). In LARGE groups, those with HIGH enrichment used less water than those with LOW enrichment ($p<0.001$). A tendency ($p=0.083$) towards lower water use was also found in MEDIUM pens with HIGH enrichment compared to MEDIUM pens with LOW enrichment.

3.3 Water usage, ingested and wasted from 0930h to 1600h

The volume of water usage (ingested plus wasted) per drinker per hour was not affected by group size ($F_{2, 26.7}=1.17$, $p=0.326$) or enrichment ($F_{1, 246}= 2.32$, $p=0.129$; Table 2). The water ingested (water usage minus wasted) per drinker per hour was not affected by group size ($F_{2, 26.7}= 0.76$, $p=0.477$) or enrichment ($F_{1, 246}= 0.99$, $p=0.320$). More water was wasted per drinker per hour in pens with LOW enrichment compared to pens with HIGH enrichment ($F_{1, 61.6} = 9.82$, $p=0.003$) and there was a tendency towards more water wastage in MEDIUM compared to LARGE pens ($F_{2, 23.2} = 3.23$, $p=0.077$). The percentage of water wasted was not affected by group size ($F_{2, 27.3}= 0.68$, $p=0.513$) but more water was wasted in pens with LOW enrichment compared to pens with HIGH enrichment ($F_{1, 74.7} = 6.46$, $p=0.013$). No interaction was found between group size and enrichment.

Table 2: LS means (SEM) of the effect of group size and enrichment on the water usage, water ingested and water wasted from 0930h to 1600h.

	Treatments						
	Group size				Enrichment		
	Small	Medium	Large	P value	High	Low	P value
Water usage* (l/drinker/h)	7.95 (0.90)	8.29 (0.62)	7.18 (0.43)	0.326	7.54 (0.43)	8.07 (0.42)	0.129
Water ingested (l/drinker/h)	7.03 (0.82)	7.33 (0.57)	6.50 (0.40)	0.477	6.79 (0.40)	7.11 (0.39)	0.320
Water wasted (l/drinker/h)	0.92 (0.13)	0.94 (0.09)	0.70 (0.06)	0.058	0.76 (0.06)^a	0.95 (0.06)^b	0.003
Water wasted (% of the volume wasted)	9.31 (1.19)	8.28 (1.13)	7.53 (1.09)	0.513	7.44 (1.09)^a	9.36 (1.09)^b	0.013

Group size: Large (48 pigs/pen), Medium (24 pigs/pen), Small (12 pigs/pen). Enrichment: Low (Wood + Hanging toy), High (Wood + Hanging toy + Grass). ^{abc}Different letters denote significant differences picked up by Tukey–Kramer test (p<0.05). * Water usage includes ingested plus wasted

3.4 Diurnal pattern of drinking behavior

The 24 h period of water use data collected from the water meters of each pen for the entire experimental period was segmented into six blocks of 4 h (logging interval 15 mins). The water use (L/pig/day) during each block and for each treatment is shown in (Figure 2). The diurnal pattern was similar for all the treatments and the water use at the drinkers increased from approximately 8am up to 4pm and then started declining.

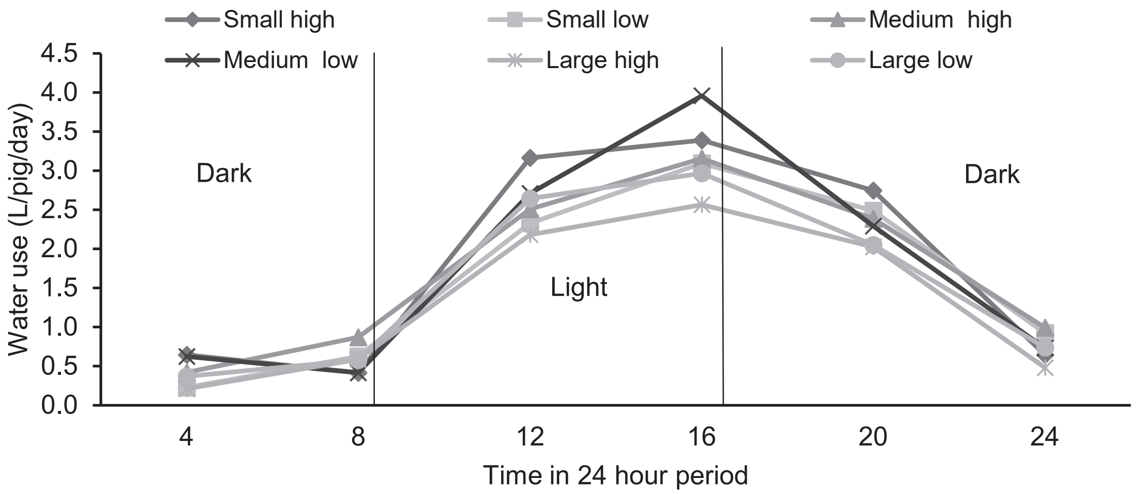

Figure 2: Diurnal pattern of drinking for the six combinations of group size and enrichment (water use/pig/day (L)) occurring during 4-hour blocks

3.5 Frequency and duration of drinker visits

Pigs in different group sizes had a similar number of drinking bouts but the number of drinking bouts was higher for pens with LOW enrichment (24.4 bouts/drinker/hour) compared to HIGH enrichment (15.5 bouts/drinker/hour, $F_{1, 18.6}$= 5.08, p=0.037) (Figure 3 a,b). However, the bout duration tended to get shorter as group size increased ($F_{2, 11.9}$ = 3.07, p= 0.084) while enrichment had no effect on bout duration (Figure 3 c,d). The total duration of occupancy per hour was not affected by the group size but there was an effect of enrichment ($F_{1, 18.6}$= 5.08, p=0.048). Pigs in pens with LOW enrichment spent more time occupying the drinker, compared to the pigs with HIGH enrichment ($p<0.05$) (Figure 3 e,f).

3.6 Animal behavior

The effects of group size and enrichment on pig behavior are presented in Table 3. There was an effect of group size ($F_{2, 8.34}$ = 16.69, p=0.001) and enrichment ($F_{1, 30.9}$ = 9.28, p=0.005) on the amount of aggressive behavior performed by the pigs. Pigs in MEDIUM (p=0.007) and LARGE (p=0.001) groups performed less aggressive behavior than pigs in SMALL groups. Pigs with LOW enrichment performed more aggressive behavior than those with HIGH enrichment (p=0.0047).

Pens with HIGH enrichment performed less harmful behaviour than pens with LOW enrichment (Table 3), but because there was an interaction between group size and enrichment ($F_{2, 46.3}$ = 5.62, p=0.007) these data must be interpreted with caution. In the SMALL groups, pigs provided with LOW enrichment performed more harmful behavior than pigs with HIGH enrichment ($p<0.001$). Although there was numerically more harmful behaviour performed in pigs with LOW enrichment in the LARGE groups, this difference was not significant (p=0.15). The amount performed in MEDIUM groups was numerically the same regardless of whether enrichment level was LOW or HIGH.

Pigs in LARGE groups interacted less with the enrichment compared to pigs in MEDIUM and SMALL groups (p=0.05), and there was more interaction with enrichment in general in the HIGH enrichment treatment ($F_{1, 59.8}$ = 21.8, $p<0.001$). There was only a tendency for an interaction between group size and enrichment ($F_{2, 59.8}$ = 2.76, p=0.071) with SMALL and MEDIUM group sizes provided with HIGH enrichment having more interactions with enrichment than LARGE.

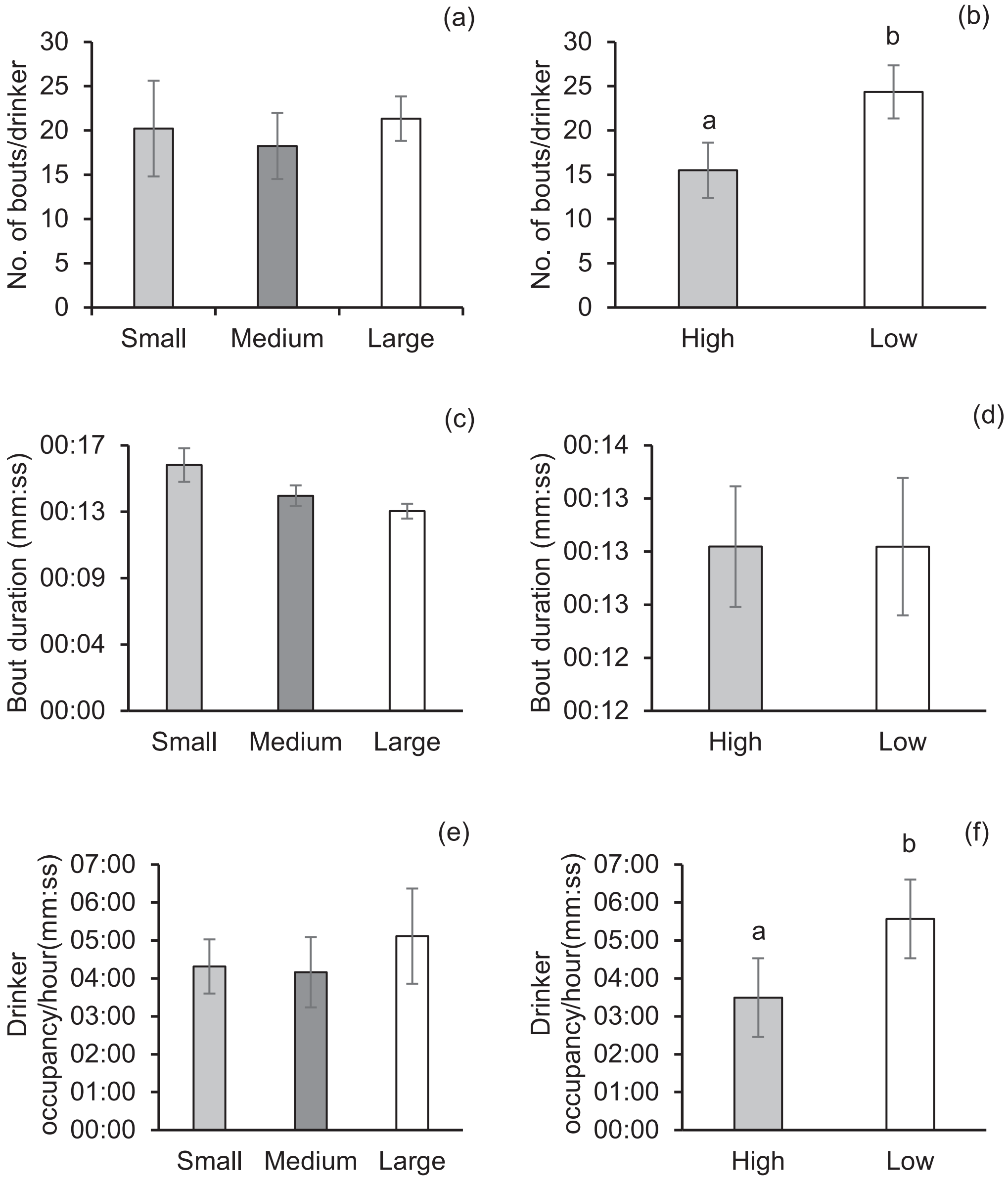

Figure 3: Effect of group size and enrichment on drinking behavior (LSmeans±SE) (a,b) number of bouts per drinker (c,d) duration of each bout (e,f) occupancy of each drinker per hour.

Group size: Large (48 pigs/pen), Medium (24 pigs/pen), Small (12 pigs/pen), Enrichment: Low (Wood + Hanging toy), High (Wood + Hanging toy + Grass) ^{abc} Different letters denote significant differences picked up by Tukey–Kramer test ($p<0.05$).

Table 3: LS means (SEM) of the effect of group size and enrichment on the average number of occurrences of aggressive, harmful, interaction with enrichment behaviours performed per 5-min observation of pens of pigs.

	Treatments													
	Group size				Enrichment			Group size*Enrichment						
	Small	Medium	Large	P value	High	Low	P value	Small		Medium		Large		P Value
								High	Low	High	Low	High	Low	
Aggression (frequency/pig/recording session)	0.22 (0.02)^{a}	0.11 (0.02)^{b}	0.07 (0.02)^{b}	0.0012	0.11 (0.01)^{a}	0.16 (0.01)^{b}	0.0047	NI	NI	NI	NI	NI	NI	NI
Harmful (frequency/pig/recording session)	0.36 (0.01)^{a}	0.20 (0.01)^{b}	0.11 (0.01)^{c}	<0.001	0.20 (0.01)^{a}	0.25 (0.01)^{b}	<0.001	0.3 (0.02)^{a}	0.41 (0.02)^{b}	0.2 (0.02)	0.2 (0.02)	0.08 (0.02)	0.14 (0.02)	0.007
Interaction with enrichment (frequency/pig/recording session)	0.31 (0.02)^{a}	0.31 (0.02) ^{a}	0.22 (0.02)^{b}	0.033	0.31 (0.01)^{a}	0.25 (0.01)^{b}	<0.001	0.34 (0.02)^{a}	0.27 (0.02)^{b}	0.35 (0.02)^{a}	0.26 (0.02)^{b}	0.23 (0.02)	0.21 (0.02)	0.071

^{abc} Different letters denote significant differences picked up by Tukey–Kramer test (p<0.05). Group size: Large (48 pigs/pen), Medium (24 pigs/pen), Small (12 pigs/pen), Enrichment: Low (Wood + Hanging toy), High (Wood + Hanging toy + Grass). NI- not included in the final model p>0.10

Table 4. Effect of group size and enrichment on animal performance (LSmeans ±SEM).

Group size: Large (48 pigs/pen), Medium (24 pigs/pen), Small (12 pigs/pen) Enrichment: Low (Wood + Hanging toy), High (Wood + Hanging toy + Grass) ^{abc} Different letters denote significant differences picked up by Tukey–Kramer test ($p<0.05$).

	Treatments						
	Group size				Enrichment		
	Small	Medium	Large	P value	High	Low	P value
ADG (g/d)	982.4 (17.5)^{a}	943.6 (17.5)^{ab}	909.9 (17.5)^{b}	0.027	944.0 (14.4)	946.5 (14.4)	0.901
ADFI (g/d)	2253.2 (42.8)^{a}	2135.7 (42.8)^{ab}	2071.9 (42.8)^{b}	0.053	2180.7 (34.7)	2126.5 (34.7)	0.284
FCR	2.29 (0.03)	2.26 (0.03)	2.28 (0.03)	0.773	2.31 (0.02)	2.25 (0.02)	0.061

3.7 Animal Performance

Table 4 summarizes the effect of group size and enrichment on animal performance. Group size had an effect ($F_{2, 18}$ = 4.46, p=0.027) on ADG with LARGE groups having lower ADG than SMALL (p=0.021). ADFI was also influenced by the group size ($F_{2,6.52}$ = 4.77, p=0.053), again with LARGE groups having lower ADFI than SMALL (p=0.047). The level of enrichment or the interaction between group size and enrichment had no effect on either ADG or ADFI. There was no effect of group size or interaction between group size and enrichment on FCR. However, there was a tendency for pigs on the LOW enrichment treatment to have a lower FCR (p=0.065).

4. Discussion

We hypothesized that a larger group size and provision of a favored enrichment material will optimize water usage by reducing waste. The results indicate that group size did not affect the water usage per pig. However, our hypothesis was confirmed regarding the provision of enrichment; pens with HIGH enrichment used less water per pig than pens with LOW enrichment and this was likely due to less water being wasted in this treatment. HIGH enrichment provision in a larger group size was associated with a reduced rate of performance of aggressive and damaging behaviors, indicating better welfare. Although in the current study pen size and group size were confounded, it is likely primarily the effect of having a larger pen, and more shared space, which drove the effects which were observed.

Water usage includes both water ingested by the animal and water wastage. None of the treatments affected the volume of water usage from 0930 to 1600h which was 7.81 L/drinker/hour on average. Approximately 89.1% of the total water usage was ingested (6.95 L/drinker/hour) and 10.9% (0.85 L/drinker/hour) was wasted. The amount of water ingested per pig was higher and wastage per pig was lower than other studies (70% ingested and 30% wasted (Chimainski et al., 2019), and >30% wasted/pig/day) (Andersen et al., 2014). Drinker design, height and flow rates affect both parameters substantially[7] and may explain the difference. The design of the drinkers in the current study meant that water which was not consumed by the pig collected in the bowl positioned under the nipple which might have led to less spillage, and this water being drunk by pigs, meaning there was less manipulation of the nipple. Moreover, in our study pigs could also drink from nipples present in the wet/dry feeders which might have influenced the total water usage and wastage, because water that is spilled from these drinker is leaking into the feeder and will be consumed together with the feed and therefore is not wasted. It should also be noted that we had some missing values for water wastage which were excluded from the calculations and this might further affect the results.

The diurnal pattern of water use over a 24h period in our study is in alignment with previous work. We found the greatest levels of water use during the day with a peak at 1600h, and a decline in the evening and night. This is similar to the pattern observed by other researchers (Bigelow and Houpt, 1988; Turner et al., 2000) and it was also reported that the maximum time spent at the drinkers was between 1800h and 1900h (Turner et al., 2000). This pattern seems to also follow the typical diurnal feeding pattern of pigs (Bigelow and Houpt, 1988).

Our findings that time spent drinking, and the number of visits to drinkers were not affected by group size, are similar to those of other researchers (Andersen et al., 2014).The results, however, contradict somewhat with those of other researchers who found that pigs in groups of 20 visited the drinkers more frequently, for longer duration and spent longer time drinking compared to those in groups of 60 pigs; however these studies had varying pigs-to-drinker ratio (10:1 vs 20:1), which likely influenced the results (Turner et al., 1999;Turner et al., 2000). We do acknowledge that our detailed observations of drinking behaviour were only carried out on one occasion during the experiment, and it is possible that the pattern of drinker use may have been different either earlier or later on during the finisher stage. Nevertheless, the results from our analysis of drinker occupancy are in line with the water use and wastage data collected over several weeks; pigs with LOW enrichment had more drinking bouts, greater occupancy of the drinker, and wasted more water both in volume and as a percentage of water usage.

Thus our study provides novel insight into the relationship between enrichment provision, water usage and drinking behavior. We provided grass as additional enrichment in the HIGH treatment as this is highly favorable to pigs, preferred even over other attractive enrichment materials such as shredded paper, and soft wood (e.g. spruce) (Chou et al., 1999, 2000). It seems that part of the pigs' motivation to forage might have been fulfilled after playing with or consuming grass. They may thus have been less likely to interact with drinkers to satisfy the need to forage, and to interact with them without consuming water. An alternative hypothesis is that grass consumption could have somewhat satiated the pigs thirst; the moisture content of fresh grass is approx. 80% (Teagasc, 2014). Thus the pigs may have been less motivated to visit the drinkers for the purpose of drinking and therefore also had less time to spill water. If this were the case, it is possible that our results are somewhat specific to provision of grass as an enrichment material; further research with other enrichment strategies should be performed to determine if the results are consistent across materials. However, it is important to note that the proportion of water which was wasted was higher in the LOW enrichment pens than in the HIGH enrichment. If the amount of water wasted has a linear relationship with the amount used for drinking, we would expect the proportion wasted to be similar across treatments. The fact that the proportion wasted was higher in the LOW treatment indicates that these pig spilled more water when interacting with the drinkers than the pigs in the HIGH treatment.

Nevertheless, the difference in water use across enrichment treatments also varied with group size. There was no effect of enrichment in MEDIUM and LARGE groups. In LARGE pens pigs have more shared space, and therefore more area is available for exploration, and this might have reduced the amount of redirected exploratory behavior toward the drinkers. Moreover, provision of grass as well as shared space had an additive effect, in reducing overall water use.

We found that pigs in SMALL groups had a higher incidence of aggressive and harmful behavior compared to those in MEDIUM and LARGE groups. Our results are not comparable to most studies of group size, because all pigs had equal access to resources in the current study, which was not the case in most other studies. For example, a study investigating the effect of group size along with variation in feeder spaces (1:10 pigs and 1:20 pigs) on the welfare of finishing pigs found that as the group size increased skin lesions, an indication of the amount of aggression, also increased

(Spoolder et al., 1999). Pigs from larger group sizes (80 pigs) also tend to be less aggressive when mixed with unacquainted pigs compared with pigs from smaller groups (20 pigs) (Turner et al., 2001). The probability of monopolizing resources declines as group size increases, and as the number of competitors increases with group size, fewer individuals get involved in costly fights (Andersen et al., 2004). Thus, in larger groups pigs appear to become less aggressive and may shift to a low-aggressive social strategy (Samarakone and Gonyou, 2009). Increased area of solid flooring and increased space allowance has also been associated with fewer tail damaging behaviors and better overall welfare in finishing pigs (Brandt et al., 2020).

Although the effect of group size and pen size are confounded in the current study, we thought that it was prudent not to alter what is likely the greater confounding effect of group size and stocking density, which would have occurred if we had not altered the pen size. Moreover, keeping the pen size the same would have meant that the smaller groups would have been managed at a stocking density which would have been approximately 4 times lower than that in typical commercial systems; thus although the results would be theoretically interesting, they would not reflect commercial reality. We must also take into account that the stocking densities across all treatments were slightly lower than that of the EU legal requirement. However the space allowance used is part of the standard operating procedure in the research center, to minimize the risk of damaging behaviors, while remaining somewhat similar to commercial reality. We consider that the level of access to pen resources (enrichment items and feeders) likely has a greater impact on performance of these behaviors than the relatively minor diversion from the legal stocking density limit. A greater number of pigs per feeder may have increased the risk of tail biting or aggression to the point where the results would not reflect typical conditions on a well-managed commercial unit.

Providing sufficient substrate to stimulate foraging and exploratory behavior has been recommended to reduce damaging behavior in pigs (Rodenburg and Koene, 2007). From the current study we conclude that providing pigs with HIGH enrichment reduces aggression and harmful behavior. Our results are in line with (Beattie et al., 2000), who concluded that pigs in an enriched environment (peat and straw) spent more time on exploratory behavior of substrates than pigs in a barren environment. In this study pigs in a barren environment spent more time in harmful behavior such as nosing and biting, and aggressive behavior such as head thrusting. Moreover, a recent study suggests that pigs with low enrichment replacement rates (i.e. enrichment materials were only replaced every second day after they had been depleted) also perform more aggressive and damaging behavior compared to pig where enrichment replacement rates were more frequent (Chou et al., 2020). Thus, in our study the continuous presence of fresh grass as a substrate to explore and eat, likely helped in reducing aggression and harmful behavior. However, it should be noted that our behavioral observations does seem a very short time period, and that there could be a risk of relatively low occurrence of some of the behaviors, and indeed this is why we clustered the behaviors observed into the categories 'aggression', harmful', and 'enrichment'.

In our study, pigs in LARGE groups had lower feed intake and lower weight gain compared with pigs in SMALL groups, although the feed conversion ratio was similar. This could be because pigs in large groups, usually the dominant pigs, control the access to the feeders (Spoolder et al., 1999). A decline in diurnal variation in feeder visit and feed consumed per hour as group size increased was also reported by other studies (Hyun and Ellis, 2002). However if feed resources and space allowance are adequate productivity is not affected by group size (Schmolke et al., 2003). Moreover, in the current study, there was a variation in feeder use, likely due to the pen design and the position of the feeders within the pen. Pigs in LARGE pens preferred certain feeders over others. Since all the feeders were not used equally it might have affected the *ad-libitum* feeding behavior of pigs and thus the overall feed intake and weight gain.

5. Conclusion

In this study we found no effect of group size on water usage or wastage but pigs with HIGH enrichment had lower water usage and wastage compared to pigs with LOW enrichment. Aggression and harmful behavior was lower only in LARGE groups and in pens with HIGH enrichment not in all group sizes. The pigs in LARGE groups had lower feed intake and daily gains compared to SMALL groups while pig/feeder ratio was equal in all pens. Thus we conclude that providing enrichment to pigs in the form of fresh grass next to wood and hanging toys reduces water usage and wastage and has beneficial effects for welfare.

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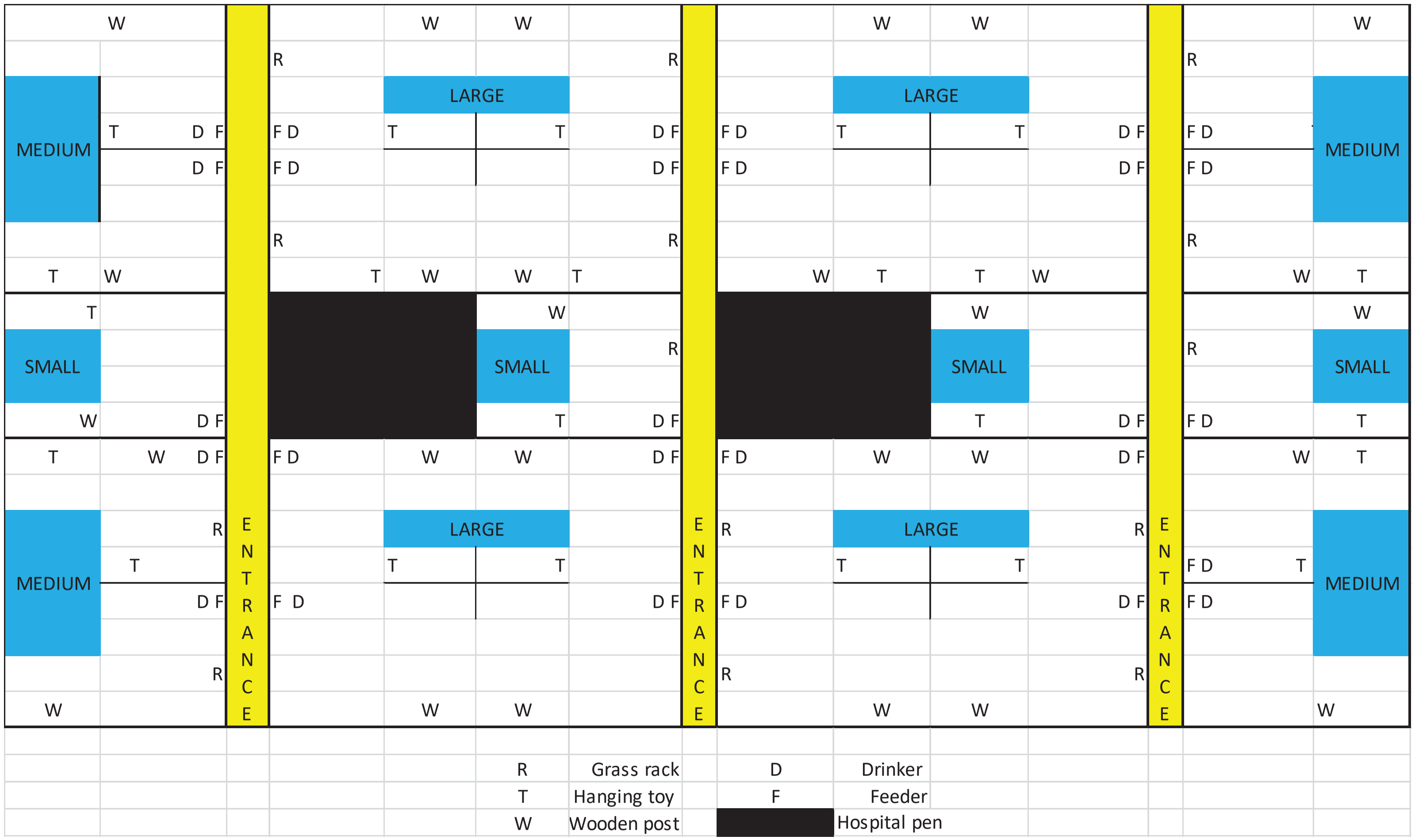

Supplementary Figure S1: Layout of the room housing pigs in group sizes LARGE (48 pigs), MEDIUM (24 pigs) and SMALL (12 pigs) and showing the position of the drinker, feeder and enrichment materials. The black pens were empty and used as hospital pens.

Supplementary Figure S2: LARGE pen with wooden box around the drinker, grass rack, hanging toy and wooden post

Supplementary Figure S3: Wooden box around the drinker used to collect the wasted water

Chapter 6

General Discussion

This thesis provides a comprehensive analysis of freshwater use along the Irish pork production chain, from cradle-to-farm-gate, while linking with animal welfare. I aimed to identify and understand what farming strategies could reduce the green and blue water use from on- and off-farm processes in pork production. I based the analysis of freshwater use along the pork production chain on detailed data collected from commercial farms. This was seen as an important means for understanding the contribution of individual farm processes and identifying farm specific strategies to reduce on-farm and off-farm freshwater use.

In the following sections, I discuss the findings of my research in a broader perspective. In section 6.1, I present the most important findings regarding on-farm and off-farm freshwater use in the pork production chain, based on data collected from 10 Irish pig farms. In section 6.2, I explore how results of this thesis are relevant to the issue of farm sustainability. In particular, I will address the environmental, economic and social (animal welfare) challenges faced by the pork production sector followed by a discussion about how my results could help address those issues. In section 6.3, I will look at the implications of our results for farmers and policy makers. Subsequently, I will look at what is required for future research work, what challenges have to be addressed, and the representativeness of the results for the pig sector within Ireland and beyond (section 6.4). The chapter ends with some concluding statements (section 6.5).

6.1 General findings of the thesis

To deepen the understanding of freshwater use in the pork production chain, I collected farm specific data from 10 Irish pig farms. This included data on pig feed usage and on-farm water use during each production stage, such as drinking, feed mixing and washing. Using these data, in Chapter 2 we quantified the on-farm and off-farm green and blue water use of Irish pork production using the water footprint (WFP) assessment method. The variation in WFP among farms was explored considering management factors, such as herd size, amount of meat produced and type of feeding system. The findings of this study showed that the average total WFP of Irish pork production, including the on-farm and off-farm water use, was 2,537 L/kg pork. Our WFP values are at the lower end of values found in literature, ranging from about 2,800 to 4,500 L/kg pork (Wiedemann et al., 2010; Mekonnen and Hoekstra, 2012; de Miguel et al., 2015; Gonzalez-García et al., 2015). This could be due to the improvement in Irish pig performance over the past 20 years, including a 30% increase in piglets born alive per litter, an increase in deadweight (carcass weight) of 20.1 kg per pig, an improved average daily gain (ADG) from weaning to sale of 150 g per day and a decrease in the amount of feed required from 3.7 to 3.5 kg of feed to produce a kilogram of pork (Boyle et al., 2022).

Off-farm feed production is by far the largest user of water, being responsible for 99% of the total WFP. The largest share of this water use (99%) was green water use. We did not find a clear link between the management factors and water usage per kg pork produced, except for a weak correlation between WFP and farm size and meat produced. The outcomes of this study formed the basis of the other Chapters (3, 4 and 5), which focus on comparing different types of feeding strategies that could reduce the freshwater use of pig feed production, and cleaning and pig management procedures that could help reduce the water usage on-farm.

Since we found that feed production is the main contributor to freshwater use in the pork production chain we explored whether different feeding strategies could reduce water use in Chapter 3. Pig diets generally include high quality feed ingredients (suitable for human consumption), such as wheat, soybean, barley and maize. These feed ingredients are primarily imported into Ireland and are also in competition with human food (Mottet et al., 2017, van Zanten et al., 2018). We thus explored whether the inclusion of locally grown feed ingredients, or by-products, in pig diets could reduce the freshwater use of the pigs feed. Locally grown feed ingredients were studied as an alternative to importing feed from water stressed regions. By-products (i.e. side streams of main crop production) were studied as they are mainly unsuitable for human consumption and as such reduce competition between human food and feed. All feeding scenarios were compared against each other by formulating pig diets according to requirements of each production stage (gestation, lactation, weaners and finishers). Locally produced feed ingredients included faba beans and peas which were used to replace imported soyabean. As our starting point was to maintain pig performance, the share of these local ingredients in the diet was high. Because the high share in the diet and the relatively high WFP of local ingredients, selecting for local ingredients did not lower the WFP of pork. However, the by-product scenario performed better than the other feeding scenarios for both WFP and food-feed competition. Human edibility of by-products is an important factor to consider in formulating pig diets. By-products that were non-human edible and not further processed, such as beet pulp, bakery by-products and oil seed meals, had a low WFP and were thus considered promising ingredients. The exact WFP is determined by their economic value, which is zero for beet pulp and bakery by-products (hence WFP is zero) and small for rapeseed meal (WFP is low but not zero). Moreover, rapeseed meal and sunflower seed meal are not considered human edible and were considered fit for future inclusion in diets.

On-farm freshwater use is another contributor to the WFP of pig production, and is addressed in Chapter 4 and 5. In contrast to feed production, on-farm processes (such as drinking and cleaning) only contribute towards blue water use. Washing of pig pens between batches is a common practice on pig farms, especially for younger and newly weaned pigs, which are more vulnerable to infectious diseases. In Chapter 4, we studied three different cleaning and disinfection methods for weaner pig pens to determine which methods use least water, while accounting for bacterial load, and thus ensuring that water use was not reduced at the expense of good hygiene. Although the results did not provide a clear indication of which cleaning method is the best to reduce freshwater use, we found that a combination of pre-soaking and use of detergent reduced washing time, which has a knock on effect of reducing labour requirements. This could thus have economic benefits for the farmers.

Another major aspect of on-farm freshwater use is drinking. Sufficient drinking water is an essential requirement to ensure good pig welfare. Although much drinking water is consumed by pigs, part of it is wasted. Besides impacting freshwater resources, water wastage also increases the volume of pig slurry, thus diluting it, and if the tanks have to be emptied very often, affecting the cost of waste disposal. Drinking water usage and wastage on-farm is affected by various factors, and to reduce drinking water wastage it is important to understand drinking behaviour. In Chapter 5 we hypothesized that a larger group size and provision of a favoured enrichment material would optimize water use by reducing waste. Our findings showed that pigs in larger groups, and hence provided with more shared space, and higher enrichment (wooden post, hanging rubber toy and fresh grass) performed less aggressive and harmful behaviour. Moreover, a providing high enrichment allowance reduced water usage and wastage, so may have benefits for the environment, as well as animal welfare.

6.2 Contribution to farm sustainability

The pig sector plays an important role in meeting global food demand, but at the same time there are rising concerns regarding the sustainability of current pig production systems and their impact on, amongst other issues, animal welfare, greenhouses gas emissions and land use changes (MacLeod et al., 2013). The EU Green Deal focuses on a farm-to-fork strategy to accelerate transition to sustainable food systems (European Union, 2020). Sustainable development is defined "as the development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland, 1987) and consists of three dimensions: environment, economics and social sustainability. Here I will address future pig farming from these three dimensions using our research findings.

6.2.1 Environmental sustainability

The detrimental impacts of livestock production on the environment is well-known. Global livestock production produces large amounts of environmental pollutants, including, amongst others, emissions of greenhouse gases and ammonia. The livestock sector is responsible for about one-third of global freshwater withdrawals (blue water use) and uses about 40% of global arable land for feed production (Poore and Nemecek, 2018; Mottet et al., 2017). Expansion of livestock production furthermore leads to increased land-use change and biodiversity loss due to requirements for animal feed (Mbow et al., 2017). A deeper assessment of driving factors is required to identify strategies to reduce these environmental consequences. I discuss here key driving factors associated with environmental impacts in pig production, such as the competition for land and water between humans and animals (i.e. feed-food competition) and nitrogen and phosphorus losses from decoupling of feed production and manure handling.

Production of animal source foods requires good quality feed, yet this mostly comes from food crops that could potentially end up on our plates for direct consumption (Mottet et al., 2017). To continue producing animal products for human consumption under the current model, we would have to produce more feed crops that compete for land and other natural resources. However, continued expansion of cropland to grow more feed and food would happen at the expense of carbon-rich forests and other natural ecosystems. Thus in Chapter 3 we investigated scenarios to replace standard pig feed ingredients (wheat, barley, soyabean, maize) with by-products from plant-source food production. Our results justified the hypothesis that using such by-products can reduce the impact on freshwater resources of pig production, and lower food-feed competition. Studies looking at the role of livestock in circular food systems confirm that pigs are efficient feed convertors and can play a key role in converting by-products and other side streams into animal-sourced food (van Zanten et al., 2018; van Hal et al., 2019). Our results confirm that also from a water use perspective, utilization of food waste or by-products in pig diets seems to be a good way to handle food losses and to convert low-value materials into high-quality products. In line with this, and since land and water resources are connected, using more by-products as pig feed could also be beneficial in terms of combatting challenges like land use change, and associated impacts such as biodiversity loss or carbon emissions. To fully understand the consequences of changing pig diets, or to identify the most sustainable feeding strategy, however, a food systems approach is needed. Such an approach includes the production as well as the consumption side of pork and covers the linkages between agricultural commodities, while assessing the various environmental issues the agricultural sector is facing. Such food system studies also emphasise the need to reduce the proportion of animal products in human diets and the need to reduce animal numbers (at least in high-income countries). In this thesis, however, we focussed on the pig production chain, and what farmers could do to reduce the WFP of pork specifically. We did not include the freshwater consequences for the alternative application of by-products, such as the use of those by-products in cattle of poultry feed or the production of fibres or fuel.

In Ireland, a large share of pig feed is imported from other countries; in other words, feed and pig production are decoupled. This decoupling can cause accumulation of nutrients from pig manure, such as nitrogen and phosphorus, in specific regions, causing emissions to the air and leaching of nutrients into the ground or surface waters. The environmental impacts associated with manure are addressed in Chapters 3 where we investigated feeding strategies with locally sourced feed ingredients in pig diets. Using locally grown feeds is a way to recouple feed and pig production and restore the cycling of nutrients in agricultural systems. Our findings of chapter 3 show that using locally sourced by-products as pig feed is beneficial for water use. Feeding local by-products also allows for recoupling of feed and pig production or in other words bringing back the nutrients to the land.

In chapter 4 and 5, moreover, we explored management strategies to reduce water usage and wastage for on-farm processes such as cleaning and drinking. Waste water on pig farms is collected in the slurry tanks, and thus directly linked to increasing manure volumes, with consequential impacts manure quality and disposal costs. Our finding that providing pigs with an improved quality of enrichment lowers both the water usage and water wastage, could thus have positive impacts for slurry management. The most common enrichment options chosen by pig farmers in Ireland are wood, hanging toys and chains, which were represented in our standard enrichment treatment. However, our results showed that providing fresh grass, which is an ample resource in Ireland, is a better option for pigs as well as water use.

6.2.2 *Economic sustainability*

Economic sustainability at farm level implies balancing revenues and costs and includes issues such farm efficiency, stable production costs, good animal health, etc. However, due to low and unstable pork prices and increased feed prices economic pressure on farmers has increased in recent years. Feed costs represent approximately 75% of production costs, and thus in the current climate of rising feed costs, the total cost of production is significantly impacted. Pig diets that incorporate by-products could help in reducing feed costs, and inedible by-products or low opportunity cost feeds could also lower the competition between food and feed (Chapter 3). However, it is important to note that all diets in our study were formulated to not only meet the dietary needs of the pigs, but to also ensure a similar level of performance. Diets fed to livestock are generally complex and require various ingredients to meet their nutritional requirements. Feeding pigs with only by-products could reduce feed costs but might also affect farm revenues as by-products are less nutrient dense (Boumans et al., 2022), and a high inclusion rate might reduce animal productivity (growth, number of pigs). To optimize pig production systems from a freshwater as well as an economic perspective, therefore, insight is needed into how pig growth rates could be optimised. In other words, we need to determine the optimal inclusion levels of different by-products from both a freshwater and economic perspectives. Since there is a possibility if these future strategies are adopted it will affect the overall farm productivity, some form of sustainable farming incentives or payments should be provided to farmers, meaning farmers can receive payment for their actions like inclusion of low opportunity cost feed.

Cleaning and disinfection procedures are essential to maintain good hygiene and to reduce disease prevalence on farms, ultimately helping to reduce economic losses due to mortality. Although the findings in Chapter 5 showed that using pre-soaking and detergents for cleaning were only as effective in cleaning as power washing, and pre-soaking followed by power washing, we did find that pre-soaking and detergents could save 4.2 minutes per pen compared to only power washing, and thus reduce labour needs. From a producer's perspective, this is beneficial for cost saving, as labour represents 6% of the cost of pig production. Therefore, further work is needed to understand the impact of using different concentrations of detergents and disinfectants involving more pens. Attention should be paid to potential environmental trade-offs as the use of different concentrations of detergents or disinfectants should be carried out with care, as these have been linked to contamination of the receiving waters (Boyano et al., 2018).

6.2.3 Social sustainability

Social sustainability can be defined as social perceptions of animal farming, including social appreciations and concerns related to animal production systems (Boogaard et al., 2011). Pig farmers also face challenges in maintaining good pig welfare, an issue which is of particular societal concern (European Commission, 2016).

Pigs in Ireland, like in many other countries, are kept in intensive production systems. These systems are characterized by big herds, low space allowance, barren environments and standardized management procedures, all of which contribute to welfare challenges, such as tail biting (Boyle et al., 2022). In this thesis I have addressed the issue of wastage of water on farm and its relationship with animal welfare from the perspective of pig management (provision of more shared space and enrichment for pigs) (Chapter 5), and cleaning methods of pig pens (Chapter 4). Improper hygiene on farm could lead to exposure of pigs to microorganisms, which could be particularly serious for newly weaned pigs. In Chapter 4 we discuss how the *Enterobacteriaceae* counts did not decline even after washing procedures; the level of *Enterobacteriaceae* present in the pens is important because it causes wide range of diseases especially post weaning diarrhoea in newly weaned pigs. One reason why levels did not differ across to the cleaning regimen applied in Chapter 4 is because high pressured washing leads to water splashing, and creates highly concentrated aerosol droplets with bacterial levels (Mannion et al., 2007). These droplets get deposited again on the pen surfaces thus reducing the impact of washing procedures. Thus as well as protocols for detergent use, soaking etc., other strategies such as reducing the water pressure while washing could have benefits (Chapter 4).

In Chapter 5 of this thesis, we explored how providing proper enrichment and more shared space to pigs not only has benefits for the environment but also for pig welfare. In bigger group sizes the probability of monopolizing resources declines as the number of competitors increases, so fewer individuals get involved in costly fights (Andersen et al., 2004). Thus, in larger groups pigs appear to become less aggressive and may shift to a low-aggressive social strategy (Samarakone and Gonyou, 2009). Pigs have a natural foraging behaviour and in barren environments spend more time engaged in harmful behaviour such as nosing and biting, and aggressive behaviour such as head thrusting. The supplementary enrichment that was provided in the high enrichment treatment meets the requirements for pigs produced on slatted floors as prescribed in Council Directive 2008/120/EC. This is more thoroughly defined in a Commission Staff Working Document on best practices with a view to the prevention of routine tail-docking and the provision of enrichment materials to pigs, published in 2016 (European Union, 2016). Our findings showed that providing high enrichment in the form of fresh grass in a large group size was associated with reduced levels of aggressive and damaging behaviours, indicating better pig welfare, with knock on benefits with regard to water wastage, due to less interference with drinkers.

6.3 Integrative solutions for farmers and policy makers

Farmers are the most important stakeholders involved in the sustainable development of livestock systems. To improve the sustainability of the livestock sector a robust policy and legislative framework is required. Local and national governments have a key role in implementation of policy options.

Based on the outcomes of this thesis there are various strategies that farmers can implement that could potentially contribute to improved water usage and pig welfare. An innovative farm concept could be developed for pig production, involving integrative solutions that address different sustainability issues. Examples of integrative solutions could be inclusion of by-products from locally produced crops (including returning of manure to local fields) that are also beneficial for pig welfare, such as beet pulp or vegetable leftovers, or the feeding of grass to reduce water usage and wastage and to improve pig welfare. These solutions address different challenges of sustainable pig farming, such as improving freshwater use, land use change, manure management and animal welfare.

To identify specific strategies to improve the overall sustainability of pig farms, an integrated assessment is required. One crucial requirement in data collection is farmer participation. There are several benefits for farmers when getting involved in such assessments, including obtaining better insight into their farms resource use, and the potential to increasing farm sustainability, and improve the market value of their products. Changes in feeding strategies is one solution which could help reduce freshwater use and food-feed competition, potentially benefitting the producer. Many Irish pig farmers are home millers and hence have a choice to source their own ingredients, and as such could select sustainable feed sources such as by-products (Chapter 3). Although there are regulatory restrictions to inclusion of by-products and low opportunity cost feed in pig diets, there are several by-products which are already recommended for use in pig diets, and many others have potential for inclusion. Considering the results in Chapter 3, it is probable that using by-products as ingredients in pig diets could reduce their impact on freshwater use, and on food-feed competition; therefore, their inclusion should be encouraged. Such strategies would play an important role in any future sustainable development goals.

Compared to off-farm strategies to reduce freshwater use of feed production, farmers have much greater control over on-farm processes (cleaning and drinking). There are specific EU legislations which laydown minimum standards that must be met for keeping pigs in intensive production systems, which place a significant focus on providing proper enrichment and living space to pigs. Use of better enrichment materials and incorporation of shared space allowance recommendations for pigs are worthy of consideration, whether in new regulations or directives, or enforcement of existing ones. Cleaning and hygiene on farms is something which is done on a regular basis. However, not using proper cleaning methods or materials can directly affect animal health and welfare, and could lead to diseases and economic losses for the farmer. In our study (Chapter 4) we found that mostly the feeders are the spaces within the pens where bacterial level remains higher even after all cleaning and disinfections. Thus these areas should perhaps be focused upon to reduce contamination while optimising water use, with consideration given to recommended detergents and disinfectants.

In the search towards sustainable farming, governments, scientists, farmers and non-governmental organisations should work together. At present, according to the Food vision 2030 report by the Irish Department of Agriculture, Food and Marine (DAFM, 2021), Bord Bia, the Irish food board, has developed a sustainability survey targeting environmental performance on farm based on carbon footprint calculations. However, to achieve the overall wellbeing of people and planet we have to come out of a carbon 'tunnel vision' and also consider other sustainable development goals. One such goal is to reduce the water resource crisis. The farm data required for both carbon and water footprint indexing are similar (e.g. farm production, feed usage etc.) and thus it could be wise to also develop a calculation matrix for water resource use. Apart from pigs, such a measurement matrix could be also developed for other livestock systems including dairy, beef, and poultry.

6.4 Future research and challenges

In this thesis, we aimed to assess the water footprint of pig farms using 10 farms. However, in some farms technical difficulties meant that water meter data was not available. Moreover, due to lack of sufficient data, we were unable to study the influence of various farm management factors on freshwater use. Therefore, future studies at country level should include a sufficient number of pig farms to obtain improved insight into freshwater use and the management practices on farms which can affect water use. There are not many studies focusing on the freshwater use of the whole pig production cycle, and learning from the outcomes of this research could enable more studies like this one to be conducted in other countries, and for other livestock systems. Similarly, this study utilised detailed on-farm water data which was collected from commercial farms, since this data is time consuming and expensive to collect, future studies should decide from the outset whether the hypothesis to be tested requires such detailed data or not.

Another important challenge we encountered during this study was the availability of feed ingredient and climate related data. For some pig farms, which were buying feed from mills, we faced difficulties in acquiring the exact diets used for each production stage. In future studies transparency of study objectives, and openness of data sharing with industry stakeholders (such as feed companies) should be ensured from the outset for accuracy in modelling. This would not only contribute to verifying and improving the information about diet composition and nutritional values, but also open the conversation on how to move forward towards a more sustainable feed supply chain. Climatic data for calculation of crop water footprint is one of the most important requirements when studying the freshwater use of livestock systems. We found that there was a significant difference in the final calculated WFP of pork when calculations were based on historic climate data (1961-1990) compared to the results that were calculated based on more recent data (1979 to present). Differences in the water footprint of major feed ingredients were found to be 2.4 fold in the case of wheat, and 5.5 fold in case of soyabean meal. Other important assumptions included those on the maximum potential yield of each crop, which was to be 1.2 times of the national average yield of the region. Thus, future research should also take into consideration importance of high quality data and awareness of researchers about this.

Livestock production also faces other external challenges such as the push for identifying alternative protein sources. The increasing world population and the environmental challenges posed by livestock production systems are encouraging the expansion of cultivated meat or the plant-based meat sector, and promoting increasing investment in these areas. Thus, for livestock production systems to address and survive future challenges it is important to adopt sustainability measures that incorporate reduction of emissions, freshwater use and land use change, and that improve animal welfare. This body of work identified several measures that could be adopted to not only reduce the freshwater use of pig production, but also potentially improve the welfare of pigs.

6.5 Conclusions

This study presents the first WFP assessment of Irish pig farming using farm specific data, which does not currently exist in the literature. The overall WFP of Irish pig farms was at the low end of previously published studies (2,537 L/kg pork). Thus, with regard to pork production, Irish systems appear to perform well when it comes to minimizing use of freshwater resources. Nevertheless, this study also indicates an opportunity for present and future pork production systems to source feed ingredients from non-water stressed areas to further reduce the burden on freshwater resources.

The use of by-products in pig diets had a beneficial effect on freshwater use, and also lowered food-feed competition. In terms of reducing freshwater use the most promising ingredients were rapeseed meal, bakery by-products and beet pulp, as they had low or no water use. To reduce food-feed competition, the human inedible by-products (i.e. bakery by-products, rape seed meal, beet pulp and sunflower seed meal) were best suited. When considering sustainability of animal feed production, human edibility of the feed ingredients is an important criteria to determine which ingredients will reduce the competition for water resources between food and feed production in the future.

In our cleaning study we found no difference in both water use and bacterial load between the treatments studies, hence power-washing without pre-soaking or detergent seems to be the simplest method, and thus perhaps the preferred option. However, if a view from the producer perspective is taken, pre-soaking and detergent use saves time and labour cost, so this would be the preferred option.

Providing enrichment to pigs in the form of fresh grass in addition to wood or hanging toys reduced water usage and wastage. Moreover, pens with larger group size and fresh grass as enrichment also had lower aggression and harmful behaviour. Thus we conclude that farm management strategies reduce freshwater use, and had in this case had beneficial effects for welfare.

To make future improvements in sustainable development and reduction in freshwater use, farmers and policy makers should work in collaboration through a framework of integrative solutions. Overall, using more sustainable feed ingredients in pig diets such as such as beet pulp and bakery waste and providing pigs with fresh grass as an enrichment source holds the greatest potential and are good for both the environment and animal welfare.

Summary

This thesis provides a comprehensive analysis of freshwater use along the Irish pork production chain, from cradle-to-farm-gate, while linking with animal welfare. The aim was to identify and understand what farming strategies could reduce the green and blue water use from on- and off-farm processes in pork production. The analysis of freshwater use along the pork production chain was based on detailed data collected from commercial farms. This was seen as an important means for understanding the contribution of individual farm processes and identifying farm specific strategies to reduce on-farm and off-farm freshwater use.

In **Chapter 2** focus is on pork production in Ireland and the freshwater use (green and blue) is studied from cradle-to-farm gate perspective using the water footprint (WFP) method. This study presents the first WFP assessment of Irish pig farming using farm specific data. We analysed on-farm and off-farm green and blue water use of 10 Irish pig farms. Detailed farm data (e.g. diet composition, production data) were combined with on-farm water meters to explore variation among farms and potential explanatory variables. Our results show that the average total WFP, including on-farm and off-farm water use, was 2,537 L/kg pork which was at the lower end of previously published studies. Green water use during the production of purchased feed was responsible for the largest share (99%) of the total WFP. On-farm blue water use formed only a minor component of the total WFP (14 L/kg pork), with drinking water playing the major role. We also found a weak negative correlation between WFP and farm size, and WFP and meat produced. The results from this study formed the basis of the following **Chapters (3, 4 and 5)** where we compare different feeding strategies to reduce freshwater use of pig feed production and also study the on-farm cleaning and pig management practices that could help reduce freshwater usage.

The objective of **Chapter 3** was to assess the impact on freshwater use of pork production by using alternative pig diets based on local feed ingredients, or by-products. Three feeding scenarios were explored (STANDARD: diets commercially used in Ireland; LOCAL: diets based on ingredients grown in Ireland; and BY-PRODUCT: diets based on by-products only). For each scenario, freshwater use per kg pork was calculated from cradle-to-farm gate, using the water footprint (WFP) method, and the competition for water use between food and feed production was accounted for by using the water use ratio (WUR). The WFP of the scenarios was 2,470 L/kg pork for STANDARD, 2,492 L/kg pork for LOCAL, and 2,205 L/kg pork for BY-PRODUCT. When we considered the WUR, none of the scenarios had a value < 1,

which means that in all scenarios, more human digestible protein (HDP) can be produced from direct consumption of food crops rather than from feeding them to pork. However, the BY-PRODUCT scenario (1.4) performed better than STANDARD (1.9) and LOCAL (2.9). Beet pulp and bakery by-products had zero WFP and no edibility and were thus considered promising ingredients. Moreover, rapeseed meal had a low WFP, and rapeseed meal and sunflower seed meal are not considered human edible and fit for future inclusion in diets. We also concluded that it is important to consider human edibility of feed ingredients in future studies, and that both the WFP and WUR methods have separate strengths and limitations, and should thus be used in conjunction; the ideal diet is one with the minimum WFP and WUR.

In the last two **Chapters (4 and 5)** we studied the farm management practices which could potentially help to reduce the on-farm freshwater use of pork production with a focus on cleaning and drinking water. There is very little knowledge available about the on-farm factors that influence freshwater use in the pig production chain. **Chapter 4** describes an experimental study to quantify the effect of three different washing treatments on freshwater use, bacterial levels [(total bacterial counts; TBC), *Enterobacteriaceae* and *Staphylococcus*] and cleaning time in washing of pens for weaning pigs. The washing treatments used were power washing and disinfection (WASH); pre-soaking followed by power washing and disinfection (SOAK), and pre-soaking followed by detergent, power washing and disinfection (SOAK + DETER). A water meter was used to collect water use data and swab samples were taken to determine the bacterial levels. The results showed that there was no overall effect of washing treatments on water use. However, there was an effect of treatment on the washing time ($p<0.01$) with SOAK and SOAK+DETER reducing the washing time per pen by 2.3 minutes (14%) and 4.2 minutes (27%) compared to WASH. Nonetheless, there was an effect of sampling time (before or after washing) ($p<0.001$) on the levels of TBC and *Staphylococcus*, but no effect was seen on *Enterobacteriaceae* levels. Thus, the washing treatments used in this study had no effect on the water use of the pork production chain. Although there was no difference in both water use and bacterial load, from a producer perspective, pre-soaking and detergent use can save time and labour costs, so this would be the preferred option.

The grower-finisher stage accounts for 64% of the total on-farm water use. Part of this is consumed by the pigs, but a part is also wasted. In **Chapter 5** we studied the different factors that affect the drinking water usage and wastage. We investigated how different group sizes and different levels of enrichment affect water usage (ingested plus wasted), water wastage, behaviour and performance in grower-finisher pigs. The effect of group size: SMALL (12 pigs), MEDIUM (24 pigs), and LARGE (48 pigs) was assessed across two levels of enrichment (LOW—wooden post, hanging rubber toy, HIGH—Same as LOW + fresh grass). There was no effect of group size on water use or wastage. Pigs with HIGH enrichment (10.4 ± 0.4 L/pig/day) used less water than LOW enrichment (11.0 ± 0.4 L/pig/day; $p < 0.001$). The water wastage/drinker/hour was lower in pens with HIGH enrichment than LOW ($p = 0.003$). The drinking bout number ($p = 0.037$) and total occupancy/hour ($p = 0.048$) was also higher for pens with LOW than HIGH enrichment. Aggressive and harmful behaviour were performed less in LARGE groups and pens with HIGH enrichment. Thus, HIGH enrichment allowance reduced water usage and wastage so may have benefits for the environment, as well as animal welfare.

Finally, **Chapter 6** brings together the overall insights from all the preceding chapters and discusses how the outcomes of this PhD research can contribute towards improving the sustainability of pig farming from an environmental, economic and social (pig welfare) perspective. I concluded that with regard to pork production, Irish systems appear to perform well in terms of utilizing freshwater resources. Nevertheless, this study also identified opportunities for present and future pork production systems to source feed ingredients from non-water stressed areas to further reduce the burden on freshwater resources. Moreover, the use of by-products in pig diets had a beneficial effects on freshwater use, and also lowered food-feed competition. Examples of promising ingredients are rapeseed meal, bakery by-products and beet pulp. In terms of cleaning procedures, power-washing without pre-soaking or detergent is recommended because it seems to be the simplest method, while pre-soaking and detergent use is recommended because it saves time and labour cost. In terms of reducing the drinking water usage and wastage on farm providing enrichment to pigs in the form of fresh grass in addition to wood or hanging toys was a helpful strategy. Moreover, pens with larger group size and fresh grass as enrichment also had lower aggression and harmful behaviour. Thus, I concluded that providing enrichment reduce freshwater use, while also having beneficial effects for pig welfare.

To make future improvements in sustainable development and reduction in freshwater use, farmers and policy makers should work in collaboration through a framework of integrative solutions. The above listed strategies hold great potential to reduce water use and are good for both the environment and animal welfare.

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Acknowledgements

When I started this PhD I was sceptical about my competence to work with livestock, especially pigs. Being from Delhi, an extremely crowded capital city, with no large scale commercial farms, I had no experience of working with livestock. After landing in Ireland, I very soon started helping other PhDs to conduct measurements on the Teagasc experimental farm including weighing pigs, moving pigs and struggling to put them inside the pens. This gave me immense experience and confidence and then I started my own PhD journey.

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Finally, I dedicate this thesis to the little angel that came into my life just for a short time. You were supposed to be a part of the final stretch of my journey, but I am sorry, I couldn't keep you. I hope you return one day and become a part of my life again. Love you forever.

About the author

Shilpi Misra was born on the 1st of October in Delhi, India. Shilpi obtained her BSc (Honours) degree in Botany, at University of Delhi in 2004. During her undergraduate studies, Shilpi developed interest in environmental science and decided to pursue her career in this area. She obtained an MSc in Environmental Studies from Teri University, Delhi, in 2007. Shilpi then worked at the Environmental department of SGS India as an analytical chemist. From 2007-2012, she worked as a Senior Research Fellow at the Centre for Environment Science & Climate Resilient Agriculture, IARI, Delhi, to do research on "Impact, Adaptation and Vulnerability of Indian Agriculture to Climate Change".

In 2012, Shilpi decided to continue her education and embarked on an adventurous educational journey to Europe. She received the Erasmus Mundus Scholarship to pursue International Masters in Environmental Technology and Engineering from IHE Delft, the Netherlands, University of Chemistry and Technology, Prague, Czechia and Ghent University, Belgium. She completed her studies with a magna cum laude and did her thesis on "Exploring the potential of iron and cerium oxide nanoparticles to reduce the uptake of arsenic by paddy rice". Her thesis was awarded as one of the best thesis in water technology sector by TNAV Flanders Water Technology Network.

After completing her MSc she worked as a Consultant at International Union for Conservation of Nature (IUCN), India on various nature conservation projects. In 2018, Shilpi received the Walsh Scholarship from Teagasc, to do a PhD in collaboration with Animal Production Systems group at Wageningen University and Research. Under the supervision, Prof. Imke de Boer, Dr. Keelin O'Driscoll and Dr. Corina van Middelaar, Shilpi's research focused on reducing freshwater use of pork production systems considering Ireland as a study area. During this PhD, Shilpi also received an award, Teagasc Walsh Scholar of the year 2021 (Runner-up) for Animal and Grassland Research and Innovation Programme.

Findings of her thesis were presented at international conferences, newsletter, research centre open days, and published in peer-reviewed scientific journals.

Publications

Journal Papers

Misra, S., van Middelaar, C. E., O'Driscoll, K., Quinn, A. J., de Boer, I. J.M., & Upton, J. Water footprint of pig farms in Ireland based on commercial farm data.

Misra S, Upton J, Manzanilla EG, O'Driscoll K, Quinn AJ, de Boer IJM, et al. Re-thinking water use in pig diets while accounting for food-feed competition. Journal of Cleaner Production. 2023; 384:135488.

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Pant D, Misra S, Nizami AS, Rehan M, van Leeuwen R, Tabacchioni S, et al. Towards the development of a biobased economy in Europe and India. Crit Rev Biotechnol. 2019; 39(6):779-99.

Conference Presentations

Misra, S., Upton, J., Manzanilla, E.G., O'Driscoll, K., Quinn, A. J. and de Boer, I. J. M., van Middelaar, C. E. Re-thinking water use in pig diets while accounting for food-feed competition. Circular@WUR, Wageningen, the Netherlands, 11-14 April, 2022

Misra, S., Bokkers, E. Upton, J., Quinn, A.J. and O'Driscoll, K. Linking animal management to behaviour, and freshwater use and waste, in fattening pigs. Proceedings of the 8th International Conference on the Assessment of Animal Welfare at Farm and Group Level, 16 – 19 August 2021. pp. 212

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Technical reports

Misra, S., et al., Pig welfare and water use. TResearch Winter 2022, 17(4), ISSN 1649-8917.

Misra, S., et al., Cleaning on pig farms. TResearch Summer 2021, 16(2), ISSN 1649-8917.

Misra, S. 2018. Sustainable Water Footprint of Pig Production Systems. Teagasc Pig newsletter.

Project outreach videos

Waterworks -Why My Research Matters?
https://www.youtube.com/watch?v=efAPjJFd86E

Every drop counts – Walsh Scholar of the year competition
https://www.youtube.com/watch?v=W9tlFyhLGww

Education and Training certificate

With the activities listed the PhD candidate has complied with the educational requirements set by the Graduate School of Wageningen Institute of Animal Sciences (WIAS). One ECTS equals a study load of 28 hours

The Basic Package	**2 ECTS**
WIAS Introduction Day	2018
Course on philosophy of science and/or ethics	2019

Disciplinary Competences	**23 ECTS**
WIAS Writing research proposal/literature survey	2018
E-learning course: "Water Footprint Assessment, concept and application"	2018
Laboratory and Animal Science Training (LAST) –Ireland	2018
APS/WIAS course Environmental impact assessment of livestock systems	2019
WIAS/PE&RC advanced statistics course Design of Experiments	2019
WIAS course Statistics for life science	2019
WIAS course A bio-based society: from principles to practice	2021

Professional Competences	**8 ECTS**
AFGDP and UCD course PhD and beyond Masterclass	2018
Wageningen School of languages Scientific Writing	2020
WIAS course Reviewing Scientific Manuscript	2021
WIAS course The Final Touch: Writing the General Introduction and Discussion	2022

Societal Relevance	**3 ECTS**
Volunteered in AgriAware Day	2018
Volunteered in Science Day	2018
Volunteered in AgriAware Day	2019
Volunteered in Open Day	2019
Volunteered in Science Day	2019
Public outreach project video, Why research matters competition	2020
Public outreach project video for Walsh scholar of the year competition (Runner-up)	2021

Presentation Skills	**4 ECTS**
LCA food conference (Poster)	2020
BSAS conference (Oral)	2021
WAFL conference (Poster)	2021
Circular@WUR conference (Oral)	2022

Teaching Competences	**6 ECTS**
Supervising three Masters students (summer placements)	2019

Education and Training total	**46 ECTS**

Colophon

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