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Résumé
Deze deskstudie geeft een overzicht van de literatuur over de gevolgen van een verhogen van het gebruik van "circulaire ingrediënten" in varkensvoeders om de circulariteit van voedselproductiesystemen te vergroten. Voor de studie werden groepen van grondstoffen geselecteerd aan de hand van twee scenario's, het eerste met het doel te verminderen van het aandeel granen, het tweede gericht op het verminderen van het gebruik van eiwitbronnen van buiten de EU, zoals sojaschroot, in varkensvoeders.
De effecten van het gebruik van deze "circulaire" grondstoffen op dierprestatie (voeropname en groei) en op b.v. karkaskwaliteit en mogelijke effecten op de gezondheid en het welzijn van varkens worden in dit rapport beschreven.

Abstract
This report reviews literature on the consequences of increasing the use of circular ingredients in pig diets to enhance the circularity of food production systems. A cluster of feed ingredients was selected and reviewed based on two scenarios, the first aiming to reduce the use of cereals in diets for pigs, the second aiming to decrease the use of protein sources from outside the EU, e.g. soybean meal, in pig diets.
The effects of the use of these "circular" ingredients has been described considering their nutritional characteristics and effects on growth performance and carcass quality, as well as their potential effects on health and welfare of pigs.

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Foreword

The program 'Vitale Varkenshouderij' (ViVa) is a private partnership between the Dutch ministry of Agriculture, Fisheries, Food Security and Nature (LVVN) and the "Coalitie Vitale Varkenshouderij (CoViVa)[1]".

Its aim is to take a targeted approach for the sustainability and innovation in the pig farming sector. This balanced approach should lead to a more vital and innovative pig farming sector, and to a more sustainable chain that produces high-quality food from a strong market position and is a crucial link in the circular economy.

A research program has been established in the form of a Public Private Partnership (PPP) entitled "Vitale Varkenshouderij" to support the ambitions of CoViVa. One of the ambitions relate to the central position of pig farming in the circular economy means strengthening the pig's position as the ultimate recycling animal. Pigs convert low-value products (e.g. residues from the food industry) into high-quality food. In addition, pig manure is valuable as a basis for green energy, as a soil improver and as a substitute for fossil fertilisers.

This report presents the results of a desk study performed by Wageningen Livestock Research in the framework of the PPP on the consequences of increasing the use of circular ingredients in pig diets on pig performance, health and welfare.

The authors thank the partners of CoViVA for their support and the members of the clusters "KBG Circulariteit en Voeders' and "KBG Circulariteit & Effecten op het varken" for their valuable input in the study.

[1] The Coalitie Vitale Varkenshouderij is a chain-wide cooperation of organisations throughout the pig chain: Producenten Organisatie Varkenshouderij (POV), Rabobank, De Centrale Organisatie voor de Vleessector (COV), De Nederlandse Vereniging Diervoederindustrie (Nevedi), Topigs Norsvin en the Dutch ministry of Agriculture, Nature and Food Quality (LNV).

Samenvatting

Dit rapport presenteert een overzicht van de literatuur over de gevolgen van een toename in gebruik van circulaire ingrediënten in varkensvoeders om de circulariteit van voedselproductiesystemen te verbeteren. De studie is uitgevoerd in het kader van het onderwerp Circulaire Economie van het Publiek Private Samenwerking (PPS) project "Vitale Varkenshouderij". Specifiek richt dit rapport zich op de nutritionele waarde en effecten van het inclusie niveau van circulaire grondstoffen in varkensvoeders en hun invloed op dierprestatie, gezondheid en welzijn.
Verschillende groepen grondstoffen werden geselecteerd op basis van twee scenario's die bijdragen aan de vergroting van de circulariteit van de varkenshouderij, als onderdeel van de meer circulaire productie van voedsel voor de mens. Het eerste scenario gaat uit van de vermindering van het aandeel granen in varkensvoeders en vervanging door alternatieve grondstoffen en bijproducten. Het tweede scenario is gebaseerd op het verminderen van het gebruik van eiwitbronnen van buiten de EU, zoals sojaschroot, in varkensvoeders. Voor deze twee scenario's werden (groepen) grondstoffen geselecteerd waarna informatie over hun voedingswaarde en hun effecten als energie- en eiwitbron op de groeiprestaties van varkens en hun effect op gezondheid en het welzijn van varkens werden beschreven op basis van informatie uit de wetenschappelijke literatuur.

<u>In het eerste scenario</u> 'minder granen' werden drie verschillende groepen grondstoffen beschreven: bijproducten van granen, natte bijproducten van aardappelen en keukenafval. De eerste twee groepen zijn goed bekend en worden thans gebruikt in varkensvoeders, terwijl keukenafval een veelbelovend duurzaam voedermiddel voor de toekomst kan zijn, echter wettelijk thans niet toegestaan vanwege veronderstelde voedselveiligheidsrisico's bij gebruik.
Een hoger percentage graanbijproducten (bijv. zemelgrint, voermeel, en andere maalderijproducten) in varkensvoeders lijkt mogelijk zonder grote consequenties voor de dierprestaties. In de literatuur werd geen negatief effect gerapporteerd op de voeropname van biggen of varkens bij het verhogen van de opname van deze producten. De gerelateerde prestaties waren vergelijkbaar of beperkt lager ten aanzien van de verteerbaarheid, groei, voederefficiëntie, karkasgewicht en aanhoudingspercentage, afhankelijk van de leeftijd en het lichaamsgewicht van de varkens en het vezelgehalte in het voer. De vezelfracties in deze grondstoffen zijn echter vaak slechts beperkt gekarakteriseerd en er ontbreekt vaak informatie over de gehaltes aan NSP en arabinoxylans in de grondstoffen en de voeders, hetgeen de interpretatie van waargenomen effecten beperkt. Verder onderzoek lijkt van belang om goede relaties te leggen tussen de samenstelling van deze grondstoffen, hun voedingswaarde en effecten op de groei van varkens. Vezels uit graanbijproducten hebben positieve effecten op de gezondheid en het welzijn van biggen, vleesvarkens en zeugen en kunnen diarree na spenen verminderen of de fysiologie, immunologie, het darmmicrobioom en het gedrag van varkens beïnvloeden. Daarnaast zijn er enkele maternale effecten op biggen aangetoond bij verstrekking van vezelrijke diëten aan zeugen. Er kunnen echter verschillen zijn in samenstelling en functionele eigenschappen van vezels, afhankelijk van de herkomst en bewerking die de bijproducten hebben ondergaan.
Het gebruik van natte bijproducten in brijvoer voor varkens heeft duidelijke voordelen vanuit circulair perspectief. Er is in de recente literatuur weinig onderzoek gerapporteerd over het voeren van varkens met brijvoeders met een verschillende grondstofsamenstelling, hoewel bepaalde vochtrijke grondstoffen veel in de NL praktijk worden gebruikt. Slechtere groei- en karkasprestaties werden verkregen door het opnemen van aardappelvezels of -pulp in brijvoeders. De groeiprestaties werden echter bijna niet beïnvloed wanneer deze producten een fermentatie- of enzymatische behandeling kregen. In tegenstelling tot eerdere studies uit de jaren 1980, gaven latere studies aan dat de prestaties van varkens die 25% aardappelstoomschillen of een mix van vloeibare bijproducten (vloeibaar zetmeel, wei en aardappelstoomschillen) kregen, gelijkwaardig konden zijn aan de prestaties van varkens die een dieet kregen gebaseerd op granen en sojaschroot. Niet gefermenteerde natte (bij-)producten hebben veelal geen nadelige effecten op de gezondheid en het welzijn. Het hanteren, opslaan en distribueren van natte producten vereist echter goede hygiëne. Daarnaast kunnen gefermenteerde natte producten hebben een prebiotisch effect met positieve consequenties voor de darmgezondheid.

In tegenstelling tot sommige Oost-Aziatische landen is het gebruik van keuken- en etensresten als diervoeder niet toegestaan in de EU. Evenwel geeft de literatuur aan dat adequaat behandeld (professioneel) keukenafval kan worden opgenomen in varkensvoeders zonder verlies van groeiprestatie, karkas- en vleeskwaliteit, op voorwaarde dat de nutriënteninhoud van deze stroom adequaat bekend is en is toegepast tijdens de formulering van het complete rantsoen. Er is weinig bekend over effecten van keukenresten op de gezondheid en het gedrag van varkens. Er werden echter wel enkele risico's genoemd in relatie tot de microbiële kwaliteit en stabiliteit (bacteriën, virussen en andere micro-organismen) alsmede concentraties zware metalen en aanwezigheid van papier, metaal of plastic.

In het tweede scenario zijn verschillende alternatieve eiwitbronnen voor sojaschroot beschreven: raapzaadschroot, peulvruchten, insecten, aquatische grondstoffen, grasproducten en "processed" dierlijke eiwitten. Raapzaadschroot en peulvruchten zijn veelgebruikte ingrediënten in varkensvoeders, terwijl andere potentieel hebben als eiwitbronnen in de toekomst.
Een groot aantal studies heeft de opname van raapzaadschroot, peulvruchten (erwten, veldbonen, lupinen) in varkensvoeders onderzocht. In de meeste studies werd er weinig of geen effect op de groeiprestaties waargenomen bij opname van 5 tot 25% raapzaadschroot in biggen voeders, of 10 tot 20% in vleesvarkensvoeders. Echter, het totale vezelgehalte in het voer kan de prestaties van biggen beïnvloeden. Op basis van talrijke studies werd een maximumlimiet van 2,2 µmol glucosinolaten /g voer afgeleid. Voor veldbonen met een laag of gemiddeld tanninegehalte (< 5-6 g/kg) gaf onderzoek aan dat opname mogelijk is tot 20-30% in biggenvoeders en 30-35% in vleesvarkensvoeders. Het tanninegehalte van sterk variëren binnen alle variëteiten veldbonen (witbloeiers en bontbloeiers). Alkaloïden in lupinen zijn van belang in relatie tot het gebruik van lupinen in varkensvoer met maximale concentraties van 0,20 g/kg voer. Daarnaast variëren de oligosachariden uit de raffinose familie tussen lupinesoorten en -cultivars en hun aanwezigheid kan een verklaring zijn voor tegenvallende dierprestaties in sommige studies, vooral bij gebruik van witte lupinen. Opname van 20% gele of blauwe lupine in het voer kan resulteren in vergelijkbare dierprestaties voor biggen na het spenen of vleesvarkens in vergelijking met op granen-sojaschroot gebaseerde voeders. Verschillende onderzoeken hebben de opname van raapzaadschroot in de voeding geëvalueerd in praktijksituaties, met een variërende gezondheidsstatus van het varkensbedrijf. Er zijn echter maar weinig studies bekend die specifiek de invloed van raapzaadschroot op de gezondheid en het welzijn van varkens hebben onderzocht, met uitzondering van de darmgezondheid (samenstelling van het microbioom en morfometrie van de darmwand). De meeste gerapporteerde effecten leken gerelateerd te zijn aan de fermentatie van raapzaadschroot vóór mengen of distributie. De effecten van peulvruchten (b.v. erwten en veldbonen) op gezondheid en welzijn zijn weinig of niet onderzocht, maar studies gericht op dierprestaties wezen niet op schadelijke effecten van veldbonen of lupinen op darmgezondheid (b.v. incidentie van diarree) of op welzijn.
De productie van insecten groeit in Europa, hoewel wetgeving en productie voor toepassing in diervoeders momenteel beperkend zijn. Insectenmeel lijkt ook een veelbelovend eiwitrijk ingrediënt voor voeders van varkens en een alternatief voor b.v. sojaschroot. De beschikbare hoeveelheid insectenmeel is momenteel beperkt t.o.v. de vraag naar eiwit voor toepassing in diervoeders, maar door de goede verteerbaarheid en gerelateerde hoge voedingswaarde maakt deze grondstof een potentieel aantrekkelijk ingrediënt in diervoeders. Macroalgen of zeewieren zijn ook potentiële eiwitbronnen, maar moeten worden geconcentreerd en/of geëxtraheerd voor toepassing. Er zijn weinig resultaten beschikbaar over effecten van gebruik op de groei en karkaseigenschappen bij varkens bij hoge inmengingspercentages in het voer. De belangrijkste vereisten voor verdere ontwikkeling van de toepassing lijken het optimaliseren van productie- en extractieprocessen. Hoewel relatief duur, zou spirulina met de juiste aminozuursuppletie in relatief hoge gehaltes kunnen worden opgenomen in voeders voor biggen of voor vleesvarkens, zonder de prestaties te schaden. Studies naar welzijn en gedrag bij de opname van insecten in varkensvoeders ontbreken. Functionele eigenschappen van gebruik van insectenmeel gericht op de verbetering van de darmgezondheid lijken niet van belang. Er zijn echter geringe positieve effecten gevonden op het darmmicrobioom en het lokale immuunsysteem in darmweefsel. Het effect op welzijn lijkt het meest veelbelovend wanneer insecten intact en levend worden verstrekt. Zowel micro- als macroalgen bevatten bioactieve eigenschappen die antimicrobieel, prebiotisch en immuun modulerend kunnen zijn en de gezondheidsstatus van varkens kunnen ondersteunen. Er zijn geen onderzoeken bekend naar de effecten van het gebruik van algen op het gedrag van varkens. Er is nog steeds een lacune in de kennis over het gebruik van gras en andere ruw voeders als ingrediënt voor voeders van varkens. Sommige prestatiestudies waren niet gebaseerd op een precieze en volledige beschrijving van de voedingswaarden gras of graskuil. De samenstelling van grasproducten varieert

naargelang de oogst- en opslagomstandigheden. Met name het eiwit in luzerne kan onderhevig zijn aan proteolyse. Verschillende recente studies wijzen op een afname van de groei en de karkasprestaties als gevolg van de opname van grasproducten in varkensvoeders. Graseiwitconcentraten lijken veelbelovende eiwitbronnen en zouden gebruikt kunnen worden als gedeeltelijk alternatief voor geïmporteerd sojaschroot. De ontwikkeling van voeders met graseiwitconcentraten bevindt zich echter nog in een experimenteel stadium. Ook zijn er nog geen volledige voederwaardecijfers voor varkens beschikbaar. Wat welzijn betreft, hebben gras en producten zoals kuilvoer en klaver een gunstig potentieel door hun vezelige karakter. Informatie over de invloed van ruwvoer op (darm)gezondheidsparameters bij varkens ontbreekt.
Bij groeiende varkens zouden bewerkte dierlijke eiwitten (PAP's), bereid uit pluimveemeel in overeenstemming met nieuwe Europese regels, ten minste 4-5% sojaschroot kunnen vervangen zonder negatieve effecten. In biggenvoeders kan pluimveemeel met een laag asgehalte en bloedmeel sojaschroot gedeeltelijk vervangen zonder prestatieverlies, maar gebruik van verenmeel en pluimveemeel met een hoog asgehalte kunnen leiden tot een verminderde voeropname en groei. Het effect van de opname van (nieuwe) verwerkte dierlijke eiwitten op de gezondheid en het welzijn van varkens is weinig onderzocht. Het lijkt erop dat door de verwerking bioactieve stoffen zijn verdwenen. De veronderstelde positieve effecten op ongewenst gedrag zoals staartbijten zijn nog niet bevestigd.

Voor alle circulaire grondstoffen is de manier waarop ingrediënten worden opgenomen (d.w.z. ten koste van welke grondstoffen in het referentievoeder) een belangrijke afweging met betrekking tot de gevolgen van het gebruik ervan in duurzame varkensvoeders. Daarnaast is de juiste bepaling van de voedingswaarde of het niveau van anti nutritionele factoren van de circulaire grondstoffen een fundamentele voorwaarde. In een deel van de onderzochte prestatiestudies ontbreekt deze informatie, waardoor ze minder relevant zijn. Bovendien worden sommige nutritionele parameters, zoals de samenstelling van de NSP-fractie, weinig gebruikt door voedingsdeskundigen en onderzoekers, wat de generalisatie van studieresultaten beperkt.

Concluderend zou een bijdrage aan meer circulaire voeding door hogere inmengingspercentages in varkensvoeders van circulaire producten mogelijk moeten zijn. Voor de twee scenario's geeft de literatuur aan dat hoge inmengingspercentages mogelijk zijn voor belangrijke grondstoffen zonder vermindering van prestaties of negatieve invloed op gezondheid en gedrag. Deze grondstoffen, die al bekend zijn en gebruikt worden, zijn graanbijproducten, raapzaadschroot, vloeibare bijproducten, veldbonen, verwerkte dierlijke eiwitten, maar ook bakkerijbijproducten, zetmeelbijproducten, DDGS, zonnebloemenzaadschroot, en erwten die niet geëvalueerd zijn in dit rapport. De belangrijkste beperkingen en mogelijkheden voor het formuleren van circulaire ingrediënten in voeders zijn gerapporteerd in de literatuur. Er is nieuw onderzoek nodig om de cumulatieve voorwaarden te bepalen van combinaties van verschillende grondstoffen in hetzelfde rantsoen. Voor nieuwe grondstoffen zoals keukenafval, insecten, aquatische grondstoffen en grasproducten zijn er meer beperkingen, voornamelijk stabiliteit en beschikbaarheid, maar de grondstoffen zouden in de toekomst deel moeten uitmaken van het aanbod aan middelen voor varkensvoer.

Summary

This report presents a review of the scientific literature on the consequences of increasing the use of selected circular ingredients in pig diets to enhance the circularity of food production systems. The study has been carried out in the framework of the Public Private Partnership project "Vitale Varkenshouderij". Specifically, the present report addresses the nutritional characteristics of the ingredients for pigs and the effects of their inclusion level in pig diets on pig performance, health and welfare.
A representative but not exhaustive cluster of feed ingredients was selected and reviewed according to two scenarios, the first aiming to reduce the quantity of cereals' grains in diets for pigs, the second aiming to decrease the use of protein sources from outside the EU, e.g. soybean meal, in pig diets. For these two scenarios, the selected candidate ingredients were described considering firstly their nutritional characteristics and effects as energy and protein sources on growth and carcass performance, followed by considering the effects of their inclusion on health and welfare of pigs.

In the first 'reducing cereals' scenario, three different groups of ingredients were described: cereal by-products, potato by-products and kitchen waste. The first two groups are well known and currently used in pig diets, whereas kitchen waste may be a promising circular feed material for the future.
A higher rate of cereal co-products (i.e. bran and middlings) in pig diets should be possible with similar or slightly decreased performance. No negative effect on feed intake of piglets or pigs was reported in literature when increasing their inclusion. Related performance was similar or slightly lower for diet digestibility, body weight gain, feed efficiency, carcass weight and yield according to the age and body weight of pigs and also related to the total fibre content of the diet. However, studies are heterogeneous regarding characterisation of the fibres in the cereal by-products and detailed information on the concentrations of NSP and specific fibre fractions such as arabinoxylans is often lacking. Generating further expertise appears useful to establish reliable relationships between dietary fibre level and growth and carcass performance. Fibres from cereal by-products have been reported for positive effects on health and welfare of pigs in all stages, and may reduce post-weaning diarrhoea or influence in some studies pig gut physiology, immunology, gut microbiome and behaviour. Some maternal effects on piglets have been shown with fibrous diets distributed to sows. However variation in composition and functional properties of the fibres may influence effects observed depending on their origin and the way of processing of ingredients potentially affecting fibre characteristics.
Wet by-products used in liquid feeding of pigs have clear benefits from a circular perspective. Surprisingly, only a few recent published studies are available on using liquid feeding systems, although feed ingredients as wet by-products of potato industry are widely used. Poorer growth and carcass performance was obtained from the inclusion of potato hash or pulp. However, growth performance was almost unaffected when these products underwent fermentation or enzymatic treatments. In contrast with earlier studies from the 1980s, later studies indicated that performance of pigs given 25% of potato peels or a mix of liquid co-products (liquid starch, whey and potato peels) may be equivalent to performance of pigs provided cereal-soybean meal diets. Most unfermented wet (by-) products have generally no adverse effects on health and well-being. However, wet product handling, storage and distribution require good hygiene. Fermented products may have a probiotic effect in some cases.
Unlike some East Asian countries, the use of kitchen and catering waste as feed ingredient is not allowed legally in the EU. Nonetheless, available information indicates that adequately treated (professional) kitchen waste could be included in pig diets without loss of growth performance, carcass and meat quality, provided that the nutritional value is adequately known and taken into account during diet formation. Effects of kitchen waste on pig health and behaviour are rarely studied. However, some hazards were mentioned, i.e. presence of specific bacteria, viruses and other micro-organisms potentially harmful for animal health as well as variation in concentrations of heavy metals and presence of paper, metal and plastic.

In the second scenario, several alternative protein sources to soybean meal were described: rapeseed meal, legume seeds, insects, aquatic ingredients, grass products and processed animal proteins. Rapeseed meal and legume seeds are frequent feed ingredients in pig diets whereas the others have potential as protein sources in pig diets in the future.

A large number of studies have investigated the inclusion of rapeseed meal, legume beans (faba beans, lupins) in pig diets. Only limited till no effects were found on growth and carcass performance for the inclusion of 5 to 25% rapeseed meal in post-weaning diets, or 10 to 20% in fattening diets. However, total dietary fibre content may impact piglet performance. A maximum limit of 2.2 µmol glucosinolates from rapeseed meal per g of diet was suggested. For faba beans with low or medium tannin content (i.e. < 5-6 g/kg), research indicated that inclusion is possible up to 20-30% in weaning diets and 30-35% in fattening diets. Large variations of the tannin content may appear among varieties within each type of beans, either colour-flowered or white-flowered. Alkaloids seem the main anti-nutritional factor for the use of lupins in diets for pigs and other animal species. Most studies confirm a maximum dietary limit of 0.20 g/kg. Besides that, the raffinose family oligosaccharides vary among lupin species and cultivars and may influence performance negatively, especially when considering white lupin. Inclusion of 20% yellow or blue lupins may result in similar performance for post-weaning piglets or fattening pigs compared to cereals-soybean meal diets. Several studies have verified the dietary inclusion of rapeseed meal in practical situations using large scale facilities or farms with challenging or varying health status. Limited research has specifically investigated the influence of rapeseed meal on health and welfare of pigs except for effects on gut health and functionality (microbiome composition and activity and morphometry of the intestinal mucosa). Most beneficial effects on health and welfare of pigs seemed to be related to intestinal fermentation of specific carbohydrates in rapeseed meal. The effects of the use of legume seeds on health and welfare was not reviewed in the present study but performance studies did not indicate any detrimental effects of faba beans or lupins on health (i.e. diarrhoea) or welfare.

Insect production is growing in Europe and receives increasing interest although legislation and production are currently restricting. Insect meals appear also as promising protein-rich feed ingredients and alternatives to soybean meal for pig feeding. The availability of insect meals for use in livestock diets is currently limited but their high nutritional value and absence of adverse effects when including this protein source in the diet of pigs make them an attractive future option for the livestock industry. Macroalgae or seaweeds have also potential as alternative sources of protein, but require concentration and/or extraction prior to use in animal feeds. Few studies on effects of their use on growth and carcass performance are available in pigs using significant dietary inclusions. Processing conditions appear to have large effects on composition and nutritional value of these aquatic protein sources. Although costly, spirulina could be included with appropriate amino acid supplementation, in post-weaning or fattening pig diets at high levels, without disadvantaging performance. Studies on welfare and behaviour with insect inclusion in pig diets are lacking. The functional properties of insect for gut health seem to be limited. However, small positive effects have been found on the gut microbiome and local immune system in gut tissue. The effect on welfare seems most promising when insects are provided intact and alive. Both micro- and macroalgae contain bioactive constituents which can have antimicrobial, prebiotic, and immunomodulatory properties and could support pig health status. No studies were found on the effects of algae on pig behaviour.

There is still a knowledge gap about use of grass and other roughages for pig feeding. Some performance studies on the subject were not based on a precise and complete description of the nutritional value of the test ingredients . The composition of forage ingredients varies according to the harvesting and storage conditions. In particular, alfalfa may be subject to proteolysis. Several recent studies indicate a decrease of growth performance resulting from the inclusion of grass products in pig diets. Grass protein concentrates appear as promising protein sources and could be used as a future candidate for partially replacement for soybean meal. However, the process of isolating protein from grass at industrial scale is still in its beginning. Limited information is available on the (variation in) nutritional value for pigs. Regarding welfare, grass and products, such as silage and clover, may have potential related to their fibrous character. Information is lacking on the influence of roughage based ingredients on aspects of gut and animal health.

In growing pigs, all processed animal proteins (PAPs) prepared from poultry meals in accordance with new European legislation, could partly replace at least 4-5% soybean meal without negative effects. In weaned pig diets, low-ash poultry meal and blood meal can partly replace soybean meal without loss in performance, but use of feather meal and high-ash poultry meal may result in reduced feed intake and daily gain. The effects of inclusion of (new-) processed animal proteins on health and welfare of pigs has been rarely studied. It has been suggested that that due to the intense heat processing during production, potential bioactive compounds present in ingredients from animal origin disappear. The hypothesized positive effect of the use of PAPs (and previously meat and bone meal) on undesired behaviour such as tail biting have not been proven yet.

In evaluating the potential of the use of circular ingredients in pig diets, it is important to consider how ingredients are included during diet formulation (i.e. at the expense of which ingredients in the reference diet). Besides that, proper determination of the nutritional value and availability of information on concentrations of anti-nutritional factors in the circular ingredients are fundamental prerequisites. Part of the reviewed performance studies lack this type of information making them less relevant. Furthermore, some nutritional parameters e.g. related to the composition of the NSP fraction in fibre rich ingredients are often unknown limiting understanding of their effects as part of the diet.

In conclusion, increasing the inclusion level of particular feed ingredients, considered as co- and rest products mostly obtained from the agro-food sector, and alternatives for imported soybean meal in pig diets could increase the circularity of food production for humans. For the two scenarios defined for the present study, literature indicates that high inclusion rates are possible for key ingredients without reduction in animal performance or negative effects on animal health an behaviour. Part of the ingredients are already known and used for a long time, e.g. cereal-by products, rapeseed meal, particular liquid by-products, faba beans, processed animal proteins, as well as bakery by-products, starch by-products, DDGS, sunflower seed meal, peas, the latter not being reviewed in the present report. The most important constraints and opportunities for the inclusion of "circular ingredients" in diets for pigs have been reported in the literature. Additional research needs to be undertaken to determine the cumulative effects and limitations when combining different circular ingredients in the same diet. For novel ingredients such as kitchen waste, insects, aquatic ingredients, grass products, there are other constraints, mainly related to their stability and availability.

1 Introduction

1.1 Background

It is the ambition of the Dutch pig production sector to make a sustainable contribution to the production of high quality animal source food while minimizing the competition between the use of products for human food and animal feed. This requires a conversion to a more circular food production system in which pigs can play a vital role by the transition of human inedible feed materials into animal source food. The latter has consequences for the future composition of pig diets and generates questions regarding the suitability and potential inclusion of specific feed materials. Therefore, in the topic Circular Economy of the Public Private Partnership project “Vitale Varkenshouderij”, attention is paid to four related items: Criteria and availability of circular feed ingredients (A), their nutritional characteristics and utilization (B), their influence on health and welfare (C) and their origin (D). The present report addresses subject B and C.

The pig is generally regarded as the most suited farm animal to make an important contribution to the circularity of food production by converting low-quality raw materials that are not suitable for human consumption (human inedible feedstuffs) into high-quality food for humans. Historically, pigs were fed with leftovers and co-products from agricultural production and kitchen waste (i.e. “schillenboer”). As a result of concentration and professionalization of the pig sector, the composition of pig diets has evolved to the ones used nowadays. Currently most diets consist of a combination of cereals grains, co-products of oil seed processing (e.g. soyabean meal and rapeseed meal) and a range of co-products from the ingredient and food processing industry. The Dutch pig farming sector has the ambition to make an important contribution in reducing the competition between food, feed and biofuel applications. The “Coalitie Vitale Varkenshouderij” strives to maximize the use of raw materials that are not suitable for human consumption in the animal feed industry. Estimates show that currently the share of raw materials that are not suitable for human consumption in the total animal feed industry is approximately 80%, with the highest inclusion in feeds for cattle and at to a somewhat lesser extent in pig diets. Despite this large scale use of leftover by the present animal feed industry there is room for a further increase in use of circular feed ingredients for pig production. Considering dry ingredients in pig diets, approximately 30% of the raw materials for compound feed are currently by-products of the food industry. In addition, 10% of the total nutrient requirements of pigs is met via feeding of moisture-rich co-products, mainly residual products from the food industry. Including a higher level of human inedible feedstuffs in future diets would contribute to the circularity of food production, but could also influence the growth performance and health and welfare of pigs. Such effects can be positive or negative, for example through an influence on intestinal health in piglets and fattening pigs, or on feelings of hunger and satiety and their influence on stereotypic behaviour in pregnant sows and biting behaviour in piglets and fattening pigs. These aspects will be addressed in the present study for a number of feed materials specified later.

The present desk study had two aims:

1) to describe nutritional characteristics and determine the influence of increasing the proportion of selected human inedible feedstuffs in diets on growth performance of pigs.
2) to describe the possible effects of the use of more circular ingredients in pig diets on the health, welfare and behaviour of pigs and to identify opportunities, risks and knowledge gaps in this area.

The study aims to provide the pig sector with opportunities to account for the described effects when formulating diets for pigs as part of a more circular food production system. Furthermore, the results of this desk study aim to give direction to follow-up research in the PPP “Vitale Varkenshouderij”.

1.2 Definitions

Circularity of food production systems is increasingly discussed in science, politics, and society. It is, however, a subject that requires further definition. The vision and interpretation of concepts of circularity can be different depending its definition, readouts in qualitative and quantitative terms and the handling perspective of stakehlders. For example, views and perspectives are different between individual pig farmers with a focus on the own farm versus EU politicians addressing the European scale. The PPP "Vitale Varkenshouderij" has contributed, together with two other PPP-projects, to the development of a shared definition and shared base within the animal nutrition sector. A focus group including scientists and representatives of the animal production sector, the feed industry, the national government and non-profit-organisations collaborated and discussed on the topic of defining circularity in the context of animal nutrition. This resulted in a report (Bremmer et al., 2023) which reflects the complexity of circularity, but also some agreements and a practical approach to move forward. Major elements of the concept of circularity of feed ingredients proposed were 1. land use, 2. use of limited resources (i.c. phosphate) and the amount and quality of the food produced using feed materials. In the context of the present desk study, human inedible feedstuffs are defined as ingredients for animal feeds which humans cannot or do not want to consume.

1.3 Scenarios

Numerous raw materials could be evaluated for their contribution to a more circular food production system. Within this report, scenarios are used to limit and demarcate the various opportunities based on discussion within the sounding boards of this project, using the interest, experience, and knowledge of the members. After creating a longlist with possibilities, scenarios were defined based on the expected impact on circularity of the food production system (Table 1). The members of the sounding boards agreed that innovation and creativity should not be limited by short term feasibility, however they are aware of practical constraints for some of the categories within the scenarios. The scenarios can be divided into two main categories. The first category is to reduce cereal grains from the diet as much as possible. Cereal grains can principally be used directly for human consumption. In a more circular food system, only the by-products or leftovers from food production or waste from human food should be included in animal diets. The focus within this category is on cereal grain by-products, liquid by-products such as potato peels and left-overs from professional kitchens. The second scenario focusses on reduction of protein sources imported from outside of the EU, to reduce the impact of i.e. transportation, global nitrogen and mineral imbalance and deforestation. Therefore, more EU grown protein sources should be included in the diet, although these might be partly human edible, and the production of protein for animal diets need to become more circular. The categories discussed in the review are co-products such as rapeseed meal and processed animal proteins, legume seeds (faba beans and lupins), and novel ingredients such as (proteins from) insects, aquatic sources, and grass.

Table 1 *The scenarios used as demarcation in this review.*

Scenario	Subcategory	Product / feedstuffs
1. Reduce cereals	By-products cereals	Cereal grain by-products
	Moist by-products (energy)	Potato co-products
	Kitchen waste	Professional (restaurants, hotel, canteen)
2. Reduce protein sources produced outside of the EU	By-products oil seeds	Rapeseed meal
	Moist by-products (protein)	Whey[1]
	Legume seeds	Faba beans, lupins
	Insects	Black Soldier Fly, other insects[1]
	Aquatic sources	Macroalgae, microalgae[1]
	Grass and clover	Grass protein, grass silage, clover silage
	Processed animal proteins	Poultry origin

[1]Fresh whey is not included in the present review pending further discussion in the ViVa guidance group on the importance of liquid whey as ingredient for liquid pig diets. Information of inclusion of aquatic protein sources and insects on performance of pigs is to be included.

In the present report a description is given on the nutritional value and effects of increasing the inclusion of feed materials in the diet, linked to both scenarios presented in Table 1, on the growth performance of piglets and growing pigs (Chapter 2). Thereafter effects on health and welfare are presented in Chapter 3.

2 Influence of circular ingredients on pig performance

In chapter 2 a description is given on the nutritional value and effects of increasing the inclusion of circular feed materials in the diet, linked to both defined scenarios: 1. reduction of the use of cereals and 2. Reduction of the use of protein sources produced outside the EU, on the performance of (growing) pigs.

2.1 Reduction of the use of cereals in pig diets

Cereals are currently one of the pillars of pig diets providing a large part of the net energy to the diet. They constitute a privileged source of nutrients (starch i.e. energy, amino acids, fibre) of agricultural origin at a competitive price. The need to increase the circularity of pig feed and to reduce competition between human and animal uses of feed resources is leading to initiatives to reduce the share of cereals in diets. Several decades ago, in the 1980s, the use of cereal substitutes was very important. The introduction of the new Common Agricultural Policy in 1992 led the price of European cereals to fall to the world price level, limiting the feed industry interest for substitutes. Consequently, many of the studies on the use of cereal substitutes (e.g. tapioca) are somewhat outdated and did not use the concepts of net energy (NE) and ileal digestible amino acids. However, some recent studies have addressed the use of by-products and energy-rich sources as alternatives to cereals.

2.1.1 Inclusion of cereal by-products

a) Background

Some specific investigations have been conducted on the use of cereal by-products in pig diets. Their composition and use have recently been reviewed by Rosenfelder et al. (2013) and by Stein et al. (2016). The impact of former food products will be discussed later in part B and C of the present report. Additionally, protein sources such as oil seed meals (e.g. sunflower seed meal and rapeseed meal) and legume seeds (e.g. pea and faba bean), also addressed in scenario B, have lower protein concentrations than soybean meal. Consequently, their inclusion in a cereal-soybean meal diet, although primarily intended as protein source, may also reduce the proportion of cereals in the diet.

b) Effects on diet digestibility and growth performance

<u>Wheat bran (WB)</u> is one of the mayor by-products in animal feeding and is frequently included in pig diets. The practiced inclusion levels are related to the intended energy concentration of the compound feed. Maximum inclusions levels of 10 % in gilts or lactating sow diets and 15% for gestating sows and fattening pigs are commonly used. Wheat bran is commonly not endorsed for piglets but Molist et al. (2011) studied a 4% inclusion in weaning pig diets as an alternative to antimicrobials in weaning pig diets, resulting in a 9.2% dietary neutral NDF[2] content, without detrimental effect on performance. The inclusion of 20% WB in the diet of 18 kg canulated pigs by Zeng et al. (2018) increased the NDF and total NSP[3] contents (5.8 and 16.9% NDF and 8.6 and 13.3% NSP, for control and WB diets, respectively) and decreased apparent ileal digestibility of dry matter (DM), energy and crude protein (CP), as well as faecal digestibility of DM and CP and decreased the apparent ileal digestibility of amino-acids (AA). Sun et al. (2020) also measured the digestibility of diets including 15 or 30% wheat bran with 58 kg canulated pigs. WB diets were less concentrated in energy and AA and had higher fibre contents (3.0, 3.2 and 3.4% crude fibre (CF), 11.8, 15.9 and 20% NDF, 6.9, 9.4 and 11.8% total arabinoxylans, for control, 15 or 30% WB diets, respectively).

[2] Parameters for fibre contents of Weende analysis: Neutral Detergent Fiber (NDF), Acid Detergent Fiber (ADF) and Acid Detergent Lignin (ADL)

[3] Non-starch polysaccharides (NSP) are complex carbohydrates, other than starch and sugar. They are primarily located in the plant cell walls and are the major part of the dietary fiber fraction of the raw materials. NSP are largely undigested by monogastrics.

Authors reported a slight non-significant decrease of ileal or total tract digestibility of organic matter or protein for a 15% inclusion compared to control diet, whereas for starch the ileal digestibility was non-significantly decreased from 89.4 to 88.7% and the apparent total tract digestibility from 91.9 to 90.9%. The 30% inclusion resulted in higher reductions of digestibility, with 82.6% ileal and 87.7% apparent total tract digestibility of diet starch. These results are in agreement with a previous study reported by Huang et al. (2015).

Wheat middlings (WM) and wheat shorts are by-products of wheat milling for flour. The names and classification of wheat middlings may vary according to countries and processes. Products can be classified from heavy to light middlings according to their decreasing starch: fibre ratio (Cromwell et al., 2000). The products with the highest ratios have higher starch content and lower fibre content than bran which results in common higher inclusion limits. Products with the lowest ratios may have an energetical concentration similar to barley which could allow 30-40 % inclusion levels without loss in performance.
Young canulated pigs (32 kg) were used in a digestibility study by Nortey et al. (2007) who reported a numerical non-significant reduction of ileal and total-tract digestibility of energy when replacing 30 % of a basal wheat-soybean meal (SBM) diet by 30 % middlings. In the same study, authors also reported a reduction of digestibility of energy with 30% of millrun, shorts, screening or bran and a non-significant reduction of ileal digestibility of energy and amino acids. Compared to wheat (72%), ileal energy digestibility was the lowest for middlings (62%), then bran (63%), screenings and millrun (64%), and highest for shorts (66%). Supplementation with xylanase enzyme significantly improved ileal energy digestibility of millrun by 19% to 76%, and screenings by 9 % to 73 %, but had little effect for middlings, bran or shorts.
De Jong et al. (2014) conducted several experiments to examine the effects of wheat middlings on piglet performance and energy efficiency. Phase 2 piglets (Exp. 1) were fed for 3 weeks with corn–SBM based diets including 0, 5, 10, 15, or 20% middlings (16% CP, 7.9% CF, 31% NDF) and balanced for AA, i.e. 3.9 standardized ileal digestible lysine (SID Lys) per Mcal of metabolizable energy (ME). Increasing middlings resulted in higher dietary fibre contents (up to 3.2% CF and 4.1% NDF for 20% WM) and linearly decreased average daily feed intake (ADFI) and average daily gain (ADG). Piglets given 20% middlings had 53 g lower ADFI and 31 g lower ADG than control piglets. For a total 5 weeks post-weaning trial, weaned piglets (Exp. 2) received phase 1 then phase 2 corn–SBM diets including 0, 5, 10, 15, or 20% middlings (16% CP, 8.5% CF, 34% NDF and 20% starch). Diets had increasing fibre contents (up to 2.9% CF and 4.1% NDF, then 3.7% CF and 5.6% NDF in phase 1 then phase 2 20% WM diets, respectively) and decreasing energy contents but were balanced for AA (4.0 then 3.9 SID lysine (Lys) /Mcal ME for phase 1 and phase 2 diets, respectively). Increasing middlings did not affect overall ADFI or ADG but decreased gain to feed ratio (G:F) at 20% WM. However, in both trials (Exp. 1 and 2), energy efficiency was linearly improved for both ME and NE as dietary wheat middlings increased. In another phase 2 trial (Exp. 3), authors arranged a factorial design with Distillers Dried Grains with Solubles (DDGS; 0 or 20%) and wheat middlings (0, 10, or 20%). Including both 20 % WM and 20 % DDGS resulted in 4.3% CF and 5.5% NDF dietary contents. No DDGS × middlings interactions were observed, and DDGS did not influence performance, but increasing dietary middlings linearly decreased ADG, G:F, and final BW, whereas ADFI was not modified. In the last trial (Exp. 4), middlings (16% CP, 8.2% CF, 35% NDF) were added to the first three diets (0, 10, or 20%) without balancing for energy, and soybean oil was added (1.4 and 2.8%) to 10 and 20% middlings diets in diets 4 and 5 to balance NE as in the control diet (0% middlings). Diets ranged from 2.4 to 2.9% CF and 3.3 to 4.1% NDF, then from 2.2 to 3.4% CF and 2.8 to 5.1% NDF in phase 1 and 2, respectively. Overall, no middlings × fat interactions occurred. G:F and energy efficiency calculated on an ME basis were impacted as middlings increased from 10 to 20%, but did not change when calculated on an NE basis.

L'Anson et al. (2013) included 12.5, 25, 37.5, and 50% of wheat millrun, a 1:2 mixture of wheat pollard and wheat bran (16% CP, 10% CF and 35% NDF) in iso-digestible energy and iso-lysine weaning piglet diets. Fibre composition of the diets were not reported but as meat- and fish meals were used as main source proteins, it can be presumed that millrun and cereals provided most of the dietary fibres. Authors reported a higher ADFI and ADG with 12.5 to 37.5 % levels compared to wheat-barley control diet whereas with a 50% inclusion, digestible energy (DE) and DM intake was similar to control but ADG and final LW were slightly numerically lower. A following trial showed that the feed conversion ratio (FCR) and CP digestibility of the 50% millrun diet was improved by liquid feeding, but not by the addition of NSP-degrading xylanase enzymes.

Garcia et al. (2015) prepared wheat-based piglet phase-2 diets containing 5, 10, 15 or 20% wheat millrun (16.5% CP, 8.6% CF, 36.9% NDF and 15.2% starch) in substitution for up to 15% SBM and 5% wheat. Diets were balanced for net energy and for amino acids (10.1 MJ NE/kg and 1.05 g SID Lys/MJ NE) and ranged from 2.1 to 3.1% CF and 11.4 to 15.7% NDF. Increasing inclusion of wheat millrun to 20% reduced diet apparent total tract digestibility (ATTD) by 4% for DM and 3% for energy, but did not affect ATTD of CP. ADFI and ADG for each week or for entire trial (day 1–21) were not affected when increasing inclusion of wheat millrun but feed efficiency (G:F) was increased by 0.12 for day 8–14 or by 0.04 for the entire trial.

According to Stein et al. (2016), there are very few published experiments reporting on effects of adding rice co-products to diets fed to pigs. However, it has been indicated that 20 or 30% defatted rice bran may be included in diets fed to weanling pigs without negative impacts on growth performance if added to a basal diet mainly containing sorghum, wheat, and meat meal (Warren and Farrell, 1990).

c) Effects on carcass parameters and meat quality

For fattening pigs, corn feed (CF; 10% CP, 5.4% CF, 5.6% fat and 60% starch), wheat middlings (WM; 18% CP, 6% CF, 3% fat and 41% starch) or rice shorts (RS; 17% CP, 10.5% CF, 25% fat and 17% starch) were introduced at 25% in corn-wheat-SBM diets from 25 kg to slaughter (Castaing et al., 1995). All diets were balanced for lysine to energy ratio (2.7 g Lys/ Mcal DE) and pigs received daily the same energy distribution. For the growing period, ADG and energy conversion ratio were similar among treatments, whereas for the finishing period, performance was higher for the control treatment. As a result of the higher fibre contents of the co-products diets (2.8, 3.5, 3.5 and 4.4% CF, for control, CF, WM and RS, respectively) carcass weight and carcass yield were reduced with by-products but lean meat percentage was not significantly modified in spite of a tendency for lower muscle depths with wheat middlings and rice shorts. Composition in backfat fatty acids was influenced by dietary treatments and C18:2 % was above usual limits with rice shorts.
The potential for reducing the levels of cereals and eliminating maize, SBM and fish meal, in finishing pig diets was explored in an applied study by Wheatherup and Beatie (1997). Authors formulated four finishing diets, ranging in cereal contents from 70% (Diets 1 and 2) to 30% (Diets 3 and 4), balanced on DE and lysine basis and fed ad-libitum to finishing pigs from 40 kg to slaughter. Diet 3 contained 30.5% cereal, 23% SBM, 7.5% copra, 6.5% extruded rapeseeds, 5% pollard meal and 17.5% corn by-product and corn gluten feed. Diet 4 contained 36.8% cereal, no SBM, 7.5% copra, 10% extruded rapeseeds, 15% pollard meal and 20.5% corn by-product and corn gluten feed. Except fatty acids profiles, chemical composition of feedstuffs and diets is not available. There were no differences in the time spent at the feeder or in the number of visits to feeder by pigs in any one of the four treatment diets. ADFI was 2.1 kg/d across all four treatments, but pigs fed the 30 % cereal diets had lower ADG (910, 910, 880, 860 g/d for treatments 1 to 4 respectively). Feed:carcass ratio was significantly higher for diets 3 and 4 (+6 and 7% compared to diet 1, respectively). The killing out percentage of pigs fed Diet 4 was lower than for Diet 1 pigs (with Diets 2 and 3 being intermediate). Muscle P2 values for Diets 1 and 2 were higher than for Diet 4 with the value for Diet 3 being intermediate. Pig fat tends to follow the fatty acid profile of the diet, and this resulted in the pig fat having a higher proportion of unsaturated fat when the by-product diets were fed. The skatole concentration was not affected by diets.

Salyer et al. (2012) conducted similar experiments to evaluate the effects of wheat middlings in growing-finishing pig diets on performance, carcass traits, and carcass fat quality. In Exp. 1, growing pigs (46.6 kg) were fed *ad libitum* in 4 phases with 4 diets (1 to 4): a corn-SBM-based control, the control with 30% DDGS, the DDGS diet with 10% or 20% middlings (14.7% CP, 8.2% CF, 32% NDF). Diets were formulated to constant SID Lys:ME ratios. Overall (d 0 to 84), pigs fed diets with increasing middlings had decreased ADG (1051, 1038, 1005 and 991 g for treatments 1 to 4, respectively) and G:F (0.327, 0.333, 0.324 and 0.322), but ADFI was not affected. For carcass traits, increasing middlings linearly decreased carcass yield and hot carcass weight (100.1, 98.1, 95.3 and 93.6 kg for treatments 1 to 4, respectively) but also decreased backfat depth and increased fat-free lean index. In Exp. 2, growing pigs (42.3 kg) were used in a 87 d 2 × 3 factorial with 2 amounts of middlings (0 or 20%; 14.6% CP, 8.4% CF and 34% NDF) and 3 amounts of fat (0, 2.5, or 5.0% of choice white grease) in diets provided *ad libitum*. All diets contained corn, SBM and 15% DDGS and were formulated to constant SID Lys:ME ratios. No fat × middlings interactions were observed. Dietary middlings or fat did not affect ADFI.

Overall, 20% middlings decreased ADG and G:F. Pigs fed increasing fat had improved ADG and G:F. For carcass traits, feeding 20% middlings decreased carcass yield, hot carcass weight, backfat depth, and loin depth but increased jowl fat iodine value. Pigs fed fat had decreased fat-free lean index and increased jowl fat iodine value.

d) Discussion

- The analysis and comparison of studies is often hampered by the lack of information on the chemical composition of cereal co-products (Wheatherup and Beatie, 1997; Nortey et al., 2007; Zeng et al., 2018; Sun et al., 2020) and/or on the composition of the fibre fraction of the compound feeds (Wheatherup and Beatie, 1997; Nortey et al., 2007; Salyer et al., 2012; L'Anson et al., 2013). It is also preferred to formulate on NE and digestible AAS in order to correctly adjust the nutrient content of feeds. Systems based on DE, ME and total AAs appeared to be less accurate (Castaing et al., 1995; L'Anson et al., 2013). Furthermore, various authors have underlined the difficulty to correctly estimate the energy value of cereal co-products, and that in some experiments the energy value calculated from the tables or from available equations may have been over- or under- estimated (Castaing et al., 1995; De Jong et al., 2014; Garcia et al., 2015).
- Available studies showed that cereal by-products have no negative effect on the diet intake of piglets, except for the Exp.1 of De Jong et al. (2014), and no effect of the intake of fattening pigs. Nevertheless, ADG and feed efficiency may be decreased by increasing levels of some cereal by-products. Results indicate that wheat middlings may be fed up 10 to 15% of the diet without negatively affecting nursery pig performance compared with a corn–SBM diet, and with no interactive effects when fed in combination with DDGS (De Jong et al., 2014). However, feeding 20 to 25% wheat middlings to growing-finishing pigs may reduce growth performance by 2 to 6% and decrease feed efficiency by 3 to 7 % as reported in the studies of Castaing et al. (1995) and Salyer et al. (2012). The 30% cereal regime studied by Wheatherup and Beatie (1997) resulted in a 5% reduction for ADG and a 7% increase for feed-carcass ratio. At slaughterhouse, negative impacts on carcass weight and dressing percentage were reported by these latter studies, as well as a lower muscle depth. In addition, the fatty acid profile of some by-products may influence the carcass fat quality (Castaing et al., 1995; Wheatherup and Beatie, 1997). The wheat millrun can be included up to 20% to replace wheat and SBM in phase 2 piglet diets when formulated to equal SID Lys content on NE value (Garcia et al., 2015), and previous results (L'Anson et al., 2013) suggested that higher introduction rates could be practiced without loss of performance.
- The favourable effect of dietary fibre on the feeding behaviour, the satiety effect and the root behaviour of pigs is well known. Lastly, the concentration of phosphorus is relatively high in wheat co-products and as is the case for wheat, due to intrinsic phytases, the digestibility of phosphorus in wheat co-products is greater than in many cereal grains (Stein et al., 2016).
- Parameters such as CF or even NDF do not give accurate information on fibre digestibility by pigs. For a precise formulation and evaluation of a high inclusion of cereal by-products in pig diets, it may be important to evaluate feedstuffs on the basis of the percentages of non-starch polysaccharides (NSP) and arabinoxylans. It is suggested by authors that NSP and mainly arabinoxylans may act as an anti-nutritional factors (ANF) that could reduce the digestibility of other nutrients (Nortey et al., 2007; Sun et al., 2020). Even so, these parameters have not been analysed or reported in most of the studies. The most frequently reported parameter is the NDF content of diets. A negative linear correlation between the concentration of NDF and the concentration of digestible energy in wheat co-products was measured by Huang et al. (2014). It is found in this literature review that levels in piglet feed up to 15-16% NDF are possible without any damage4. On the other hand, dietary NDF content higher than 17 % can lead to a negative impact on growth performance of piglets fed with bran or millrun in diets balanced for energy and amino acids. Unfortunately, for fattening pigs, most studies did not report the fibre composition.
- In addition, it should also be underlined that the digestive utilization of wheat by-products such as wheat bran or wheat screening or middlings, and millrun may be enhanced by carbohydrase supplementation (Nortey et al., 2007; Zijlstra et al., 2010; Agyekum and Nyachoti, 2017; Zeng et al., 2018).

[4] Remarkably, despite middling inclusion up to 20%, NDF concentrations in the diets reported by De Jong et al. (2014) were lower than 6%.

- Lastly, processing technology may also change the coefficients of apparent total tract digestibility of total and soluble non-starch polysaccharides, CF, NDF and ADF in fibre rich diets for pigs (reviewed by De Vries et al., 2012).
- To conclude, it should be possible to increase the rate of cereal co-products in pig diets with similar performance or at the cost of a moderate decrease. However, it remains difficult to estimate the conditions for this substitution to cereals. The literature indicates a decrease in diet digestibility, reduced growth and feed efficiency, lower carcass weight and carcass yield. The literature is also heterogeneous regarding the characterisation of the nature of the fibres in the ingredients. Further expertise appears useful to establish reliable relationships between fibre dietary levels and growth and carcass performance.

2.1.2 Inclusion of potato liquid by-products

a) Background

Liquid by-products coming from the potato processing and transformation industry are major sources of ingredients for the animal feed industry, but are nevertheless relatively undocumented. When available on a liquid or wet form, these by-products are mostly valued for pig feeding. In a study of Scholten et al. (1997), the total part of liquid products (liquid starch, peelings, whey) corresponded to 35% of the DM of the ration in the growing period and 55% in the finishing period. In Dutch pig farms, a maximum proportion of 12.5% (fattening pigs) to 17.5% (gestating sows) is commonly used for potato peels, according to the same authors. In North-France, the survey by Moreau et al. (1993) revealed that French farmers typically use 30% potato peel mash with 39-40% liquid starch, or 34% potato peel mash with 20-21% liquid starch and 15-16% whey.

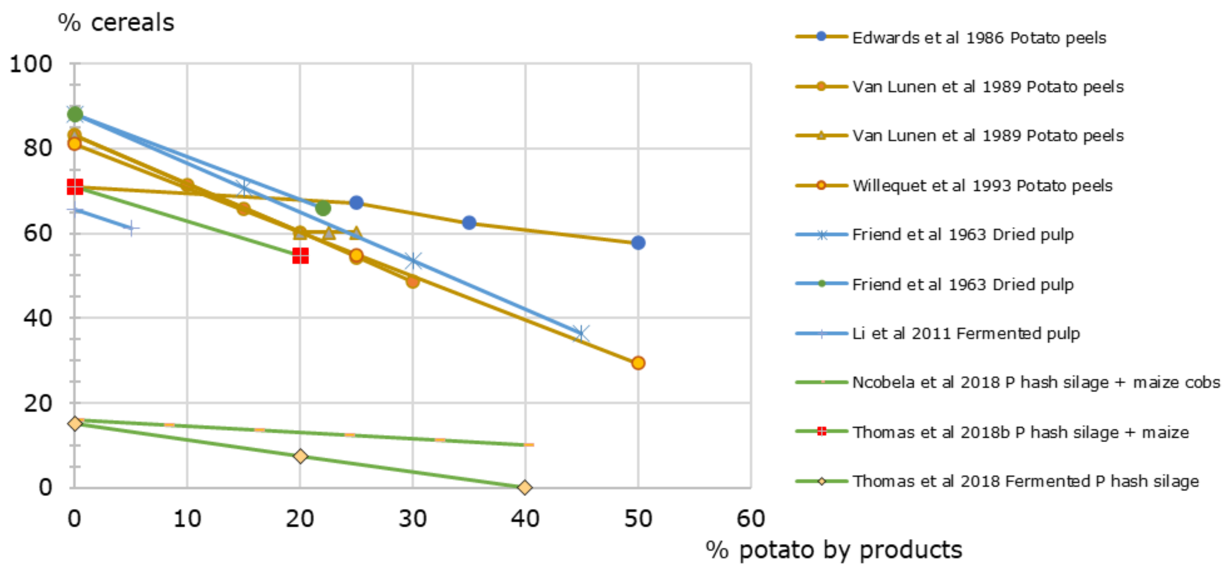
b) Composition of potato liquid by-products.

Studies evaluating the effects of potato by-products as alternative feed resource for pigs are available for three main ingredients.
Potato pulp is a raw product obtained from the production of starch from raw potatoes and is composed of cell walls of potato tuber including skin, and residual cells containing starch that are mixed with potato liquid (Mayer and Hillebrandt, 1997, quoted by Ncobela et al., 2017). Depending of the origin and processing type, potato pulp has high moisture content, low crude protein and starch contents and is rich in cellulose, hemicelluloses, pectin and salts (reviewed by Ncobela et al., 2017). Average composition values for pressed or dehydrated pulps are about 5-11% CP, 15-20% CF and 19-44% starch on DM (INRAE-CIRAD-AFZ, 2017; CVB, 2023). Raw potatoes have been used in ruminant diets but have low palatability in pigs because the starch resists to enzymatic attack and contains protease inhibitor, which reduces protein digestibility. Cooking renders the potato starch susceptible to enzyme attack and destroys the antinutritional factors, by this means increasing their palatability and utilization.

Potato hash is a by-product derived from the production of chips (Nkosi et al., 2011). The largest portion of potato hash is peels, then starch, rejected raw potatoes and the product also contains small quantities of yellow maize. Potato hash has high water and starch contents. Potato hash has granules of resistant starch (amylose) that are resistant to endogenous enzymes (reviewed by Ncobela et al., 2017). This product is suitable for ensiling in the farms if mixed with wheat or corn brans.
Potato pulp and potato hash have similar compositions although the proportion of starch may vary. They differ from potato peels because of a higher fibre content. Studies by Li et al. (2011) for potato pulp and by Thomas et al. (2018a) for potato hash showed that fermentation allows the use of non-digestible fibre and starch by microorganisms and increases the nutritional value. The heat generated during the fermentation is sufficient to ‘cook’ the potatoes.

Potato peels (or liquid potato feed) are the outer epidermal layer of potatoes that is removed during processing including lye, steam treatment and abrasion. The peeling procedures, particularly heat and pressure, highly influence nutrient composition, particularly the starch content of potato peels. References from Tables and literature show that different nutritional profiles are available depending to the processing methods by the plants. Potato peels have low DM content, starch content ranging from 400 to 575 g/kg, and 100–170 DM g/kg of crude protein, 40-115 DM g/kg of crude fibre.

A data analysis from the bibliography shows that a 20% inclusion of potato by-products may result in a decrease of 15-20 % of the cereal part of the pig diet (Figure 1). However, in most of the experimental diets prepared for the studies, the content in SBM and other protein sources was also slightly increased in order to have similar CP and AAs contents than in the control diet.



Sources: Friend et al., 1963; Edwards et al., 1986 ; Van Lunen et al., 1989 ; Willequet et al., 1993 ; Li et al., 2011 ; Ncobela et al., 2018; Thomas et al., 2018a b.

Figure 1 *Effects of inclusion of potato by-products on inclusion of cereals in pig fattening diets.*

c) Effects on performance and carcass parameters

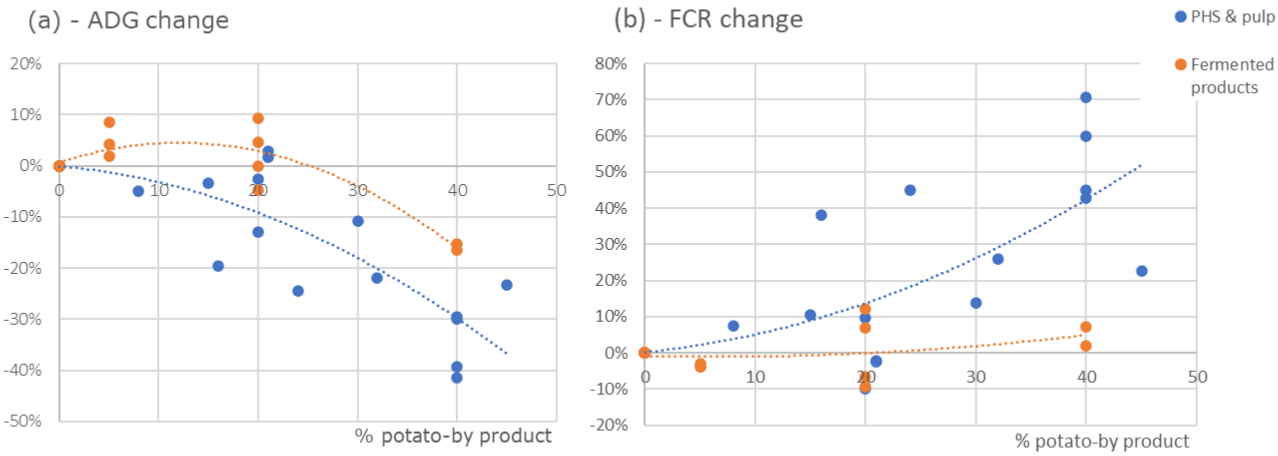
Potato pulp

Dried molassed potato pulp (89% DM, 7.9% CP, 8.7% CF and 3% ash on DM) was used by Canadian authors (Friend et al., 1963) to replace barley in growing pig diets and to replace oats in finishing pig diets. A 22% potato pulp resulted in significantly lower ADG of growing pigs (-8% and -4% for Exp. 1 and 2, respectively) but leaded to a non-significant ADG improvement of finishing pigs (+3% and +9% for barrows and gilts, respectively). At slaughtering, a significant reduction of the dressing percentage was measured for gilts (from 78.2 to 76.1%), but not for barrows. The feed to carcass gain ratio was not significantly improved for both sex (-2%). The distribution of graded levels of potato pulp by the same authors (Friend et al., 1963) indicated that 15% potato pulp led to a non-significant slight reduction of ADG (-3%) but 30% and 45% resulted in significant reductions of daily gain (-10 and -19%, respectively). Feed efficiency of the fattening period was reduced by all levels of potato pulp (Feed to carcass gain ratio: +11, +14 and +23% for 15, 30 and 45% potato pulp, respectively). These researchers also measured that the apparent digestibility for potato pulp was 81, 75 and 76% for dry matter, crude fibre and energy, respectively, but the crude protein was only 26% apparent digestible, probably partly because of a high microbial fermentation and protein production in the hind gut.

Li et al. (2011) introduced 5% of fermented potato pulp (65% DM, 14% CP, 13% CF and 3.7% ash on DM) in starting, growing or finishing corn-SBM diets given in dry feeders. The inclusion of fermented potato pulp increased feed intake (+2%) for growing pigs and increased weight gain for starting (+4%) and growing (+8%) pigs. Feed conversion was improved (-4%) for growing pigs and showed a tendency to improve for starting (-4%) and finishing (-3%) pigs fed fermented potato pulp compared to control pigs. Fermented potato pulp increased dry matter digestibility of starting and finishing diets and energy digestibility of growing diets. The carcass characteristics of finishing pigs were not modified by fermented pulp. The same group of authors reported that 5% of fermented potato pulp tended to increase feed intake of lactating sows and to reduce the weight loss at weaning (Xue et al., 2011).

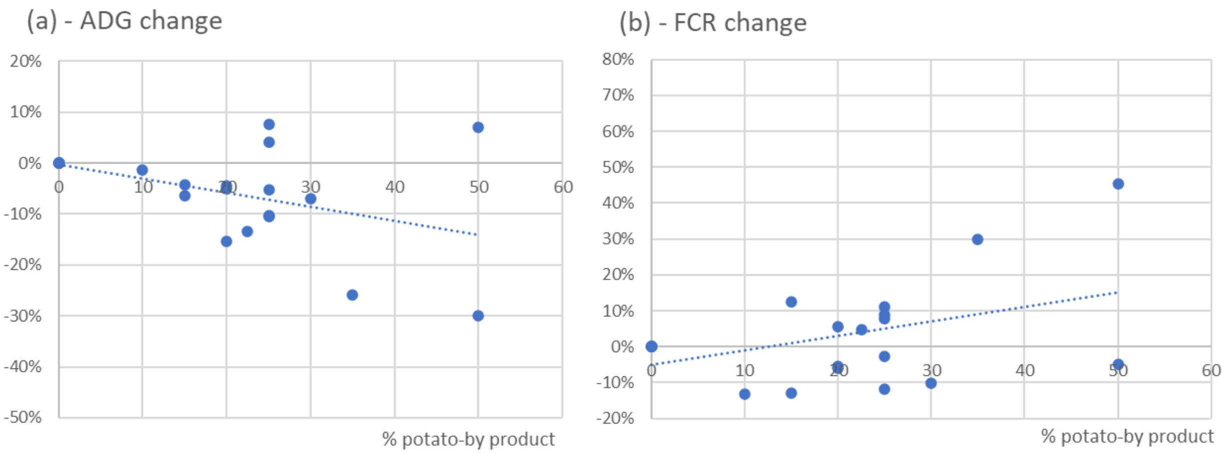
Potato hash silage

Potato hash silage (PHS), a subcategory of potato pulp, was studied by authors of South-Africa to replace corn and corn by-product (hominy chop) but the high fibre content and the poor starch digestibility had some impact on pig performance. Thomas et al. (2010) introduced 40% of potato hash (ensiled with 30 % wheat bran) that was treated with or without LAB inoculants, which reduced dramatically pig ADG (-30-39%) and increased FCR (+40-60 %) when compared to the control. In a following study, Thomas et al. (2013) measured a huge reduction of carcass weights and dressing percentage (from 84 to 73-76%) of pigs fed with 40% of potato hash. A similar reduction in performance yield was reported by Ncobela et al. (2018) who increased up to 40% levels of ensiled potato hash (including 30 % maize cobs) in the diet of slow-growing pigs. A quadratic increase of ADFI was observed up to 24 % inclusion, probably to compensate for ingestion of indigestible content, and then decreased for 32-40 % levels, whereas ADG was linearly decreased with increasing levels of potato hash. This could be explained by the very high NDF content (63%) of the by-product, resulting in 41% NDF in the final compound feed containing 40% PHS. The same group of authors (Thomas et al., 2018b) distributed 20 % of a silage of potato hash and maize cobs (70:30) with a lower NDF content (46%) to lightweight fattening pigs (28-67 kg) in two commercial farms. In farms 1 and 2, ADG was numerically improved or not significantly impacted compared to the control treatment, for the silage that was initially treated with a xylanase (+9 and -5%). However, poorer performance was obtained for the non-treated silage (ADG: -3 and -13%, for farms 1 and 2, respectively). Lastly, the same authors proposed to ferment potato hash as a liquid feed. A 20% inclusion of one 8 hours fermented product inoculated with xylanase or not, did not degraded ADFI (-2 and +7%, respectively) and ADG (+5 and -5%, respectively) of fattening pigs compared to control pigs, but a 40% inclusion resulted in lower ADFI (-9 and -15%, respectively) and ADG (-15 and -16%, respectively).



PHS: potato hash silage; Pulp: potato pulp. Sources: Friend et al, 1963; Li et al, 2011; Thomas et al, 2010, 2018a, 2018b.

Figure 2 *Incidence of the inclusion of raw or fermented potato by-products on ADG (A) and FCR (B) of fattening pigs.*



ADG: average daily gain; FCR: feed conversion ratio; Sources: Edwards et al, 1986; Nicholson et al, 1988; Van Lunen et al, 1989; Willequet et al, 1993.

Figure 3 *Incidence of the inclusion of potato peelings on ADG (A) and FCR (B) of fattening pigs.*

Potato peels

Potato peelings are largely used for feeding fattening pigs with liquid feed systems and effects on performance, carcass quality, animal health and welfare were studied by researchers in UK, Canada, The Netherlands and France.

Edwards et al. (1986) used different proportions of potato peels (11% DM, 14% CP, 6% CF and 11% ash on DM) to replace barley in a conventional fattening pig meal. A 25% DM inclusion did not affect ADFI, but ADG was lower (-5%) and DM FCR was higher (+8%). 35 and 50% inclusion rates caused poor performance (ADG: -26 and -30%, respectively; FCR: +30 and 45%, respectively) compared to control treatment and pigs could not be slaughtered at the same time. Nicholson et al. (1988) used likewise potato peeling product (12-15% DM, 12-17% CP) at graded levels of replacement of the control diet for liquid fed finishing pigs. Inclusion of steam peels at 15 and 20 % of the ration dry matter reduced reasonably ADG gain (-6 and -5%, respectively) and feed efficiency (FCR: +13 and +6%, respectively). However, a 25% had a higher negative effect on fattening performance (ADG: -10%; FCR: +11%) compared to control pigs. The authors measured that apparent digestibility by pigs was 81% for dry matter, 61% for crude protein, 82% for organic matter and 77% for gross energy of potato peels. The same group of authors (Van Lunen et al., 1989) distributed different barley-SBM diets containing levels of 0, 10, 15, 20, 25% and 30% of similar potato peels (14% DM, 16% CP and 13% ADF on DM) which was supplemented with methionine. They obtained numerically but not significantly lower ADFI and ADG of pigs given 10 to 20% of potato peels but FCR was also decreased.

Carcass characteristics were similar. In the second feeding trial, a comparison was made between a constant level of inclusion (20%) and two increase-with-age inclusion levels (20 then 25, or 20, then 25, then 30%). Results showed also slight but not significant decreases in ADFI or ADG or increase in FCR compared to control. No change in performance resulted from the increasing level of inclusion with age. The trial digestibility of potato peels by pigs showed values to be 88% for DM, 78% for CP and 86% for energy. Later, Moreau et al. (1992) made a survey of the use of liquid by-products by 60 pig farms of North-France. Potato peeling was used by 63% of farms (incorporation ranging from 10 to 54% and mean at 34%) and mean composition characteristics were: 18% DM, 13% CP and 48 % starch on DM). The performance data were collected in six farms. It appeared that ADG of 2 farms using liquid wheat starch and potato peels or 3 farms using liquid starch feed, potato peels and whey were slightly lower than the control farm using only wheat starch feed (764, 777 and 839 g/d respectively). However, digestible energy to gain ratio were quite similar (44.9, 42.9, 45.9 MJ/ kg gain, respectively). Lean meat and dressing percentages were higher when potato peeling was included in the pig ration (52.9, 53.7 and 55.2% muscle percentage, and 76.3, 78.5 and 78.5 % dressing percentage, respectively). Simultaneously, the same group of authors measured that apparent digestibility coefficients were 93% for DM and OM, 78% for CP and 91% for gross energy (Sourdioux et al., 1993).

Willequet et al. (1993) included 25 then 50% of potato peels in the diet of grower-finishers fed a control wheat-SBM diet in 3 liquid meals per day. Pigs given 25 and 50% peels had higher ADFI (+4 and +3%, respectively) and carcass daily gain (+8 and +7 %, respectively) compared to control pigs. FCR was consequently improved (-3 and -5%, respectively). Therefore, carcass weight was increased by peels but lean meat percentage was significantly lower for 25% peel pigs compared to control and 50% peel pigs (55.6 vs 57.4 and 56.5%, respectively). Dressing percentage was decreased for 50% peel pigs compared to control and 25% potato peel pigs (76.1 vs 77.6 and 77.5%, respectively). Lastly, Scholten et al. (1997) compared to a control compound diet, liquid feeds including 22% then 35% liquid wheat starch, 5 then 12.5% potato peels and 4.5 and 7.5% feed whey for the growing and finishing periods, respectively. ADG was significantly improved (+4%) and FCR significantly decreased (-4%) with by-products. The FCR was deeply decreased (-6%) if the liquid feeding was additionally restricted for the finishing period. In the two studies by Willequet et al. (1993) and Scholten et al. (1997), authors indicated that the value of the by-products was initially underestimated, which may have explained the better growth performance of pigs receiving liquid co-products.

d) Conclusions

The use of potato hash or pulp appears to lead to poor growth and carcass performance when included at 30-40% in the diet.

For inclusions of 15-20%, the performance degradation will be less marked, especially for older animals and for products with a lower fibre content (Figures 2 and 3). The same inclusion levels may allow comparable ADG and FCR results if fermentation or enzymatic treatments are applied to the potato hash of pulps. For potato peels, literature offers contradictory results about impact on pig performance (Figures 4 and 5). The earlier British and Canadian studies from the 1980s may show declines in performance for 25% inclusions, whereas gain and feed conversion were not significantly negatively affected with 15-20% potato peels on a dry matter basis. More recent works showed that performance equivalent to cereal-meal diets is possible with inclusions above 25% of mixed liquid co-products (liquid starch, whey and peels) or potato peels, in agreement with the inclusion rates for potato peels of 12 to 30 % DM which are currently applied by French or Dutch farmers.
This may be the result of a better appreciation of the nutritional value of ingredients and nutrient requirement values for the animals involved in the most recent studies. However, all authors agree that by-products have a greater variation in crude protein, crude fat, starch than standard feeds and ingredients. Part of the variation in starch content can possibly be explained by the fact that, depending on the degree of fermentation of the by-product at the time it is delivered to the pig farmer, the conversion of starch to soluble starch, organic acids and alcohol may have already taken place. The difficulty is therefore to correctly estimate the composition of liquid co-products and to calculate the correct energy and nutrient values. Although a great expertise exists among pi farmers, advisors and feed companies, little scientific information has been published on the use of potato co-products and other wet by-products, probably due to the lack of experimental pig facilities using liquid feed in Europe. It should be think about how to make up for this absence.

2.1.3 Inclusion of kitchen waste

a) Background

Approximately one third of the world production of all agricultural products (1.3 billion tonnes of food) is not consumed but lost or wasted (Gustavsson et al., 2011). This includes losses at primary production, processing of crops into food products, and their distribution and consumption. For EU-27/28 it was estimated that 43-47 million tonnes were wasted by households and 11-14 million tonnes by food service and catering (e.g. hotels and restaurants) (EC, 2010; Stenmarck et al., 2016). Adopting a dry matter content of 30% (Zu Ermgassem et al., 2016b), this would be an equivalent of 13-14 and 3-4 million tonnes of dry matter wasted in the EU by households and professional kitchens, respectively. Food waste from household and professional kitchens, earlier referred to as swill, was commonly used in pig diets in the EU in the last century. The usage decreased in the late 20th century because of abundant availability of cereal grains and other feed materials at competitive price. It was banned in EU in 2002 after the foot-and-mouth disease epidemic in UK, which was linked to the illegal feeding of uncooked food waste to pigs (EC, 2002). In contrast, the recycling of food waste is actively promoted in South East Asia, including South Korea, and Japan (Zu Ermgassem et al., 2016). In Japan, animal feed is the priority use of food waste and feed from recycled food waste is known as "Ecofeed". Ecofeed manufacturers are required to heat food waste containing meats for a minimum of 30 min at 70°C or 3 min at 80°C (Sugiura et al., 2009). Nonetheless, household wastes are not currently recycled into animal feed in Japan because they are vulnerable to contamination by foreign objects (e.g. cutlery) (Sugiura et al., 2009), low in quantity and heterogenous in composition (Liu et al., 2016), whereas these wastes are used in animal feed in South Korea, where food waste is screened for potential contaminants before use (Stuart, 2009). Despite the ban on the use of kitchen and catering waste and the potential risk for animal and human health, the interest in using the substantial volume of these resources has increased in the last few years. A brief summary of nutritional characteristics is provided and discussed in the next paragraph, and potential effects on pig health are presented in paragraph 3.2.2. It was not the aim of the present report to address potential hazards of feed safety, as these are reviewed elsewhere recently (e.g. Georganas et al., 2022).

b) Composition

The composition of kitchen and catering waste is heterogenous and highly variable, depending on the origin and way of processing (Ho and Chu, 2019; Georganas et al., 2020).

Fisgativa et al. (2016) summarised 70 studies and Esteban-Lustres et al. (2022) reviewed over 25 studies with data on the composition of waste from household kitchens, professional kitchens, mainly restaurants and university canteens, and organic waste from municipalities. Although the aim of these reviews was primarily to determine properties for biorefinery or anaerobic digestion, results are indicative for use as feed material as well. Mean results of these two studies, as summarised in Table 1, were generally in good agreement, apart from a higher content of ash and lignin in the wastes evaluated in the study of Fisgativa et al. (2016). This is likely the result of inclusion of samples of organic fraction of municipality waste, which may contain garden litter with plant material (leaves and branches) and soil. Within the study of Esteban-Lustres et al. (2022), samples of household waste were generally higher in ash and lignin content as well. Overall, the results suggest that kitchen and catering waste represent a relevant amount of protein, lipid and starch principally suitable for animal feed, but the composition varies substantially in relation to origin of the material. Insight in the nutritional composition in relation to origin, and preferably homogenisation of material from various origins to realise a less variable composition would be required for the rational inclusion in animal diets (Fausto-Castro et al., 2020; Boumans et al., 2022).

Table 2 *Composition of food waste from household, professional kitchens and municipalities (% in DM, except moisture).*

Source	Moisture	Ash	Lipid	Protein	Hemicellulose	Cellulose	Lignin	Starch
Fisgativa et al. (2016)	77±8	12±8	13±7	19±11	8±4	8±7	6±5	36±21
Esteban-Lustres et al. (2022)	78±9	6±3	15±7	15±5	8±4	12±11	2±2	32±16

based on reviews of Fisgativa et al. (2016) and Esteban-Lustres et al. (2022).

Dou et al. (2018) summarised results of 12 studies in which nutritional characteristics of food waste from professional kitchens and households were provided for use in feed for pigs, poultry or ruminants. The mean composition of the food waste, 22±5% dry matter, 19±5% crude protein, 22±7% lipid, 39±9% nitrogen-free extract and 6±3% crude fibre, agrees reasonably well with food waste composition in the two reviews summarised above. Georganas et al. (2020) addressed the presence of amino acids, fatty acids, micronutrients and bioactive compounds in food waste and noted the relatively high salt content that needs to be taken into account. Although these data support the potential value of catering waste as animal feed, information on nutrient digestibility as required for proper evaluation of nutritional value, is scarcely available.

c) Growth performance

In the feeding trials reviewed by Dou et al. (2018), the percentage of food waste used in diets ranged from 10% to 100%. Responses in terms of body weight gain and/or feed efficiency varied depending on animal species, length of the feeding trial, and type of food waste and inclusion rate. A number of studies reported no difference in performance comparing diets with vs. without substitution. For example Myer et al. (1999) observed no effect on ADG and an improvement in FCR in growing finishing pigs when a maize SBM diet was up to 80% replaced by a mixture of restaurant waste (60%), soybean hulls and ground maize. Likewise, Kjos et al. (2000) did not observe a negative impact of including up to 100% of a mixture of food leftovers and food processing by-products on growth performance and feed efficiency. Other studies reported a reduction in growth performance with incremental inclusion of food waste. For example Westendorf et al. (1998) observed a decrease in ADFI and ADG in growing finishing pigs when more than 25% of the corn SBM diet was replaced by *ad libitum* access to cooked cafetaria waste. The authors related this effect to the low and variable dry matter content (11-35%) of the latter product. The total tract digestibility of the cooked cafetaria waste was equal or higher than the digestibility of the basal corn soybean diet. Chae et al. (2000) observed a significant reduction in growth performance with 20 to 40% dried restaurant and household waste in the diet of growing finishing pigs at the expense of corn and SBM. From the published results, it seems that large variation in protein content and deficiency in some essential amino acids may have caused these effects. In addition, it cannot be excluded that drum-drying the food waste may have hampered the protein quality by decreasing protein digestibility and/or reducing amino acid availability. Takahashi et al. (2012) observed a drastic decrease in growth performance when a control diet based on cereal grain and oil seed meal was replaced by an incremental proportion of Ecofeed largely based on bread crumbs and other grain processing by-products.

This reduction was likely caused by a substantial reduction in lysine content of the Ecofeed diet. More recently, Giamouri et al. (2022) observed a reduction in feed intake and growth rate in a first small scale study but not in a second study when 8 to 10% dried hotel residues were included in the diet at the expense of corn and SBM. FCR was not affected by dietary treatment. Summarizing from multiple studies, zu Ermgassen et al. (2016) reported a 13% lower growth rate for pigs with a 50% substitution rate. This effect seems largely caused by a low DM content of the wet food waste based diets, variation in composition of food waste, lack of information on digestibility of nutrients in food waste and incomplete standardisation of nutrient content of food waste based diets.

d) Carcass and meat quality

In the studies of Myer et al. (1999) and Kjos et al. (2000), a high inclusion level of food waste (above 40-60%) reduced the firmness of backfat of pigs. This effect was presumably related to the fatty acid pattern of the food waste, which can be relatively high in unsaturated fatty acid content. Westerhof et al. (1998) and Kjos et al. (2000) did not observe an effect on sensory quality of pork from different diets as determined by a taste panel. Zu Ermgassem et al. (2016) reviewed a number of meat quality criteria and did not observe any impact on these characteristics apart from an increase in marbling score and content of monounsaturated fatty acids. The first effect was caused by a study with low lysine diets while the latter was likely related to the fatty acid pattern of food waste in various studies.

e) Conclusion

Use of kitchen and catering waste as animal feed is not allowed in the EU. Nonetheless, based on the available information, it seems likely that adequately treated (professional) kitchen waste can be included in pig diets without loss of performance, carcass and meat quality, provided that the nutrient content is adequately known and taken into account. The latter can be a limiting factor for the use of small and variable quantities of catering and kitchen waste.

2.2 Increase of protein sources originating from EU

2.2.1 Inclusion of rapeseed meal in pig diets

a) Background

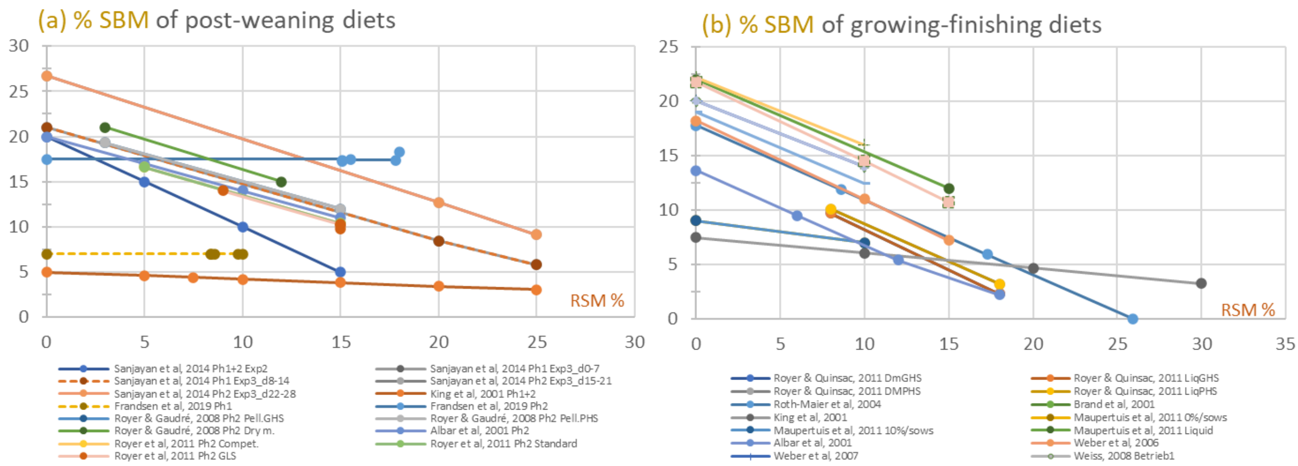
Rapeseed meal (RSM) is an oilseed co-product obtained by pressing and solvent extraction of oil from rapeseed (*Brassica nappus*). Compared to soybean meal, the mean crude protein (339 g/kg) and net energy (0.79 EW) content of rapeseed meal are lower, largely due to a higher fibre content from the hulls that are not commonly removed prior to oil extraction as in soybean processing. Rapeseed and rapeseed meal are characterised by the presence of anti-nutritional factors from the group of glucosinolates (GLS): isothiocyanate (ITC), characterised by a bitter taste that may reduce palatability of feed and reduce feed intake, and vinyl-thiooxazolidone (VTO), which may cause physiological disorders due to its effect on the thyroid gland. Glucosinolates are plant metabolites found in all Brassica seeds, and presumably play a role in the protection of the plant against insects. Pigs are more sensitive to dietary glucosinolates than other farm animals. In addition, rapeseed contains erucid acid (C22:1) which has toxic properties at high intake level. The quality of rapeseed meal as feedstuff has improved considerably in the last decades. Rapeseed meal is now generally obtained from "00" type seeds, with low levels of glucosinolates and erucic acid. The lower level of glucosinolates in RSM (below 15 μmol/g), has allowed to increase the incorporation in pig diets. The influence of rapeseed meals, thiocyanates and glucosinolates has been intensively studied by Schöne et al. (1991; 1993; 1997a; 1997b; 2002). A higher inclusion of RSM in pig diets depends on the digestibility and nutritional value, as well as a low content of anti-nutritional compounds. Excess heat can decrease protein digestibility and cause non-enzymatic transformation of the intact glucosinolates (Jensen et al., 1995, quoted by Frandsen et al., 2019). On the other hand, a low temperature during processing may also decrease protein digestibility, due to reaction between proteins and isothiocyanates formed by hydrolysis of glucosinolates as result of insufficient inactivation of myrosinases and other enzymes (Ochetim et al., 1980; Jensen et al., 1995; all quoted by Frandsen et al., 2019).

Additionally, the high fibre content of rapeseed meal may limit its inclusion level, especially in high energy diets. Dehulling could be a method to reduce the fibre content by half, but the feasibility of this process is impeded by the high oil content in the hulls (Carré et al., 2015).

b) Effects on diet composition

The development of rapeseed cultivation for biofuel production in the mid-2000s, particularly in Europe, enhanced the volume and use of RSM in pig feeds. Several European studies were undertaken to provide information on feeding piglets, growing pigs and sows with RSM. For the present report, a total of 14 studies were selected from the literature to prepare a dataset on the use of RSM as an alternative protein source to replace soybean meal. Studies were undertaken in Germany (Roth-Maier et al., 2004; Weiss et al., 2004; Weber et al., 2006, 2007; Weiss, 2008), France (Albar et al., 2001; Royer and Gaudré, 2008; Maupertuis et al., 2011; Royer and Quinsac, 2011; Royer et al., 2011), Australia (King et al., 2001), Canada (Sanjayan et al., 2014), South-Africa (Brandt et al., 2001), and Denmark (Frandsen et al., 2019). All RSM were solvent extracted with the exception of the study of Frandsen et al. (2019) who tested several processes using warm and cold pressing of rapeseed. In all studies, diets were formulated on the basis of available table values for the nutritional value of RSM and balanced for NE and digestible amino acids. Exceptions were the trials of King et al. (2001) and Brandt et al. (2001), in which diets were evaluated on a DE basis and total amino acids. Additionally, all German trials used ME and total or digestible amino acid contents.

The relationship between the inclusion rates of RSM and SBM in the experimental diets is displayed in Figure 4. In many studies, increasing the level of RSM resulted in a linear reduction in SBM inclusion, both in post-weaning and fattening periods. However, in several studies, the rapeseed meal partly replaced other protein sources such as fish meal, terrestrial animal products or, in weaning diets, whey or protein concentrates. In some studies, the increasing inclusion of rapeseed meal resulted in a slight decrease in the use of cereals in fattening and post-weaning diets, in order to have equivalent diets in energy and protein concentration.



SBM: soybean meal; RSM: rapeseed meal. Sources: Albar et al., 2001; Brand et al., 2001; Frandsen et al., 2019; King et al., 2001; Maupertuis et al., 2011; Royer and Gaudré, 2008; Royer and Quinsac, 2011; Royer et al., 2011; Sanjayan et al., 2014 ; Roth-Maier et al., 2004; Weber et al., 2006, 2007; Weiss, 2008.

Figure 4 *Incidence of the inclusion of rapeseed meal on soybean meal percentage in post-weaning (a) and growing-finishing (b) diets.*

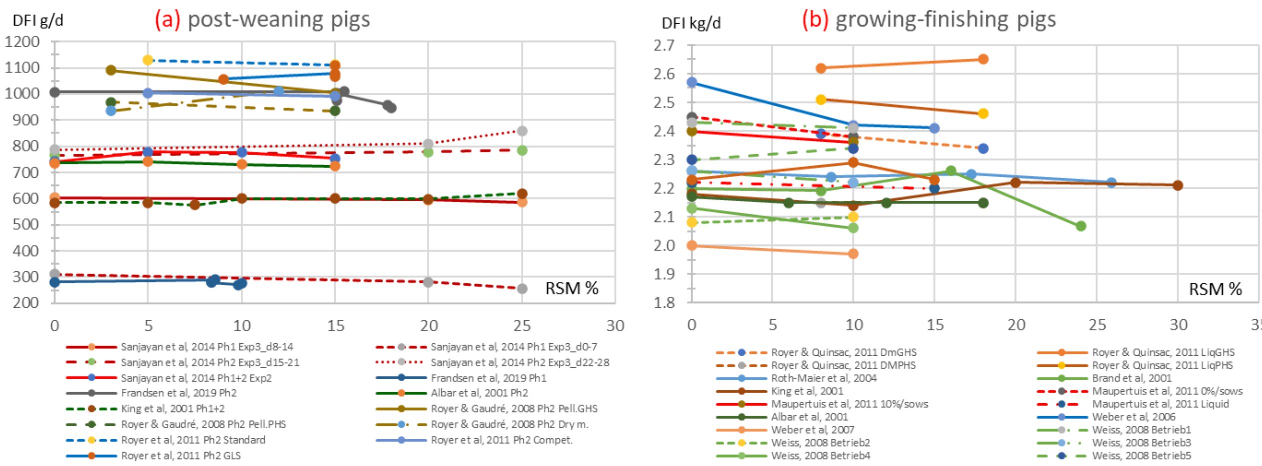
c) Effects on performance of weaned piglets

Previous studies investigated performance of piglets fed with increasing levels of RSM for phase 1 or phase 2 periods or both. All treatments within a study were given diets with the same NE and digestible amino acid content, except the study undertaken by King et al. (2001) with 7 inclusion levels of RSM up to 25%. Overall, it appears that RSM has little influence on piglet feed intake (Figure 5) and growth performance.
In the phase 1 nursery period, weaned pigs fed with up to 10 % of RSM obtained with warm or cold pressing had similar ADFI and ADG (Frandsen et al., 2019). In the study reported by Sanjayan et al. (2014), piglets given 20 or 25 % RSM had numerically but not significantly lower ADFI and ADG than control piglets in week 1. However, in week 2, piglets fed RSM diets had a numerically higher ADG than control piglets.

In the phase 2 period, 15 % to 18 % of RSM produced with cold pressing caused a 3 to 6 % lower feed intake, resulting in a decrease of 4 to 7 % in ADG, while the same percentage of RSM from warm pressing did not negatively affect performance (Frandsen et al., 2019). In one of the trials reported by Royer and Gaudré (2008), the piglets provided a phase 2 diet with 15 % RSM had a lower ADFI (-8%) and ADG (-7%) compared to piglets given a SBM based diet. In all other studies, piglets given diets with up to 25 % RSM had a similar performance in the phase 2 period as piglets fed with diets without RSM. In all these studies, the feed efficiency of the RSM diets was not different from the control diets. One exception was the study of King et al. (2001) for which all RSM fed pigs had a lower FCR than the control pigs, indicating that the diets similar on digestible energy and total amino acids may be not balanced for net energy and digestible amino acids.

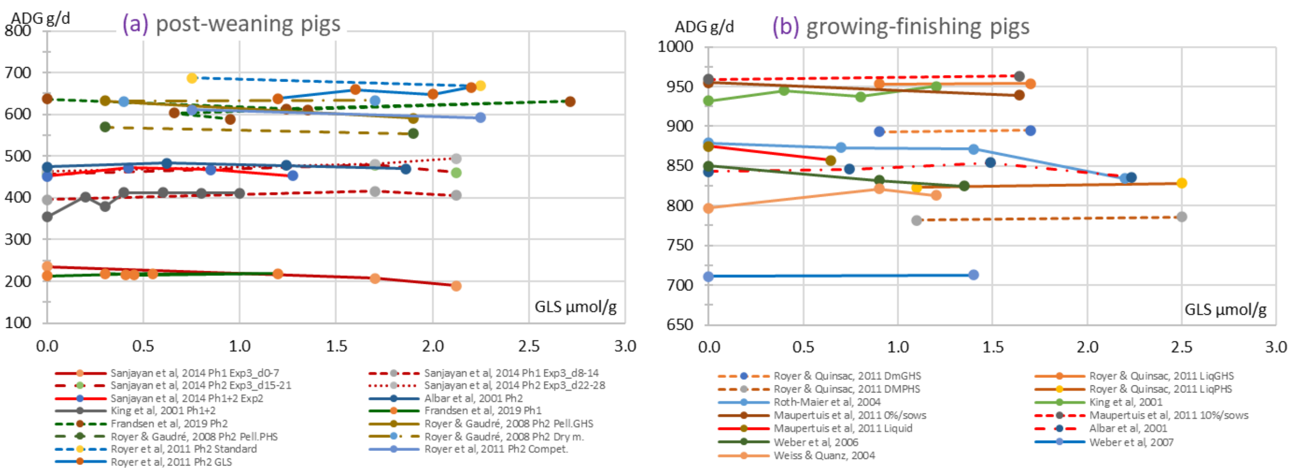
d) Effects on the performance of growing-finishing pigs

In most of the studies, an increase of RSM at the expense of SBM in the growing-finishing diets did not significantly affect the feed intake (Figure 5), ADG and FCR of fattening pigs. However, in the study of Weber et al. (2006), the feed intake was slightly (up to 6%) reduced by the inclusion of rapeseed at 10-15 % and 15-20% in the growing and finishing diets, respectively. However, these lower amounts of feed were better utilised by the pigs of the RSM groups, as shown by an improvement in FCR by 0.1 kg/kg (-4%). At slaughter, the dressing percentage and the lean meat percentage of the carcasses was not influenced by the inclusion of RSM in the pig diets during the fattening period, apart from a slight non-significant decrease of the lean meat percentage in the trial reported by Roth-Maier et al. (2004). These findings differ from older studies as those of Wetscherek et al. (1990, 1992; quoted by Roth-Maier et al., 2004) that reported a higher carcass fat content with 15% RSM. On the other hand, Brand et al. (2001) reported a significant but minor higher meat in carcass content for pigs fed 24 % RSM than for pigs given 8 % RSM. A possible explanation could be that recent feed tables provide a better estimate of the nutritional value of the rapeseed meal. In addition, it can be speculated that processes during crushing and oil production have been improved, thus reducing the risk of overprocessing resulting in a loss of digestible amino acids, in particular of lysine (Salazar-Vilanea et al., 2016a, 2016b; Dauguet et al., 2019). As well, the protein and glucosinolate contents of the rapeseed meal batches are dependant of the de-oiling factory origin (Dauguet et al., 2019).



DFI: daily feed intake; RSM: rapeseed meal. Sources: Albar et al., 2001; Brand et al., 2001; Frandsen et al., 2019; King et al., 2001; Maupertuis et al., 2011; Royer and Gaudré, 2008; Royer and Quinsac, 2011; Royer et al., 2011; Sanjayan et al., 2014 ; Roth-Maier et al., 2004; Weber et al., 2006, 2007; Weiss, 2008.

Figure 5 *Incidence of the inclusion of rapeseed meal on daily feed intake in post-weaning (a) and growing-finishing (b) by pigs.*



GLS: glucosinolates; ADG: average daily gain. Sources: Albar et al., 2001; Brand et al., 2001; Frandsen et al., 2019; King et al., 2001; Maupertuis et al., 2011; Royer and Gaudré, 2008; Royer and Quinsac, 2011; Royer et al., 2011; Sanjayan et al., 2014 ; Roth-Maier et al., 2004; Weber et al., 2006, 2007; Weiss, 2008.

Figure 6 *Incidence of the glucosinolate content of the diet on daily gain in post-weaning (a) and growing-finishing (b) by pigs.*

e) Impact of dietary content of glucosinolates on performance of pigs

Among the antinutritional factors of rapeseed, glucosinolates are known as one of the main factors that could influence pig performance. For several studies, authors have calculated the dietary content of glucosinolates from the analysed level in the RSM. For fattening pigs, results show no apparent influence of the GLS concentration up to 1.7-2.5 µmol/ g diet on the ADG of the pigs (Figure 6). For weaned pigs, calculated GLS levels in diets did not show an apparent influence of the GLS concentration up to 2.25 µmol/ g diet on the ADG of the piglets (Figure 6). Since the amount of glucosinolates ingested per kg body weight are the highest in nursery pigs, studies were undertaken in phase 2 post weaning (12-27 kg pigs) to test the impact of dietary GLS content. Batches of RSM with different glucosinolate contents (12, 15 or 16 µmol/g DM) were used to prepare diets with a constant 15% RSM inclusion but increasing glucosinolate content of 1.2 to 2.2 µmol/g feed. In this range no effect of GLS concentration on piglet performance was observed (Royer et al., 2011). These results are in line with those of Frandsen et al. (2019) who did not observe a reduction in feed intake and gain for RSM with an analysed GLS content of up to 3.1 µmol/g feed, despite an increase in thyroid gland. In contrast, a lower feed intake and gain were observed for cold pressed RSM, despite a low glucosinolate content, presumably because the processing temperature was insufficient to inactivate myrosinase.
Overall, feed intake and growth rate are little affected by the level of glucosinolates in the feed, even when exceeding the recommended limit of 2.0 µmol/g glucosinolates, and the earlier proposed tolerance level of 0.78 µmol /g diet by Tripathi and Mishra (2006). However, the analysed glucosinolate content may depend on the analytical procedures due to the presence of degradation products that are generally not detected. According to Frandsen et al. (2019), the glucosinolate content is often based on intact glucosinolates in the rapeseed meal or cake, without taking transformation products after pressing or due to later pelleting into account. Finally, dietary iodine content may influence the sensitivity of the thyroid for a negative effect of glucosinolates. In most of the studies, the recommended iodine supplementation level was adopted as adequate for thyroid function.

f) Impact of feed competition

It may also be speculated that feed intake could be influenced by the fibre content of the feed, which may reach 45 g/kg crude fibre in a feed with 15% rapeseed meal. Therefore, a high fibre control diet (4% CF and 49 g ADF/kg) prepared with barley, wheat bran, corn gluten feed and containing 5% rapeseed meal was compared to a diet with 15% rapeseed (5.2% CF and 72 g ADF/kg) in a study reported by Royer et al. (2011). In addition, piglets were housed under standard or highly competitive conditions for access to feed (62 or 35 mm trough length/piglet respectively). The glucosinolate content of the 15% RSM feed was 2.25 µmol per g DM. The competition strongly decreased piglet intake and growth, but no interaction between the level of rapeseed meal and the degree of competition was apparent.

However, the lightest piglets at weaning consumed less feed (-6%) and had a lower ADG (-8%) with the 15% oilseed cake feed than with the control feed, which was not the case for medium and heavy piglets. It can be concluded that when the fibre content of the feed is high, the addition of extra rapeseed meal can raise the fibre content and cause a decrease in performance. Further trials are needed to confirm the effects of feed fibre content on piglet adaptation to a feed containing rapeseed meal.

g) Impact of liquid feed distribution on fattening performance

Previous research has shown that RSM can be used at high rates in fattening feeds (Schöne et al., 1997a, 1997b; Albar et al., 2001; Weiss et al., 2004). Nonetheless, since most studies have been carried out on dry feeding, a lower incorporation of RSM in liquid feeds was often recommended because a lower palatability was assumed in a liquid medium. Similarly, there was a concern that lower incorporation rates should be applied for commercial pig farms with poorer hygienic status than those in experimental animal facilities. A specific study was therefore undertaken, using growing pigs previously reared under good sanitary conditions or poor sanitary conditions in the post-weaning phase, to evaluate either dry or liquid feed including 8 or 18% RSM in the fattening diet (Royer and Quinsac, 2011). The research facility was set up with automated liquid-feeding for liquid-fed pens and identical pens with dry feeders. The overall performance and health were better in the experiment with pigs raised under good sanitary conditions than with pigs from poor sanitary conditions. In both trials, liquid-fed pigs had a higher ADFI and ADG than dry-fed pigs, but carcass lean meat content tended to be lower. Despite this, in both trials there were no significant differences in ADFI, ADG and carcass quality between control pigs and those fed 18% RSM. These results are in agreement with those obtained in Germany for pigs receiving liquid feeding with 10 % and 15% of RSM in the growing and finishing period, respectively (Weber et al., 2007; Weiss, 2008).

h) Conclusion

A large number of studies has been conducted to determine the influence of 15 to 25% of RSM inclusion in diets of weaned pigs and growing finishing pigs, primarily at the expense of SBM. Unlike earlier experience, most studies conducted in the last two decades did not indicate negative effects of RSM inclusion on growth performance and carcass quality. Even in weaned pigs, only a minor insignificant reduction in feed intake was observed with an inclusion level up to 25%. For the lightest weaners, the addition of extra rapeseed meal may raise the fibre content and reduce performance. Experimental diets for growing pigs generally did not exceed 18% since at that level, SBM was largely excluded from the diet. Similar results were obtained when RSM was included as part of a liquid diet, irrespective of the feeder space or the hygienic status of the experiment. The absence of negative effects is likely due to the general use of 00 rapeseed with relatively low levels of glucosinolates and erucic acid, that have anti-nutritional properties. A dietary concentration up to 2.2 μmol/g feed does not seem to hamper feed intake and performance, irrespective of the age and body weight of the pig. Analysed levels need to be interpreted carefully since depending on the methods used, not all metabolites may be included. Inclusion of RSM requires adequate insight in the nutritional value (NE and digestible amino acids) in relation to the process characteristics used in processing plants. Both under- and overprocessing of rapeseed during oil extraction may impose negative effects on amino acid availability due to insufficient deactivation of anti-nutritional factors and protein damage.

2.2.2 Inclusion of legume seeds in pig diets

The use of legume seeds or pulses for animal feed in Europe has declined sharply for the last decades, mainly due to low profitability and lack of public support for cultivation, but also due to the need to favour organic nitrogen valorisation in crops of the livestock regions. As a result, pulses now account for only a very small part of the volume of compound feeds for pigs. However, legumes appear as an essential element to improve the sustainability of pig farming. They reduce the need for imported soybean meal and reduce fossil energy requirements as they do not require nitrogen fertiliser. While pulses seeds have digestible and metabolizable energy contents similar to wheat, net energy contents are lower due to the higher protein and lower starch content. The protein of legume seeds is well supplied with lysine compared to soybean protein, but is less rich in methionine and cystine, threonine and tryptophan. The most widely grown legume seeds in Europe are peas, faba beans and lupins. All are relatively high in crude protein with 24, 30 and 38% of DM for peas, faba beans and lupins, respectively.

Peas and faba beans also contain starch (52 and 44% respectively) which lupins do not. On the other hand, peas and faba beans are fat-free while lupins have an oil content of 7-10%. In this section we will look at the value of faba beans and lupins in pig diets.

2.2.2.1 Use of faba beans

a) Background

Faba beans (*Vicia faba L.*) are a feedstuff rich in protein (22–32% CP) and lysine, but poor in methionine. As reviewed by Crepon et al. (2010), growth performance and feed efficiency of animals fed diets including faba beans may be impacted by anti-nutritional factors in faba beans such as tannins, lectins, protease inhibitors, vicine, and covicine. There is, however, a considerable difference in the presence of anti-nutritional factors between varieties, in particular regarding the content of condensed tannins (white vs. coloured flowering and seeded varieties). It has been reported that tannins and polyphenolic compounds can form complexes with protein in the feed and reduce the protein digestibility in monogastric animals (Garrido et al., 1991; Jansman et al., 1995). Another concern with condensed tannins is a reduction in feed intake due to a bitter taste (Jansman, 1993).

b) Influence of antinutrients for different cultivars or types of faba beans

Faba beans without tannins (mean: 0.1 g/kg DM) had higher pig faecal digestibility for protein (88.4 vs. 80.0%) than isogenic FB with tannins (mean: 6.7 g/kg DM) in the experiment of Grosjean et al. (2001). Energy digestibility coefficient and digestible energy were also improved (90.0 vs. 78.7% and 16.7 vs. 14.7 MJ/kg DM). Authors underlined that these differences may be explained by the effect of tannins and to a lesser extent by the effect of fibre, as tannin-free faba beans have also lower fibre levels. Besides that, vicine and covicine contents had few effects on protein and energy faecal and ileal digestibility of growing pigs according to Van der Poel et al. (1992), Grosjean et al. (1995) and Grosjean et al. (2001). Recently, Nyende et al. (2023) established that a high-tannin, high in vicine and covicine cultivar (Florent, 13.8, 5.5 and 3.4 g/kg, respectively) had lower energy, protein and amino acid digestibility than two medium-tannin cultivars both with vicine and covicine (Snowbird: 5.9, 6.3 and 3.3 g/kg, respectively; Snowdrop: 7.9, 7.2 and 3.5 g/kg, respectively). Interestingly, a fourth cultivar with high-tannin but least vicine and covicine content (Fabelle: 14.1, 0.6 and 0.4 g/kg, respectively), was intermediate in energy but not different in protein or amino acid ileal digestibility than medium-tannin cultivars.

The work of Vilariño et al. (2004) showed differences in standardised ileal CP digestibility within varieties belonging to the same faba bean genotype: white-flowered white (79 to 83%) and especially coloured (77 to 83%). For the latter, ileal digestibility of amino acids was the most heterogeneous, whereas the amino acid profile was relatively constant whatever the type of bean. Similarly, Ivarsson and Neil (2018) investigated variations in nutritional and antinutritional components among 11 colour-flowered and 5 white-flowered faba beans cultivars, using a total of 84 samples. They found no effects of flower colour, but significant effects of cultivar within flower colour for starch, CP and NDF. The colour-flowered cultivars had a greater content of condensed tannins and the white-flowered cultivars a greater content of vicine and covicine. Within the colour-flowered cultivars, Alexia had the greatest (7.68 g/kg DM) and Julia the smallest (6.05 g/kg DM) tannin content. The enzymatic *in vitro* digestibility of DM, OM, CP, and calculated standardised ileal digestibility of CP was higher in white-flowered than colour-flowered cultivars. However, on a yield per hectare basis, colour-flowered cultivars yielded more ileal digestible CP and starch than white-flowered cultivars. Furthermore, most of varieties produced in France, main EU producer for faba beans, are coloured-flowered. The white-flowered varieties that have been registered in France or EU have lower yields and are less cropped (Véronique Biarnès, Terres Inovia, personal communication). About vicine and covicine, some spring bean varieties have a lower content but not all. The most widely grown varieties of faba bean are therefore those with coloured flowers and variable vicine-covicine content, as both types exist. Varieties that had both white flowers and low vicine-covicine content (as Fevita) were not developed because of a very low yield per ha.

c) Performance and digestibility with faba beans

In the 1980’s, early trials concluded that inclusion levels of faba beans should be limited to 10% in piglet or pig diets whatever the type of faba bean variety, and that at rates in excess of 10%, ADG tended to reduce and FCR to increase (reviewed by Crepon et al., 2010). However, more recent trials with diets supplemented with amino acids, have showed that higher inclusion rates of low or medium-tannin beans should not alter growth performance of weaning or fattening pigs.
Indeed, using a low- and a medium-tannin variety of beans (cv. Victoria and Marcel, <0.05 vs 4.65 g tannins per kg), Royer et al. (2010) used the equations for predicting gross energy and amino acid composition of the beans, then the available digestibility coefficients for beans with or without tannins, to prepare iso- net energy and iso- ileal digestible amino acid diets at 0, 10 or 20% inclusion rate in phase 2 nursery period, then 0, 20 or 35 % in growing and finishing periods. For both post-weaning then growing-finishing experiments, authors reported no effect of the level of faba beans with low or medium-tannin content on ADFI, ADG, FCR or carcass traits. In their post-weaning study, Ivarsson and Neil (2018) prepared six weaner experimental diets similar in net energy and standardised ileal digestible CP and amino acids with the control diet containing SBM and potato protein, and the experimental diets with 10 or 20% beans of two colour-flowered cultivars: Julia (6.05 g/kg tannins) and Fuego (6.87 g/kg tannins), and 20% of Gloria, a white-flowered cultivar (0.23 g/kg tannins). Feed intake was highest in piglets fed 10% Julia and smallest in pigs fed 20% Fuego, which could reflect the 27% greater tannin content for Fuego than Julia. However, ADG and G:F were not reduced in 20% Fuego compared to the control diet, and colour-flowered cultivars had no negative effect on ADG. Indeed, pigs fed the diets with 20% faba bean inclusion had better G:F ratio than pigs fed the control diet, irrespective of cultivar. Thus, authors concluded that the current level of tannins in commonly used colour-flowered cultivars is not a major issue for weaner pigs fed nutritionally well-balanced diets. These results are confirmed by those of Nyende et al. (2022) who found that performance of weaned piglets fed iso- net energy and iso SID Lys phase 1 and phase 2 diets with 20 then 30% of three zero-tannin (Snowbird, Snowdrop and Tabasco, < 2 g/kg tannins), high vicine and covicine cultivars and two medium-tannin (Fabelle and Malik, 5.3 and 2.7 g/kg) lower vicine and covicine cultivars was not influenced by the concentrations in tannins. Indeed, growth performance of piglets was more related to feed intake than diet nutrient digestibility. These authors suggested that vicine and covicine instead of condensed tannin content of faba bean cultivars could be more relevant to growth performance in weaned pigs.

For the fattening period, the distribution of 20% faba beans (cv. Fiord, 4.8 g/kg tannins) to growing-finishing pigs did not modify growth performance or carcass characteristics compared to a fishmeal-based diet, in the study of Brand et al. (1995). However, Partanen et al. (2003) found that the inclusion of 26% and 32% of a white-flowered Faba bean (cv. Kontu) in diets balanced for NE and digestible amino acids decreased feed intake and growth rate of growing pigs and could affect meat ultimate pH and colour, but authors did not indicate the tannin concentration of the faba beans. They although concluded that faba beans could be used up to 20% for growing pigs and without restriction for finishing pigs. Also, a higher inclusion level of 35% was tested as satisfying for fattening pigs in the study reported by Royer et al. (2010).
These later results agree with those of White et al. (2015) who compared four fattening pig diets with 30% of either white-flowered peas (cv. Prophet, 1.06 mg/g TIU], spring coloured-flowered faba beans (Fuego, 5.2 g/kg DM tannins), spring white-flowered faba beans (Tattoo, 0.0 g/kg DM tannins), or winter coloured-flowered faba beans (Wizard, 1.3-3.1 g/kg DM tannins) to a SBM control diet. Pigs were fed *ad libitum* and results showed no difference of ADFI, ADG and FCR for both growing and finishing periods. A complementary trial in metabolism crates indicated that dietary treatments with SBM, Prophet (peas), Fuego and Tattoo (faba beans) did not affect faecal digestibility of protein, metabolizable energy content, or N balance. At slaughterhouse, pigs fed with the pea-based diet had a greater dressing percentage than pigs given faba bean-based diets and pigs fed with the SBM or pea-based diets also had greater lean meat percentage than pigs from the faba-bean diets. Mean skatole concentrations for all pigs were below the accepted maximum threshold (0.2 µg/g). Previously, the same group of authors (Smith et al., 2013) compared a control diet based on SBM (14 and 12% for grower and finisher periods, respectively), with eight diets including the same cultivars of peas (Prophet) or faba beans (Fuego) at 7.5, 15, 22.5, and 30%, gradually and completely replacing SBM. Diets were formulated to be isoenergetic for NE and with the same standard ileal digestible Lys content and were distributed *ad libitum*. There were no effects on grower ADG, ADFI, and G:F, and pea and faba bean diets resulted in similar finisher performance, in spite of a quadratic effect of pulse inclusion on finisher ADG, as ADG tended to be higher with 30% pea or faba bean than for initial inclusion levels.

There were no associated effects on ADFI or G:F. Pulse inclusion linearly increased faecal DM content both in grower pigs and finisher pigs. There were no effects on carcass quality or backfat skatole concentrations, but indole concentration was linearly reduced with increasing pulse inclusion.

d) Treatments of faba beans

Several processes such as soaking, boiling, dehulling, cooking, enzyme treatment, fermentation and extrusion were reviewed by Kaysi and Melcion (1992) and Rahate et al. (2021) as feasible ways to eliminate the anti-nutritional factors of faba beans. Kaysi et Melcion (1992) underlined that effectiveness of the treatments depends on the values taken by the control parameters of the processes, which must be optimised with regard to nutritional but also industrial criteria. The most effective treatments were found out by Rahate et al. (1992) to be bioprocessing (Fermentation + phytase treatment) or extrusion. They reviewed that after the dehulling of faba beans, phytic acid was increased whereas tannin and polyphenol contents were reduced as both are largely present in the hulls. With dehulling, condensed tannins are reduced by 92% and polyphenol content is reduced by 81%. Dehulling is also reviewed as improving the protein content. Another simple process as air-classification can be used for improving the protein concentration and decreasing antinutrients of the faba beans (De Santis et al., 2016; Vogelsang-O'Dwyer et al., 2020).

An experimental study on young pigs reported by Zaworska-Zakrzewska et al. (2022) showed that extrusion increase the nutritional value of faba beans, especially by reducing anti-nutritional factors, but in comparison with raw beans, growth performance, digestibility of nutrients, intestinal structure and physiology of the digestive tract of pigs were not improved when the content of faba beans in the diet was below 10%. Protease supplementation of the pig diet allowed to reduce protein and oil levels in the diet while maintaining the same performance, which reduced the cost of feeding. However, extrusion and enzyme additives did not improve the pig growth performance in this study. Tusnio et al. (2021) also used extruded faba bean seeds as source of protein in phase 1 weaning diets balanced for metabolizable energy and ileal digestible amino acids and concluded that their content should not exceed 25%. At 30% dietary level, corresponding to 4.4% CF, 15.7% NDF and 0.267 g/kg tannins, extruded faba beans reduced feed efficiency and increased tunica muscularis thickness in the large intestine. Besides that, inclusion of 20–30% faba bean seeds in a diet had no negative impact on selected microbial activity indices.

e) Combination of several alternative protein sources

Interestingly, Grabez et al. (2020) substituted in full the 14.3% SBM of a growing-finishing pig diet with 18% RSM and 16.1% faba beans. Diets gave no overall differences in ADG, ADFI or carcass traits. However, FCR was increased by 5% for the finishing period but as RSM and faba beans were not analysed for fibre and ANF contents, no relation could be found to explain this reduction of feed utilization. Essentially, feeding RSM-faba beans had a positive effect on meat quality as sugar related compounds in meat were lowered, and lightness, yellowness, warmed-over flavor and flavor attributes were significantly reduced.
Sobotka and Fiedorowicz-Szatkowska (2021) also determined the effect of partial (50%) and total replacement of SBM with RSM (6.85 mol glucosinolates / g dry-non-fat mass), alone or in combination with low-tannin faba beans (cv Albus, 2.7 g tannins /kg DM) or low-alkaloid yellow lupine (cv Taper, 0.07 g alkaloids /kg DM) in grower and finisher diets. They found that 16% SBM in grower diets or 9% SBM in finisher diets can be half then totally replaced with 12% then 13% RSM, or by 6% RSM combined with protein from faba beans (10 then 12%) or lupines (6 then 7%) in pig diets. All diets resulted in high daily gains and high feed conversion efficiency, without any negative influence on carcass quality. Treatments had no effects on nutrient and energy digestibility, N balance, serum of blood carbohydrate and protein metabolism or biochemical parameters of liver and kidney function.

f) Conclusion

In summary, the concentration of tannins in colour-flowered beans is higher than in white-flowered beans, while the latter have medium to high levels of vicine and covicine. Also, there are very large variations of the tannin content between varieties within the same type of beans. All studies showed that tannins of faba beans have a negative effect on protein and energy digestibility and on pig performance, whereas most authors consider the impact of vicine and covicine to be of less importance for pigs.

However, for faba beans with low or medium tannin content (i.e. < 5-6 g/kg), studies indicate that bean incorporations are possible up to 20-30% in weaning diets and 30-35% in fattening diets without degrading health, growth and carcass performance or meat quality, apart from a reduction in dressing percentage
The use of enzymes, the dehulling or thermo-mechanical treatment of the beans should allow risk-less use of faba beans at high inclusion levels. Nonetheless, the number of results on pig performance is limited and does not allow to know to what extent the inclusion of treated faba beans could be increased.

2.2.2.2 Use of lupins

a) Background

Lupin is an interesting feedstuff for increasing the circularity of pig diets because of its high protein and lipid content. Lupin cultivation is highly developed in Australia and Central or Eastern Europe but remains small in Western Europe. The genus includes many species of lupins. Only three of them are commonly cultivated and receive European support: white lupin (*Lupinus albus*), blue or narrow-leaved lupin (*Lupinus angustifolius*), yellow lupin (*Lupinus luteus*). Tolerated levels of lupins in diets for pigs are dependent of the total amount and diversity of dietary alkaloids and of the high fibre content (Noblet et al., 1995; Kim et al., 2007). Cropped varieties are sweet lupins with low alkaloid contents (less than 5% bitter seeds and 0.4 g/kg alkaloids). The sum of raffinose family oligosaccharides (raffinose, stachyose, verbascose; RFO) is reported as 66, 41 and 89 g/kg and the NSP content as 281, 357 and 273 g/kg for white, blue and yellow lupins, respectively, by Kim et al. (2007). Several studies have been undertaken on the effect of lupin levels in pig diets on the performance of piglets or pigs, but results showed some contrasts.

b) Effects on performance of weaned piglets

For feeding piglets, a white lupin batch (cv Ares; 36% CP and 12% CF on DM, 85 g of total RFO and 0.14 g alkaloids per kg DM) and two blue lupin batches (cv Boltensia; 30% CP and 15% CF on DM, 72 g RFO and 0.62 g alkaloids per kg DM) (cv Bora; 35% CP, 14% CF on DM, 70 g RFO and 1.07 g alkaloids per kg DM) were used by Cherriere et al. (2003). Authors formulated phase 2 diets with identical levels of net energy and ileal digestible amino acids for three experiments. The 0, 5, 10 and 15% lupin inclusions in Exp.1 (White Ares) and Exp.2 (blue Boltensia) did not influence total post-weaning ADFI of piglets, but ADG was linearly decreased and FCR increased by white lupin in Exp.1 whereas in Exp.2 performance was unaffected. In Exp.3 (blue Bora), ADFI was significantly lower at inclusion rates of 20 and 30 % compared to the control, probably in relation to the higher alkaloid concentrations and ADG was significantly lower with all levels of this lupin inclusion.
Five weaner diets were formulated by Kim et al. (2008) to progressively substitute 8.7% SBM for yellow lupins (0, 5, 10, 15 and 20%), with adjustment based on the equivalent ileal digestible amino acid contents per MJ of digestible energy. The yellow cultivar Wodjil was used (36% CP, 35% NDF, 0.2 g/kg alkaloids). As the concentration of yellow lupin increased in the diet, the FCR significantly increased at weeks 1 and 3. Overall, the dietary treatments did not modify ADFI, ADG and liveweight after 21 d, but the FCR tended to be linearly increased by the yellow lupin inclusion, directly resulting from a lower DE concentration. A following trial examine the supplementation of an enzyme combination of proteases, amylases, cellulases and other α-galactosidases and xylanases residual activities (VegPro®, Alltech Inc.), either in a control SBM-based diet or in a yellow lupin-based diet (15%), using a 2 × 2 factorial design. The lupin inclusion did not influence piglet performance. The enzyme preparation tended to improve ADFI and ADG for week 1 whereas lupin inclusion had no effects. For FCR, an interaction occurred during weeks 1 and 2 as enzyme improved the FCR in the pigs fed the lupin diet only but not in the pigs fed the control diet.
In a following study, Kim et al. (2012) used the Australian blue cultivar Coromup (32% CP, 24% NDF, 37% NSP, 54 g/kg of raffinose) at 6, 12, 18 and 24%, with or without dehulling, to replace whey and skim milk powder in weaner diets for 21 d age piglets (6.4 kg) with a same DE per kg and g SID lysine /MJ DE. After 3 w, all piglets given raw lupin seeds had similar performance than control SBM piglets. By contrast, piglets receiving 24% of dehulled lupins grew slower than pigs fed the other diets mainly as the result of a decreased feed intake. Digestive health parameters (faecal consistency, number of antibiotic treatments, and incidence of post-weaning diarrhoea) were low and unaffected by treatments, but pigs fed diets containing with 18 or 24% of dehulled lupins had a higher faecal β-haemolytic *Escherichia coli* score on day 3 after weaning. Moreover, inclusion of 24% of whole lupin or more than 18% of dehulled lupins increased plasma urea nitrogen levels. The faecal digestibility of the dry matter decreased in all lupin diets compared with the control diet.

Kasprowicz-Potocka et al. (2013) used yellow lupin (cv Lord; 131 g RFO and 0.10 g alkaloids /kg) or blue lupin (cv Graf; 80.6 g RFO and 0.15 g alkaloids /kg) in weaning diets balanced on ME and total lysine. Additionally, both lupins were germinated resulting in higher CP contents and in lower ANF contents. Raw and germinated yellow lupins, raw and germinated blue lupins were introduced at 16.0, 14.5, 20.5 and 17.5% in Exp.1 and 24.0, 22.0, 31.0 and 26.5% in Exp.2, respectively, in substitution to SBM, wheat and barley. In Exp.1, ADFI, ADG, and final weights were not modified by diets, but FCR was numerically higher for animals fed on the raw or germinated yellow lupin diets. Lupins and germination significantly decreased feed intake in Exp.2, with intake of the germinated blue lupin diet significantly lower than of other diets, and ADG numerically lower for all lupin diets compared to the SBM diet.
Sijmondsbergen et al. (2022) recently measured piglet performance and nutrient digestibility of phase 1 and phase 2 diets with 19% blue lupine (cv. not reported) compared to standard diets with SBM. Diets were balanced for NE and total amino acids, but anti-nutritional factors and chemical composition of the lupin seeds were not reported by authors. In a second trial, piglets were fed either a control phase 1 then phase 2 diets with soybean meal or diets in which some soybean was replaced by pea (7.5/15 %) or blue lupine (5.3/10.5 %). In both trials, ADFI and ADG were not significantly different among the dietary treatments. No significant difference of the faecal consistency was measured among the groups. In the first trial, nitrogen retention and total tract digestibility of fat, CF and DM was not affected by replacing soybean protein with lupine.

c) Effects on performance of fattening pigs and sows

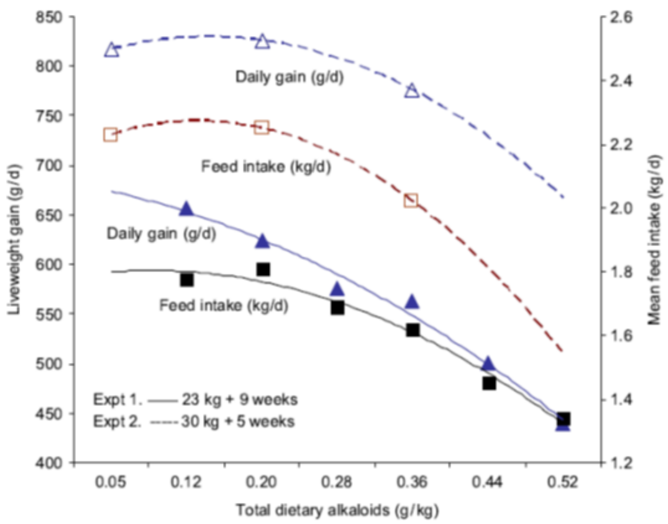
For growing-finishing pigs, Noblet et al. (1998) evaluated the digestive utilization of whole or dehulled seeds of blue lupin (cv. Gungurru; 36% CP, 18% CF, 28% NDF for whole seeds) at 25 % in diets for growing pigs or adult sows. This inclusion did not affect feed intake. The ileal digestibility of CP was close to 80% for the whole- or dehulled seeds which confirmed the interest of lupin as source of protein. As lupins have a low starch and sugar content and a high fibre fraction, the contribution of the large intestine to the digestion of the energy of the lupins was particularly high (40-50%) when compared to the average pig diets. This high fibre also led to an increased energy digestibility in adult sows than in pigs. Digestibility coefficients of energy were improved by dehulling.
Roth-Maier et al. (2004) also used a blue (cv. Bolivio; 33% CP, 14% CF, 40.8 g RFO /kg OM, 0.5 g alkaloids /kg) and a yellow lupin (cv. Borsaja; 40% CP: 12% CF, 73.5 g RFO / kg OM, 2.3 g alkaloids/kg) to prepare, without or with a combination of several types of xylanases, β-glucanases, cellulases and other enzymes (Rovabio® excel), growing-finishing pig diets with similar ME and apparent digestible amino acids, in which 20% of lupin replaced SBM and barley. Pigs were fed *ad libitum* and during the growing period, had significantly higher ADG and F:G, whereas ADFI was slightly numerically increased. For the finishing period, pigs fed the lupin diets without enzymes had higher ADFI than control pigs, whereas ADG and F:G were not modified. The lupin species and enzymes effects were never significant except the FCR of the finishing period which was decreased by enzyme. Carcass traits (slaughter weight and yield, fat and muscle depth or lean meat %) were not affected by lupin in the diets or by enzyme supplementation.
Lastly, Degola and Jonkus (2018) used a batch of the blue Sonet cultivar (32.8% CP) but the content in ANF was not analysed. Lupins were included at 12 or 15% in two fattening diets completely replacing 15% SBM, but with the other ingredients kept constant. The inclusion of lupins resulted in similar ADFI, but decreased ADG and feed efficiency in both growing and finishing periods and did not significantly affect carcass traits. However, authors underlined that their diets were not formulated to ensure deficiencies of limiting amino acids.

d) Discussion

- Several studies have highlighted the possibility of incorporating lupin into weaning diets without compromising performance or gut health. This was showed with yellow lupins at levels of 16 % (Kasprowicz-Potocka et al., 2013) and 20% (Kim et al., 2008). For blue lupins, performance similar to the control SBM diet was observed with levels up to 15% (Cherrière et al., 2003; cv. Boltensia), 19% (Sijmonsbergeen et al., 2022), 20% (Kasprowicz-Potocka et al., 2013) and 24% (Kim et al., 2012). All diets of these studies were balanced for net energy and digestible amino acids, or had similar levels of SID amino acids per MJ of digestible or metabolizable energy (Kim et al., 2008, 2012; Kasprowicz-Potocka et al., 2013). In the study of Kim et al. (2008), the lower FCR with the yellow lupin inclusion was related to a lower digestible energy content.

In the recent studies of Degola and Jonkus (2018) or Zmudzinska et al. (2020) poorer performances of fattening pigs fed blue or yellow lupins may be explained by diets not balanced on net energy and digestible amino acids. However, some treatments in the studies reported by Cherrière et al. (2003) or Kasprowicz-Potocka et al. (2013) indicated lower ADFI with 20 and 30 % inclusions of blue lupin, or for 31 % of raw or germinated blue lupin, respectively. Besides that, Cherriere et al. (2003) also measured a significant deterioration of the FCR with 15% white lupin without any drop of the ADFI, which agreed with the results of King (1981).

- Kasprowicz-Potocka et al. (2013) suggested that the differences in alkaloid composition among the lupin species could partly explain some lower feed intake response. Pigs are sensitive to the presence of alkaloids in diets, and it appears that both the total amount of dietary alkaloids and individual alkaloid profiles are important factors influencing the acceptability of lupins by pigs (Kim et al., 2007). According to literature on swine tolerance to lupin quinolizidine alkaloids (Godfrey et al., 1985; Cheeke and Kelly, 1989), pig productivity is unaffected by dietary alkaloids up to 0.20 g/kg, but could be depressed when the alkaloid level reached 0.30-0.35 g/kg from more or less 25% lupin inclusions (Figure 7). Indeed, the second blue lupin (cv Bora) used by Cherrière et al. (2003) had a alkaloid content of 1.1 g/kg DM that resulted in dietary levels of 0.20 and 0.30 g/kg for the 20 and 30% inclusion treatments. Hanczawoska et al. (2017) also used 8% of blue lupin with high alkaloid content (0.99% on DM) in the fattening diets resulting in a dietary concentration of 0.79 g/kg that decreased ADG and FCR. Surprisingly, a high alkaloid level is reported by Roth-Maier et al. (2004) for the yellow lupin (0.23%) resulting in a 0.46 g/kg content in the fattening diet, but without any effect on ADFI of growing or finishing pigs. On the other hand, alkaloid concentrations reported by Kasprowicz-Potocka et al. (2013) for the yellow (0.10 g/kg) and blue (0.15 g/kg) lupins were small and resulted in low concentrations (0.02 to 0.05 g/kg) of the weaning diets, but authors found a high level of alkaline phosphatase in the blood of pigs fed raw yellow seeds indicating biliary obstruction and implication of liver in the detoxification and degradation of toxic substances.



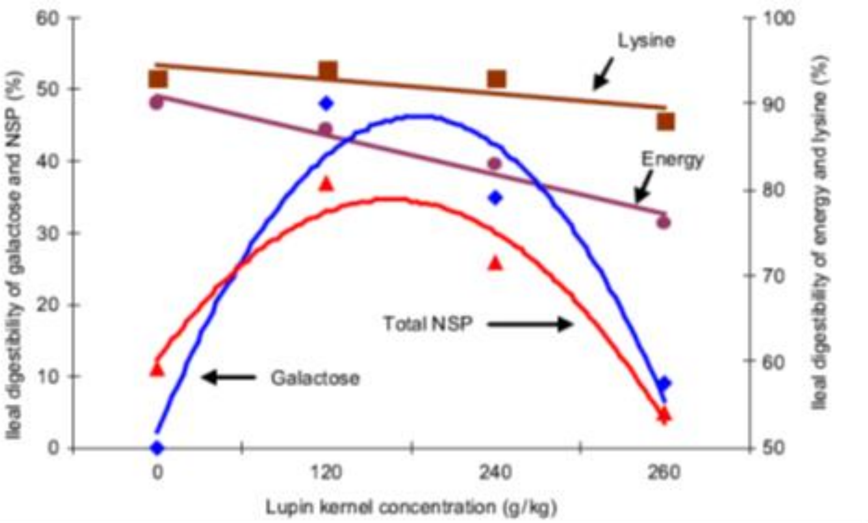
Adapted from Goffrey et al., 1985 by Kim et al., 2007.

Figure 7 *Effect of dietary concentration of alkaloids from blue lupin on performance response by growing pigs fed ad libitum.*

- The lupin species and cultivars also differ in the level and composition of the oligosaccharides and of the non-starch polysaccharides (NSP). It was reviewed by Gdala et al. (1997) that the raffinose family oligosaccharides (raffinose, stachyose, verbascose; RFO) dominate among lupin seed oligosaccharides, and that sucrose, by contrast to soybean, constitute only a small proportion of total soluble sugars of the different lupin species (25-35 g /kg DM). Also, in lupin seeds, stachyose is the main sugar present (50-55% of total α-galactosides). In the performance studies of Cherriere et al. (2003), Roth-Maier et al. (2004) and Kasprowicz-Potocka et al. (2013), the total RFO content in the lupin seeds ranged from 40 to 131 g/ kg. The stachyose proportion was comparatively higher in seeds of yellow or white lupin than in blue lupin seeds, which is consistent with the observations of Gdala et al. (1997).

As monogastric animals don't have α-galactosidase enzyme, a high dietary level of α-galactosides may cause an increase in osmolarity of the small intestine and have an adverse effect on the ileal digestibility of nutrients in piglets (Wiggins, 1984; Krause et al., 1994; all quoted by Gdala et al., 1997). Stachyose and raffinose are fermented in the hindgut leading to hydrogen production and to undesirable effects as flatulence. However, degradability may differ among oligosaccharides and explain differences between species and varieties of lupins. Consequently, Cherriere et al. (2003) suggested a relationship between the higher stachyose and verbascose contents of white lupins and the significant deterioration of the FCR, while raffinose could have little effect. The low performance measured for 15% white lupin could therefore be due to the stachyose. However, the mechanisms behind these inferiorities associated with white lupin are still unclear according to Kim et al. (2007). Another hypothesis was mentioned by King (1981) and Roth-Maier et al. (2004) about a potential detrimental effect on feed intake because of the strong accumulation of soil manganese in white lupin seeds (up to 1200 mg/kg DM).

- Lupins have around twice higher content in non-starch polysaccharides (NSP) than peas or SBM (Kim et al., 2007). Literature indicates that galactose and glucose are the main components of lupin seed NSP (in total 60-66%), and uranic acids, arabinose and xylose have a lower value (Gdala et al., 1997; Kim et al., 2007). Variations exist among species with a higher level of galactose and uranic acids in blue lupin as compared with yellow and white ones (Gdala et al., 1997; Kim et al., 2007). Regrettably, in most of the performance studies that we have reviewed, NSPs were not reported, and fibre composition was only based on CF or NDF values. The nutrient digestibility and energy utilization of lupin seeds by pigs is largely determined by the NSPs according to Kim et al. (2007). These authors underlined that the maximum ability to digest lupin kernel NSP and galactose in the small intestine of 45 kg pigs may be around 200 g/kg, which is equivalent to 260 g/kg of whole lupin seeds. In the research of Van Barneveld et al. (1995), the inclusion of blue lupins (cv. Gungurru) above this level significantly decreased ileal digestibility of NSP and galactose, which could indicate a maximum tolerance of the small intestine to physiological modifications by NSP such as increased water-holding capacity, osmolarity and gas production in the gastrointestinal tract (Figure 8). Kim et al. (2007) also suggested that the inclusion level of lupins in finisher pigs could be increased above this level as heavier pigs have a better capacity to digest NSPs.



NSP: non-starch polysaccharides. Adapted from van Barneveld et al., 1995 by Kim et al., 2007..

Figure 8 *Effect of lupin kernel concentration on ileal digestibility of NSP, galactose, energy and lysine in 45 kg pigs.*

- Accordingly with a higher NSP content, the results of Roth-Maier et al. (2004) and Kim et al. (2008) show that multi enzyme supplementations to blue or yellow lupin-based diets could improve the performance of the weaned piglets or fattening pigs. Kasprowicz-Potocka et al. (2013) described that germination may modify the content of alkaloids, as they are degraded and used as a nitrogen source during germination. In the experiment of these authors, germination of yellow and blue lupins had no positive impact on ADG and FCR, which may be a result of the presence of newly formed alkaloids, but also of the permanence of NSP during germination.

Zaworska-Zakrzewska et al. (2020) showed that fermentation by bacteria and yeasts could improve the nutritional value of seeds. They measured that total RFOs were completely reduced in fermented blue lupine seeds (from 65 to 0 g/kg), whereas total alkaloid contents and their composition were unchanged. Fermentation of seeds also increased the CP and decreased phytate phosphorus, fat and nitrogen-free contents.

- Whereas Noblet et al. (1998) found no negative impact of the dehulling of lupins, dehulled seeds resulted in a decreased feed intake and higher faecal β-haemolytic *Escherichia coli* in the study of Kim et al. (2012). The latter authors suggested that an excess inclusion of fermentable lupin kernel fibre could have limited the physical capacity of the digestive tract and reduced the feed intake. This could be due to the higher amount of polysaccharides of lupin kernel endosperms, leading to increased viscosity and fermentation by-products in the gastro-intestinal tract and limited feed intake, possibly by increasing gastric distension and digesta transition time. These authors concluded that dehulled lupin should be used in post weaning diets at a lower inclusion level than whole lupins.
- Previous studies did not indicate any detrimental effects of lupins on health or welfare. Moreover, no effect on faecal consistency was found by Sijmonsbergen et al. (2022) with the replacement of SBM with lupin, which is consistent with the measurements of Kim et al. (2012). The latter authors, additionally, reported that the average percentage of days with diarrhoea in post-weaning period was reduced with the incorporation of blue lupin in the feed. There was no effect of the inclusion of lupins in the fattening diets on the carcass traits in the studies of Roth-Maier et al. (2004) or Degola and Jonkus (2018), which is corroborated by the findings of Cebulska et al. (2021).

e) Conclusion

The performance of post-weaning piglets or growing-finishing pigs fed up to 20% yellow or blue lupins may be similar than for pigs fed soybean meal-based diets, if diets are formulated on the basis of equal amounts of ileal digestible amino acids per MJ of net energy. The impact on performance of higher inclusion rates may be related to the cultivars or species of lupins. Literature suggests that blue lupin (*L. angustifolius*) or yellow lupin (*L. luteus*) are more appropriate for pig feeding than white lupin (*L. albus*).
Alkaloids are one of the main limiting factors for the use of lupin in feed and most studies confirm the maximum dietary limit of 0.20 g/kg. The content for the different raffinose family oligosaccharides varies among lupin species and cultivars and may explain some poor performance, especially for white lupin. However, many studies did not analyze RFO, which complicates the assessment of this parameter. As lupins are low in starch and rich in plant walls, fibre content criteria should be taken into account when formulating feeds with lupins. Several studies indicate that the high amount of NSP provided by lupins limits the digestive utilization by young pigs. However, most studies do not report the same wall criteria. More information is needed to determine the threshold levels of NSP and RFO that could negatively influence piglet and pig performance and establish the optimum inclusion levels of lupins.

2.2.3 Inclusion of insects, aquatic ingredients and grass products

2.2.3.1 Use of insect meals

a) Background

Insect rearing has been seen in the recent years as one of the ways to enhance food and feed security (Van Huis et al., 2013; Makkar et al., 2014). As underlined by these authors, insects grow and reproduce easily and have a high feed conversion efficiency, because they are cold blooded. Production on a large scale of insects such as black soldier fly larvae (BSF), house fly maggot meal (HF), mealworm, locust meal, house cricket, mormon cricket and silkworm pupae is nowadays technically effective in developed countries (Veldkamp et al., 2012). In the last decade, scientific research and development on insect rearing has resulted in more knowledge on rearing management and techniques, substrate optimization and safety, chemical composition and nutritional requirements of insects, genetic make-up of the insects and economics of the production sector. Numerous challenges have still to be addressed to develop the insect market for feed and food in Europe (Veldkamp et al., 2022a). These obstacles are mainly associated with policy making, legislative solutions, standardization and certification of mass-produced edible insects (Żuk-Gołaszewska et al., 2022).

In 2021, an EU regulation has authorised the use of Processed Animal Proteins derived from farmed insects (insect PAPs) in pig and poultry feed. Following this regulation, the demand for insects as feed is expected to grow, leading to an increase in the production capacity of the sector (IPIFF, 2024). With approximately 4,000 tonnes of insect PAPs and almost 10,000 tonnes of insect feed products generated in the EU in 2022, the production of insects for feed is expected to increase in the coming years. A questionnaire of 2023 showed that the total production capacity of the European insect sector may reach circa 650.000 tonnes of insect PAPs by 2030 if appropriate conditions are met (IPIFF, 2024).
Insect farmers use mainly cereal-based diets and search for alternative insect diets has been undertaken to avoid feed-food competition and improve sustainability and economics of insect rearing. Gianotten et al. (2020) showed that several by-products of plant origin offer potential, and that a combination of wheat middlings and rapeseed meal with brewery grains as moisture source for feeding mealworms resulted in the highest larval growth and feed efficiency. However, these ingredients are also feedstuffs for animal nutrition. Consequently, the diversification of the inputs authorised as insect substrates may encourage insect farming (Moruzzo et al., 2021; Sogari et al. 2023). Studies reported by Smetana et al. (2019) have shown that feeding livestock with BSF could be more beneficial than soy meal or fishmeal, if insects are fed on unutilised side-streams intended for composting or anaerobic digestion. According to the insect sector (IPIFF, 2024), a third of the food waste generated presently in the EU may be used as insect substrate. Examples of such products are former food products containing meat and fish or catering waste. The insect industry expects the approval of meat and fish containing former foodstuffs in establishments producing insects for the feed markets by 2026-2027 (IPIFF, 2024).

b) Composition

Based on their nutritional composition, insects are promising protein-rich feed ingredients alternative to e.g. soybean meal for pig diets, as underlined by Veldkamp et al. (2012) in their feasibility study. The nutritional components of Black soldier fly (*Hermetia illucens*) and other main insect species have been well studied. The chemical composition of several insect species: Black soldier fly (BSF) larvae, House fly maggot meal (HF), meal worm, locust meal, house cricket, mormon cricket and silkworm pupae is compared in Table 3 to SBM and fish meal. Insects have a high protein content varying from 42 to 76% of DM, comparable to soybean or fish meal and a fat content higher than in SBM and fishmeal (Veldkamp and Vernooij, 2021).

Table 3 *Main chemical constituents and amino acid composition of insect meals compared to fish meal and soybean meal.*

	Black soldier larvae	**House fly maggot meal**	**Meal worm**	**Locust meal**	**House cricket**	**Mormon cricket**	**Silkworm pupae**	**Silkworm pupae (defatted)**	**Fish meal**	**Soybean meal**
Constituents (% in DM)										
Crude protein	42.1	50.4	52.8	57.3	63.3	59.8	60.7	75.6	70.6	51.8
Lipid	26.0	18.9	36.1	8.5	17.3	13.3	25.7	4.7	9.9	2.0
Calcium	7.6	0.5	0.3	0.1	1.0	0.2	0.4	0.4	4.3	0.4
Phosphorus	0.9	1.6	0.8	0.1	0.8	1.0	0.6	0.9	2.8	0.7
Ca:P ratio	8.4	0.3	0.4	1.2	1.3	0.2	0.6	0.5	1.6	0.6
Amino acids, g/16 g N										
Lysine	6.6	6.1	5.4	4.7	5.4	5.9	7.0	6.1	7.5	6.2
Methionine	2.1	2.2	1.5	2.3	1.4	1.4	3.5	3.0	2.7	1.3
Threonine	3.7	3.5	4.0	3.5	3.6	4.2	5.1	4.8	4.1	3.8
Tryptophan	0.5	1.5	0.6	0.8	0.6	0.6	0.9	1.4	1.0	1.4

Adapted from Makkar et al., 2014.

Indeed, some insect meals as black soldier fly larvae, housefly maggot meal, mealworm or silkworm contain as high as 36% oil, which can be isolated and used for the preparation of biodiesel; the rest of the defatted meal, rich in CP, can be a protein resource in the feed industry (Makkar et al., 2014).
The amino acid profile of the insect species is close to the profile in soybean meal and fishmeal (Veldkamp and Vernooij, 2021).

Lysine levels are lower in mealworm, locust meal, house cricket and Mormon cricket than in soybean meal, but are adequate in black soldier fly larvae, housefly maggot and silkworm pupae meals (Table 3). Overall, levels of essential amino acids in insect meals are appropriate for animal nutrition. However, major limiting amino acids such as methionine, threonine and tryptophan may be relatively low in some insect sources when including them in diets for piglets and growing pigs. Makkar et al. (2014) calculated that a 50:50 mixture of black soldier fly larvae and housefly maggot meals would provide a balanced amino acid composition for use in feed as SBM replacer.

Black soldier fly larvae are also very rich in Ca (7.6%) with the highest Ca:P ratio of 8.4, while for other insect meals the Ca levels are very low as reviewed by Makkar et al. (2014). The latter authors underlined that Ca fortification of the substrate on which insects are raised can increase the Ca level in the larvae meals. The Ca:P ratio is varying from 0.19 to 1.18 in insect meals other than that in black soldier fly larvae (Makkar et al., 2014). In some insects (e.g. housefly maggot meal and mormon cricket) P levels are particularly high (1.0–1.6%). In their review, Lu et al. (2022) pointed out that the content of minerals and other nutrients in BSF larvae significantly varies across studies, as a result of different growth stages of the insects used, variation in nutritional substrates for their culture and differences in environmental conditions and processing methods applied to obtain the final insect products used.

c) Effects on digestibility and performance

Makkar et al. (2014) reported that feeding studies with pigs have confirmed a good palatability of diets containing insect meals. Interestingly, a recent study by Ipema et al. (2021a,b) demonstrated that pigs are highly motivated to consume and interact with live BSF larvae, and they prefer live BSF larvae over a range of other feed and enrichment items. However, most feeding studies with diets containing insect meals have been conducted on fish and poultry, and less information is available for pig nutrition.
According to Makkar et al. (2014), the digestibility of insect proteins and their utilization *in vivo* are good. In their review (Veldkamp and Vernooij, 2021) found that digestibility of nutrients changed in weaned piglets when SBM and fishmeal were replaced by yellow mealworm (*Tenebrio molitor*; TM) and when soybean products were replaced by BSF larval meal. In growing pigs, 10% TM inclusion in the diet resulted in a higher nutrient digestibility compared to fishmeal, meat meal and poultry meal based diets (Yoo et al., 2019). The variability in nutrient digestibility of insect products in different studies is mainly due to differences in diet composition when insect products are included. The heterogeneity of the results in studies may also be attributed to the insect species, the insect life stage (adult, larva or pupa), the insect rearing substrate, and processing techniques and conditions (temperature at drying, extraction techniques, chitin removal) which all may influence the nutritive value of the insect products used (Veldkamp and Vernooij, 2021).
Veldkamp and Vernooij (2021) reviewed five performance studies showing that 1 to 10% inclusion of mealworm (*Ptecticus tenebrifer*, PT or TM), housefly larvae and full-fat or defatted BSF larvae in replacement of SBM or fish meal in weaned piglets diets, did not result in consistent effects on growth performance. Accordingly, the review by Lu et al. (2022) also indicated that BSF larvae have no negative effects on feed intake, nutrient digestibility and growth performance of piglets. The use of BSF larvae oil in replacement of corn oil up to 6% improved growth performance linearly in weaned piglets (Van Heugten et al., 2019).
In growing pigs, dietary inclusion of up to 14% BSF larvae in replacement of fishmeal did not affect growth performance in the experiment reported by Chia et al. (2019) whereas inclusion of 11% HF larvae replacing fishmeal improved growth performance in another study (Dankwa et al., 2000). In finishing pigs the replacement of SBM by 4% BSF larvae resulted in improved growth performance compared to 0 and 8% inclusion (Yu et al., 2019). Veldkamp and Vernooij (2021) underlined that the effects of insect products on growth performance results is highly dependent on study design, formulation of diets and nutritional value of insects included in the feed formulation matrix. According to the latter authors, some of the observed effects related to the dietary inclusion of insects products are likely also related to the previous points.

d) Effects on carcass quality

The replacement of 11% fishmeal by ground sun-dried HF larvae in growing pigs diets in the study of Dankwa et al. (2000) had no effect on dressing percentage and eye muscle area, but shoulder fat content at 30 kg BW was higher as result of a high energy content of the diet containing non defatted HF larvae. In the above-mentioned study of Yu et al. (2019), 4% BSF larvae powder in the diet improved carcass traits and meat quality of finishing pigs.

Chia et al. (2019) found that replacing 50% of fish meal with BSF larvae increased the muscle protein content, while BSF larvae at any level increased muscle total fat content, but had no effect on muscle water content. Lastly, Altmann et al. (2019) found that the feeding of BSF larvae had very little effect on pork quality parameters and sensory attributes.

e) Conclusion:

In conclusion, insect meals, including those derived from Black soldier fly larvae, *Tenebrio molitor*, and housefly maggots, offer a promising alternative to traditional protein-rich feed ingredients in pig diets. Their high nutritional value and environmental sustainability without adverse effects on growth performance, product quality and health status, make them an attractive option for the livestock industry. Further standardised digestibility and growth performance experiments are warranted to optimize inclusion levels and fully explore the potential of insect meals in improving swine nutrition and production efficiency.

2.2.3.2 Use of aquatic ingredients

a) Background

Two types of algae are distinguished: micro- and macroalgae or seaweed. Seaweeds or marine macroalgae, belong to the most principal marine resources. Classified by pigmentation, there are three taxonomic groups, including red algae (*Rhodophyta*), brown algae (*Ochrophyta, Phaeophyceae*), and green algae (*Chlorophyta*). Xie et al. (2023) counted over 200 species of seaweeds that are cultured or wild-harvested for multiple industries, and 32 green algae, 64 brown algae and 125 red algae that are commercially used. Bioactivities of seaweed-derived polysaccharides may be used to enhance the immune system, improve the oxidative stability of meat and fats, or promote intestinal health as prebiotics especially in weaned piglets [See part 3.3.3 of this report]. Besides being rich in beneficial bioactive compounds, macroalgae may also have a role as feed ingredients in animal diets. After harvesting, seaweeds need specific processing for preservation, homogenization and storage, or increase of concentration of nutrients, through treatments as acidification, dewatering, pressing, fermentation and drying, for use in compound feed (Øverland et al., 2019). Furthermore, macroalgal products may be processed as protein sources or as extracted bioactive compounds for application as feed additives (Øverland et al., 2019).
Microalgae are generally eukaryotic organisms, although cyanobacteria, such as spirulina, which are prokaryotes, are included under microalgae due to their photosynthetic and reproductive properties (Ravishankar et al., 2012). Microalgae range in size from about 5 μm (Chlorella) to more than 100 μm (Spirulina). Whereas macroalgae occupy the littoral zone, microalgae are found in fresh and saline waters, in littoral habitats and in the ocean waters (as phytoplankton). At present, several species of microalgae are mainly used as live feed in aquaculture (Brown et al., 1997; Becker, 2013a). The microalgae genera *Chaetoceros, Thalassiosira, Tetraselmis, Isochrysis, Nannochloropsis, Pavlova* and *Skeletonema* are all used for bivalve molluscs, for the larval and early juvenile stages of crustaceans and certain fish species, and for zooplankton used in aquaculture food chains (Guedes and Malcata, 2012). The use of microalgae as ingredient in animal feeds could contribute to improving food security in the future (Ravishankar et al., 2012) because microalgae have rapid growth and the cultivation can take place in non-arable land, but their high production costs make microalgae currently an uncompetitive option for use in pig diets according to Lamminen et al. (2019).
Spirulina is the common name for two *Arthrospira* species: *A. platensis* and *A. maxima*, which occur naturally in tropical lakes with high pH and high concentrations of carbonate and bicarbonate. Spirulina is cultivated around the world for dietary supplements and as whole food for humans, and for production of supplements for animal feeds (Becker, 2013b). Spirulina does not require arable land, but is produced in a water culture in photobioreactors or race-way ponds (Taelman et al., 2015) and is thereafter dried resulting in a powder that can be immediately included in animal feeds. Economic and technical challenges need to be overcome before spirulina can become a major feed ingredient according to Altmann and Rosenau (2022). Spirulina is expensive compared to other protein feedstuffs. Cultivation of spirulina remains small-scale and derived products are primarily used as nutritional supplements for humans (Chen et al., 2016). Lastly, although spirulina is often proclaimed as a sustainable source of protein, its environmental footprint is variable based on the production system and regional climate. For example, spirulina is not more sustainable to produce than soybean meal according to the LCA analysis van Smetana et al. (2017) but may be more sustainable than fishmeal.

b) Composition

Macroalgae are rich in carbohydrates (up to 70% of DM) and lipid fraction is usually lower than 5% of the DM. Costa et al. (2021) reviewed that some species of brown algae belonging to the genera *Laminaria, Saccharina, Hizikia* and *Arame* have a lipid content as low as 0.5 to 1.0% DM. The lipid component is mainly composed by triacylglycerols, phospholipids and glycolipids. Ash content varies widely, typically from 10 to 50% on DM basis. Hence, macroalgae may contain a high mineral content (Review of Costa et al., 2021). Protein content varies widely among macro algae groups (Costa et al., 2021). Brown algae were shown to be lower in protein content, such as 0.6 to 16% in DM in *Laminaria* sp., while red algae have a higher protein content with values between 24 to 44% in DM in *Porphyra* sp. However, macroalgae usually present a high-quality protein, particularly red seaweeds, since they are rich in essential amino acids, with the exception of methionine and cystine. A database of amino acid data for 121 macroalgae species was assembled from the literature by Angell et al. (2016). These authors found that the quality of protein (% of essential amino acids in total amino acids) of many macroalgae is similar to traditional protein sources. Notably, the commercially produced red seaweeds *Gracilaria* and *Pyropia*, brown seaweeds *Hizikia* and *Laminaria* and green seaweed *Ulva* all have a high ratio of total essential amino acids to total amino acids. However, macroalgae have substantially lower concentrations of total essential amino acids, methionine and lysine (on a whole biomass basis, % dry weight) compared to traditional protein sources. Also, in the whole seaweed form, macroalgae have a lower concentration of protein, and specifically low concentrations of essential amino acids relative to the requirements of monogastric animal species in livestock production. Consequently, the concentration or direct extraction of protein from macroalgae could be an important way in their development as an alternative source of protein in diets for pigs and poultry (Angell et al., 2016).
Concentration of the protein fraction in macroalgae may be undertaken with conventional methods as well as with novel technologies such as enzyme-assisted or microwave-assisted extraction, pressurized liquid extraction and pulsed electric field. The extraction of protein from macroalgae is challenged by the complex polysaccharide cell wall and extracellular matrix (Øverland et al., 2019). The removal of non-protein components may also allow to concentrate protein in macroalgae. Angell et al. (2016) indicated than this can be achieved by rinsing biomass with freshwater to reduce the ash content or by extraction of soluble polysaccharides with minimal protein losses. However, the resulting protein fraction has rarely been studied. Angell et al. (2016) reviewed that the crude protein of macroalgae protein extracts has been determined in a limited number of studies (range 33 to 86% dry weight). They reported that total essential amino acids, methionine and lysine increased substantially in protein extracts compared to the whole seaweed. Extracts have higher concentrations of total essential amino acids and lysine than SBM, but concentration of methionine was similar to that of SBM. Notably, cystine was absent in all extracts, suggesting that it may be destroyed by the extraction process. As example, Wong and Cheung (2001) isolated protein concentrates from two red seaweeds (*Hypnea charoides* and *Hypnea japonica*) and one green seaweed (*Ulva lactuca*). Protein extraction yield (46, 45 and 36%, respectively), protein content (83, 85 and 76%) and *in vitro* protein digestibility (89, 89 and 86%) was higher in concentrates from *H. charoides* and *H. japonica* than from *Ulva lactuca*. All three protein extracts were rich in leucine, valine and threonine but lacked cystine.
Microalgae may have a protein content of 20-60% of dry matter and variable contents of lipids, depending on species and growth conditions (Brown et al., 1997; Becker, 2013b). Production of microalgae may therefore have a potential to be a suitable source for partial replacement of protein and lipids in animal feed. Spirulina contains a superior crude protein content of 50-70% in dry matter (mean: 63%) compared to a soybean meal (Altmann et al., 2019; Lestingi, 2024). In addition, spirulina contain antioxidants, such as β-carotene and vitamin E and are known to have a high content of gamma linolenic acid, which could result in increased levels of this omega-6 fatty acid in animal derived products.

c) Effects on performance

Most the research on whole seaweed inclusion into animal feeds as a source of protein has focused on aquatic livestock, especially commercial marine herbivores (i.e. sea urchins), that feed naturally on macroalgae (Angell et al., 2016). Conversely, inclusion of macroalgae in diets of commercial fish (herbivores or carnivores) at levels higher than 10% results in reduced growth and feed utilisation (Angell et al., 2016). There is little literature on incorporating macroalgae as a protein source into the diets of poultry and swine. Many studies that examined the functional effects of macroalgae and their extracts on immune function, gut health, and meat quality had low inclusion levels (<5%) and macroalgae did not replaced traditional protein sources in the feed of poultry and swine (reviewed by Angell et al., 2016 and Corino et al., 2019).

Eight studies on weanling pigs and two studies on grower and finisher pigs were reviewed by Costa et al. (2021) to analyse the effect of dietary inclusion of brown or mixed seaweeds on the growth performance of pigs. Some reports evaluated the use of macroalgae as dried whole algae (*L. digitata* and *Laminaria hyperborea*), dried and ground algal leaves (*Ecklonia cava*), processed whole algae extract (i.e. *A. nodosum*) or brown, red and green algae mixed extract but the majority of studies added extracted polysaccharides (i.e. laminarin and/or fucoidan) from brown seaweeds (i.e. *Laminaria* sp.) to diets for pigs. Low amounts of algae were incorporated (up to 1 to 2% in the diet), which consequently conferred algae compounds a role as supplement with functional constituents rather than as a supplier of nutrients. The collected data showed inconsistent results on growth performance of pigs. The relationship between the level of macroalgae inclusion and G:F in pigs is dependent on the algae species, the development stage of the pig and the bioactivity of the polysaccharides present in the macroalgae.

The low levels of protein and metabolizable energy, and high mineral content of intact brown seaweeds like *Laminaria* spp. and *A. nodosum*, prohibit their use as replacements for major protein sources in feed for monogastrics (Øverland et al., 2019). Jones et al. (1979) recorded weight loss in pigs fed 10% of a meal produced from *A. nodosum*, an algae that contains less than 10% of protein in the DM. Similarly, Whittemore and Percival (1975) concluded that the residue from *A. nodosum* after extraction of alginate was poorly digested and unsuitable as a protein and energy source for pigs. Øverland et al. (2019) underlined that studies with red macroalgae showed the potential as feed ingredients for fish, but few studies have been carried out with pigs and poultry. The relatively low nutritional value might explain negative effect on performance at high inclusion levels in some fish experiments. In chicken studies, dietary inclusion of 3-4% green macroalgal meals (*Ulva* genus, *Polysiphonia*) showed a potential as substitute for conventional feed protein sources (Abudabos et al., 2013). A few studies that have incorporated whole seaweeds at levels higher than 5% had no negative effect on growth or feed utilisation up to 10% in chickens and up to 15% in ducks, but showed reduced performance with inclusion levels of 20 or 30% in chickens (Ventura et al.,1994; El-Deek and Brikaa, 2009).

Recently, Krogdahl et al. (2021) evaluated the protein value and effects on nutrient digestibility of two macroalgae (brown *Saccharina latissimi* and red *Palmaria palmata)* in minks, used as model of monogastric animals. A dried whole biomass and a protein concentrate of the macroalgae were included in the diets in order to supply 200 g of crude protein per kg of diet. The diets with macroalgae were less palatable than the fish meal diet. The animals fed the whole *Saccharina* diet had a significantly higher water intake and urine production than the other animals, supposedly due to the very high ash content of the macroalgae. With this diet, urine concentration of iodine was 300 times higher than for the fishmeal-based diet. Apparent digestibility coefficient for total amino acids showed low values for all the macroalgae products: 57 and 73% for the whole and protein concentrated *Saccharina* products, and 59 and 70% for the two *Palmaria* products, respectively. Apparent amino acid digestibility coefficients showed great variation among amino acids and were particularly low for histidine (<0 and 27% for the whole *Saccharina* and *Palmaria* products, respectively) and methionine, and cystine showed negative values for both *Saccharina* products. Krogdahl et al. (2021) concluded that only the *Palmaria* protein concentrate might be considered for use as a protein source.

Macroalgae protein extracts in addition to high concentrations of essential amino acids, have also high *in vitro* digestibility as reviewed by Angell et al. (2016). Moreover, 12% dietary inclusion of protein extracts from two red macroalgae resulted in a similar growth and measured health parameters in rats compared to providing a casein based control diet, and resulted in the same protein digestibility, nitrogen balance, and net protein utilization (Wong et al., 2004). According to Angell et al. (2016), these results indicated that macroalgae protein extracts may be used as a protein source in compound feeds for monogastrics.

Three microalgae were evaluated as nutrient sources in a digestibility experiment with adult mink (Skrede et al., 2011). The microalgae *Nannochloropsis oceanica*, *Phaeodactylum tricornutum* had similar crude protein content (47.7 and 49.0% of DM, respectively), amino acid composition and lipid content (8.4 and 7.4%, respectively), whereas *Isochrysis galbana* contained 20.1% CP and 16.2% lipids. All sources were fed at 60, 120 and 240 g /kg as is, replacing fish meal. There was a significant linear reduction in digestibility of CP and lipid with increasing dietary inclusion of all algae products. The apparent CP digestibility determined for *N. oceanica, P. tricornutum* and *I. galbana* was 36, 80 and 19%, respectively. The individual amino acid digestibility showed acceptable values for *P. tricornutum*, but low and highly variable values for *N. oceanica* and *I. galbana*. It was concluded that among the investigated algae, P*. tricornutum* was the preferable source of digestible nutrients.

Whereas several investigations evaluated effects on performance and gut health of pigs of supplementation (0.2 to 2%) with spirulina (Reviews of Holman and Malau-Aduli, 2012; Lestingi, 2024), few have investigated the effects of the introduction of spirulina as feed ingredient in pig diets on performance of pigs. Earlier studies by Février and Sève (1975) concluded to no specific problems when feeding piglets or sows with spirulina but advised to restrict their supply to a level not exceeding 25% of the total dietary proteins, as a larger proportion of algae led to an insufficient supply of digestible nutrients and thus reducing growth and feed efficiency. The study of Martins et al. (2021) indicated that growth performance of post-weaning piglets was reduced by the incorporation of 10% spirulina in the diets, which was mediated by an increase in digesta viscosity in small intestine and relative length of small intestine and a lower ATTD of protein, as a consequence of the resistance of microalgal proteins to the action of endogenous proteases and peptidases. Whereas the use of carbohydrases in the diet did not improve the digestive utilization of this microalgae, the dietary supplementation with a specific enzyme that cleaves the peptidoglycan of prokaryote cell walls increased ATTD of crude fat and acid detergent fibre. The incorporation of spirulina, individually and supplemented with enzymes, did not impair meat quality traits. In their trials, Neumann et al. (2018) showed that SBM could be fully replaced by spirulina in diets for piglets and growing pigs (21 and 13%, respectively) without compromising net protein utilization. However, these authors underlined that supplementing diets with free histidine in combination with lysine, methionine and threonine improved the AA balance of diets containing spirulina. In additional trials by Altmann et al. (2019), spirulina as feed ingredient in growing and finishing diets did result in slightly but not significantly lower carcass weights compared to the SBM-fed group.

d) Effects on meat quality

The use of macroalgae as whole biomass was shown to modify meat colour and mineral composition in the study reported by Jerez-Timaure et al. (2021). Fattening pigs fed with 4% brown macroalgae *Macrocystis pyrifera* had less red intensity (a*) meat compared to either the control or the group fed 2% macroalgae. Meat ash content was increased in the 4% group compared to the other groups, although having significantly less Mn, Fe and Cu. Thus, the lower colour intensity of meat from pigs fed with 4% macroalgae could result from the highest availability of antioxidants from the algae that prevent myoglobin oxidation and therefore, colour development. Moreover, the lowest availability of dietary Fe could also have contributed to these differences. The preceding study of Dierick et al. (2009) showed a significant iodine accumulation in tissues of pigs supplemented with 2% *A. nodosum*. Furthermore, seaweed polysaccharides such as laminarin, fucoidan, and ulvan have antioxidative properties and their supplementation in pig diets (0.4-0.9%) may decrease lipid oxidation in the muscle of pigs (reviewed by Ribeiro et al., 2021).
Altmann et al. (2019) investigated the meat quality of barrows reared on diets containing spirulina with a total substitution of SBM by spirulina (9.5% of the diet) in finishing diets. Use of the spirulina diet compared to the control diet did not affect meat and fat quality: i.e. meat pH, water holding capacity, proximate composition, meat and fat colour, lipid oxidation in meat and fatty acid composition of backfat. However, the backfat of spirulina fed barrows had a marginally lower proportion of mono-unsaturated fatty acids (MUFA) and increased PUFA compared to the SBM-fed control. Nonetheless, authors signalled that soybean oil was included in greater levels in diets containing spirulina, which also likely confounded the effects of inclusion of spirulina as a feed ingredient (Altmann et al., 2019).

e) Conclusion

Seaweeds provide an opportunity to supply a novel source of protein for pigs but only after the isolation or concentration of the protein fraction from carefully selected species. Notably, some commercially produced red seaweeds, brown seaweeds and green seaweed have a high ratio of total essential amino acids to total amino acids. These seaweeds also have relatively high concentrations of essential amino acids on a whole biomass basis. There is also the possibility to complement the traditional methods of protein concentration and extraction with industrial processing procedures employed for grasses and leaves. This research should focus on optimising the yields (proportion of total protein extracted) and the concentration of essential amino acids in the extract or concentrate, and examine the functional properties, digestibility, and performance in *in vivo* growth performance trials.
Although little literature is available, it appeared that use of spirulina as ingredient in substitution to soybean meal may result in a higher viscosity of intestinal digesta in weaned piglets.

By contrast, others results showed that spirulina could be included at high rates in diets for piglets or fattening pigs, with appropriate amino acid supplementation, without disadvantaging pig performance or product quality.

2.2.3.3 Use of grass products

a) Background

Forages are important sources of energy and protein for animal feeding. Production and use of grass (rye-grass) and legumes (alfalfa, clover) is a common solution for reducing the protein dependency of cattle farms, but it has been less explored in pig farming. However, the exploration for the use of forages as feed resources has been more intense in organic pig farming, as improving the farm autonomy is a more important issue than in conventional production, and as European regulation for organic pig production requires the supply of roughage to animals. This interest could also be relevant for the conventional production as forage may help to express the innate motivation of pigs for rooting and feed manipulation. Furthermore, the use of grass and forage could reduce the amount of humane edible feedstuffs used for pig diets. In addition, introduction of legumes in the crop rotation could improve the farm agronomic performance, and thus the overall economic performance. For the present report, 11 studies on the use of forages for growing or finishing pigs (i.e. 62 experimental treatments) have been selected as providing information on the composition and intake of diets and/or forages as well as on animal performances. From this, it appears that grass products and forages could be a valuable ingredient to decrease the share of cereals in pig diets.

b) Effects of dehydrated alfalfa meal on performance

The use of grazed or dehydrated alfalfa in pig diets is ancient and has earlier been described (Danielson et al., 1969; Kass et al., 1980). Former reviews limited the incorporation rate for growing pigs to 10% (Heuzé et al., 2013) due to the high fibre content and consequences on energy and protein digestibility.
Higher inclusions rates have been studied and by Danielson et al. (1969) and the substitution of corn by 2, 4, 8, and 16% dehydrated alfalfa meal did not significantly affect ADG whereas 32% dehydrated alfalfa meal significantly reduced ADG. In the study of Kass et al. (1980), a level of 20% alfalfa meal (i.e. 26% cell wall in the diet) had no significant effect on ADG and FCR but 40 or 60% alfalfa meal significantly depressed ADG and FCR compared with 0 or 20%. In both studies, the digestibility coefficients of DM, CP, energy and CF were lowered as a result of increased alfalfa intake.

In a more recent study, Thacker and Haq (2008) evaluated graded levels of dehydrated alfalfa meal of good quality (19.9% CP on DM) in barley-soybean meal growing and finishing diets formulated to supply the same amounts of digestible energy and total amino acids. The increasing incorporation of alfalfa meal resulted in a linear decrease of performance for all periods. The 7.5% inclusion non-significantly impacted ADFI, ADG and FCR of -2.9, -3.7 and +0.9% respectively, whereas a 30% inclusion significantly affected ADFI, ADG and FCR of -22, -27 and +15 % respectively. However, during the finishing period, ADFI and ADG were increased and FCR decreased for the diets including 7.5 or 15% dehydrated alfalfa meal, whereas the 22.5% inclusion non significantly impacted ADFI, ADG and FCR of -1.5, -4.6 and +3.9% respectively. However, the 30% inclusion still affected performance significantly (-7, -14 and +7% for ADFI, ADG and FCR, respectively). Carcass traits were generally unaffected by dried alfalfa meal. The greater gut capacity of finishing pigs and the higher number of cellulolytic organisms in adults may explain these differences.
Although, the substitution of 10 or 20% alfalfa meal (15% CP, 50% NDF) to corn and SBM in finishing corn-bran-SBM diets balanced for lysine: ME ratio but with decreasing energy content, had a negative effect on ADG of fattening pigs in the study reported by Chen et al. (2014a). The faecal digestibility was significantly decreased for DM, OM, CP and NDF. However, for pigs given 5% alfalfa meal, ADG and FCR, nutrient total tract digestibility and intestinal nutrient flow were unaffected. Authors underlined that the lack of response for the latter pigs may have been caused using a basal diet containing dietary fibre (5% wheat bran), which may have diminished the negative effect of alfalfa fibre. Additionally, faecal digestibility of energy reduced linearly with the increase in alfalfa fibre. The study of Chen et al. (2014a), also showed the different effects of soluble fibres and insoluble fibres on energy digestibility.

Lastly, Drique and Calvar (2021) obtained a numerically lower ADG (-5 and -10 %, respectively) and higher FCR (+6 and +10%, respectively) for growing pigs fed with 5 or 10% dried alfalfa meal included in iso- net energy and digestible amino acids diets, whereas for finishers, ADG was not impacted by 5 or 10 % meal (0 and -1 %, respectively) but FCR was still higher (+3.5 and +5%, respectively) than for control pigs fed without forage. In the same study, a group of pigs fed 95 % of the control diet was given *ad libitum* access to alfalfa pellets which resulted in poorer performance for growing and finishing periods.

In conclusion, although older studies did not show a consequent decline of animal performance when providing diets with up to 15-20% dried alfalfa meal, more recent studies with balanced diets for amino acids per unit of energy, showed a significant decrease in performance with above 5-7% incorporation of alfalfa meal. The authors advised not to exceed these levels. Additionally, results of most studies are in accordance with a lower nutrient and energy digestibility of the pig diet when the inclusion level of alfalfa meal increases. Finishing pigs have a better capacity to ferment fibre in the hindgut, but there is little agreement on the maximum inclusion level of alfalfa without lowering animal performance.

c) Effects of grass or alfalfa silage

In a few recent studies, the effects of distribution of grass or alfalfa silage either mixed with feed as a whole diet or given as complementary forage, was studied.
Bikker et al. (2014) mixed a grass silage (32% DM, 19.2% CP and 20.5% CF in DM) stored in plastic bales at 10% and 20% with growing and finishing compound diets of the pigs. They observed a similar total net energy intake but a lower ADG (-5.5%) of the experimental pigs compared to control pigs, resulting in a significantly higher feed energy conversion ratio (+6.3%). At slaughtering, the carcass weight and dressing percentage of the grass-fed pigs was significantly decreased whereas the lean meat percentage was not affected.
Reducing the length of silage materials has been studied to reduce the sorting of silage by pigs prior to ingestion and improve nutrient utilization by pigs. Presto Åkerfeldt et al. (2018) obtained better total tract digestibility of OM (31 vs 24%), N (17 vs 8%) and energy (36 vs 24%) of 20% included grass/red-clover silage (33% DM, 19 % CP, and 46% NDF %) when the feedstuff was finely chopped using extrusion. Authors underlined that a shorter particle length increased the silage consumption to be almost fully completed. This was also reflected in an increased time spent eating in the trough. On the other hand, pigs fed with larger silage particles were rooting on the floor for a longer time indicating that they sorted out the silage to a greater extent.
Silage or wrapped hay of alfalfa have been studied in several recent studies. Ferchaud et al. (2019) distributed *ad libitum* in racks alfalfa (2 batches in bales: 75 and 53 % DM) to medium to severely restricted finishing pigs. Pigs given *ad libitum* both compound feed and alfalfa had higher ADG (+5.7%) than control pigs fed *ad libitum* with only compound feed, indicating a proper free intake of alfalfa, but their lean meat percentage was non significantly lower. The 10, 15, 20% feed restriction resulted in a 44, 64 and 86 % increase of forage intake, respectively, compared to pigs given *ad libitum* compound feed and alfalfa. Pigs that were 10, 15 or 20% restricted, however, had significantly lower ADG, compared to *ad libitum* fed pigs given alfalfa (-8, -16 and -21%, respectively) or to *ad libitum* fed pigs not given alfalfa (-2, -11 and -17%, respectively). Lean meat percentage and carcass yield were not influenced by dietary treatments.

Drique et al. (2022) substituted alfalfa silage (62% DM, 18% CP, 33% CF and 62% NDF on DM) at 10 or 20 % to corn, barley and sunflower meal in diets of growing finishing pigs, calculated for identical NE and digestible AA contents. The nutritional values of alfalfa silage were based on previous results of Renaudeau et al. (2021) with assumed concentrations of ileal digestible lysine, methionine, threonine and tryptophan of 0.0, 1.6, 0.0 and 0.8 g/kg, respectively. Pigs of all treatments had a similar DM intake, but 10 or 20 % of alfalfa silage decreased ADG of 5 and 10 % respectively and increase feed energy to gain ratio of 6 and 14 %, respectively. Dressing percentage of experimental pigs was lower, but muscle percentage was not modified. Authors underlined that the poor quality of the alfalfa silage could be held responsible. Although the target DM value for the alfalfa silage was 35%, a too long drying time in the field increased the DM content to 62% for the silage, probably with a loss of protein nitrogen.
In the following experiment of Drique et al. (2022), alfalfa hay (46% DM, 22% CP, 21% CF and 38% NDF on DM) or red-clover/ryegrass wrapped in plastic bales (52% DM, 15% CP, 26% CF and 47% NDF on DM) were given *ad libitum* to pigs restrictively fed 95 % of the control diet using liquid feeding. The 5% restricted pigs offered *ad libitum* alfalfa hay from bales had significantly lower ADG (-17 %) and higher FCR (+28%) during the growing period compared to control pigs fed 100 % according to plan with compound diet.

For the finishing period, pigs had a similar ADG but FCR of alfalfa pigs was higher than of control pigs (+11% on DM). ADG for the total fattening period was decreased by 6%. Final weight was similar between groups whereas alfalfa pigs had significantly higher lean meat percentage (+2%). With red-clover/ryegrass, the performance of the pigs did not differ from the control pigs during the growing period. But for the finishing period, silage fed pigs had a significantly higher ADG (+7.5% on DM) than control pigs whereas the FCR was numerically but not significantly increased (+2.5%). For the total fattening period, ADG was significantly increased (+5%), whereas lean meat percentage and final weight were not significantly impacted. Authors attributed the better performance with red-clover/ryegrass compared to alfalfa silage to a higher protein nitrogen content. This could be attributed to the protective action of polyphenol oxidase against proteolysis phenomena in red-clover/ryegrass, as reported by Renaudeau et al. (2021) for red clover silage. The crude protein values (6.25 x N) of the silages were not an indicator of amino acid availability for pigs, as protein nitrogen losses may occur during fermentation of the silage in the bales, reducing their amino acid contents.

To conclude, it appears that low inclusion rates of up to 10% of grass or alfalfa silage may result in a similar DM or energy intake by pigs, but could lead to up to 5% reduction of ADG. Furthermore, in all studies, pigs that were fed restrictedly but were proposed *ad libitum* a complementary forage, failed to obtain a growth performance similar to control pigs fed according to plan. A relevant exception is the performance obtained for finishing pigs given red-clover/ryegrass wrapped in plastic bales in the study reported by Drique et al. (2022). It should be noted that silages may undergo chemical transformation during harvesting and storage related to fermentation and proteolysis appears as a challenging phenomenon. Besides that, differences in the energy and protein contents and digestibility of fresh alfalfa products may be related to the fibre components present and to unfavourable effects of saponins (Sen et al., 1998; Stoedkilde et al., 2019).

d) Effects of alfalfa leave meal or silage

As the chemical composition differs between stem and leaves of alfalfa, the nutritional value may be related to the stage of maturity of the alfalfa, and hence to the leaf to stem ratio (Luckett and Klopfenstein, 1970; Christian et al., 1979; all quoted by Lindberg and Cortova, 1995). Today, new alfalfa fractionation methods could make possible to separate the leaves (rich in protein) from the stems (rich in fibre) at harvest time (Renaudeau et al., 2020). Leaves are then dehydrated before being ground into a fine powder.
Renaudeau et al. (2020) studied the effects of 5, 10, 15 or 20% inclusion of dried alfalfa leaf meal in wheat-soybean meal diets on the faecal digestibility and performance of the pigs. The inclusion of 10, 15 or 20% of leaf meal decreased significantly ADG (-10, -11 and -13%, respectively) and increased FCR (+12, +13 and +15%, respectively) compared to control pigs. Coefficients of digestibility of OM, N and gross energy were 56, 44 and 51% respectively and the SID lysine content was calculated at 7.5 g/ kg DM in a 2nd trial with amino acid-free diets. Calculated SID coefficients for amino acids were low in agreement with the previous results of Reverter et al. (1999) and maybe related to the heating treatment.
Calvar et al. (2020) included 5% of alfalfa leaf meal in the growing and finishing diets of liquid fed pigs in a commercial farm. Diets were based on wheat, corn, triticale, soybean, rapeseed, and sunflower meals and were balanced for NE and digestible AAs. Authors reported that despite a similar feed intake, ADG was decrease by 21% which resulted in a lower final body weight.
Additionally, Renaudeau et al. (2021) measured for alfalfa leaf silage (26% DM, 26% CP and 24% NDF), digestibility coefficients of 76, 69 and 71% for OM, N and gross energy, respectively. For red-clover leaf silage (27% DM, 19% CP and 27% NDF), the digestibility coefficients were 76, 64 and 70 % for OM, N and gross energy, respectively. Indeed, these authors observed important proteolysis phenomena during the production of alfalfa silage, leading to a loss of about 70% of the essential AAs prior to use as feed ingredient. The proteolysis associated with microbial deamination of protein and amino acids in alfalfa silage strongly reduces the contents of amino acids (particularly Arg, His, Lys and Thr). The phenomenon is less important for red clover silage (-30%) due to the presence of polyphenol oxidase.

e) Effects of protein concentrates from grass

Grass protein can be extracted from biomass as ryegrass or clover to obtain grass protein concentrates (Hermansen et al., 2017). Such extraction process is currently under prototype development in Denmark to overcome the lack of protein feedstuffs and the lack of fertilizers for organic farms.

Danish researchers have developed a green bio-refinery process of grass that produces several coproducts, including a protein concentrate for monogastric feeding, a pulp fraction for ruminant feeding and a residual juice for organic fertilizer (Santamaria-Fernandez et al., 2020). The characteristics of the grass based feedstuffs are variable and the actual and future improvement of bio-refining processes should ensure a higher protein content and digestibility of the protein concentrate. The highest protein concentrate obtained in Denmark was produced from mixed ryegrass, alfalfa and clover, with a predominance of ryegrass, as reported by Vils et al. (2020). This product had high protein (51.9 % for 92 % of DM) and fat (12.8 %) contents, with a relatively high concentration of methionine and tryptophane, but was low in content of cystine (Vils et al., 2020; Santamaria-Fernandez and Lübeck, 2020).

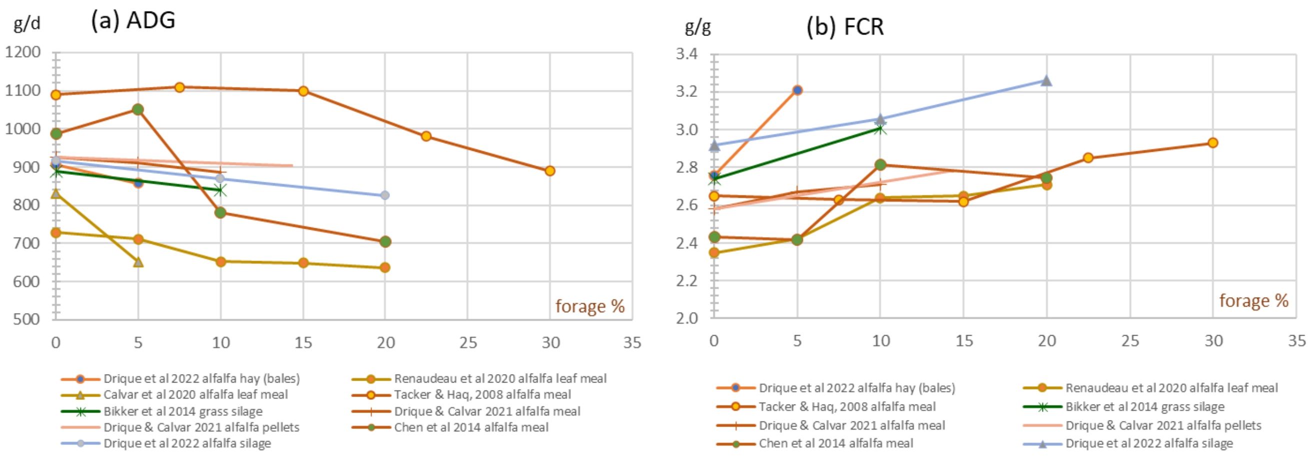
First results (Lærke et al., 2019; Jensen et al., 2020) showed a medium high protein content and nitrogen digestibility of the protein concentrate (33-38% (DM basis) and 55-64%, respectively). The further improvement of the process increased the protein content, from 33% in 2016 to 38% in 2017 (Santamaria-Fernandez et al., 2017, 2019), then from 46 to 54% in 2018 (expressed on DM with 98% of DM/kg) (Stødkilde et al., 2018, 2019, 2021). The protein digestibility of biomass concentrate appears variable due to variable concentrations of minerals, association and/or binding of the protein fraction to the fibre components present and the presence of various antinutritional factors, such as saponins in some lucerne varieties (Stødkilde et al., 2019). Only a few data are available on the digestibility of amino acids from grass protein concentrate in pigs. The digestibility of amino acids reported by Lærke et al. (2019) was significantly lower than values for SBM. It was measured, however, for a product with a low protein content (33–38% on DM basis) and for which the processing conditions to obtain the protein isolate were not yet optimised.

f) Conclusions

There is still a knowledge gap in the field of the grass utilisation for pig feeding. Most performance studies were not based on a precise and complete picture of the nutritional value of the different raw materials used. In addition, measurement of the intake of forage given *ad libitum* is difficult. The introduction of forages in the diet of pigs affects the fattening performance, when the lack of knowledge on the nutritional value of these raw materials leads to a non-optimal supply of amino acids. Besides that, it appears that the composition of forage ingredients varies according to the harvesting and storage conditions. In particular, alfalfa may be subject to proteolysis. Consequently, the forages used in animal trials may have a different digestibility and nutritional value than supposed.

Studies on the use of green biomasses are in agreement regarding the overall impact on growth performance of pigs. In the case of using diets balanced in net energy and amino acids, analysis of dose-response results indicates a 4.8% linear reduction of ADG over the entire fattening period and a 4.4% increase for FCR for 10% inclusion of a forage compared to the control diet without inclusion of a forage (Figure 9). Finishing pigs are less impacted than growing pigs. Furthermore, final body weight and carcass yield are decreased by the use of grass products while carcass lean meat percentage is not affected.

Grass protein concentrates appear to be promising protein sources and could be used as alternative protein source for imported soybean meal in diets for pigs. However, the quality and nutritional value of these feedstuffs need to be improved via further optimization of the processing steps involved.



ADG: average daily gain; FCR: feed conversion ratio. Sources: Bikker et al, 2014 ; Calvar et al, 2020 ; Chen et al, 2014 ; Drique and Calvar, 2021 ; Drique et al, 2022;Renaudeau et al, 2020 ; Tacker et al, 2008.

Figure 9 *Effects of the inclusion of forages on average daily gain (a) and feed conversion ratio (b) of growing-finishing pigs.*

2.2.4 Inclusion of processed animal proteins

a) Background

Animal by-products have been banned from feed for pigs and poultry for almost two decades since the extended feed ban in 2001. The Processed Animal Proteins (PAPs) that are allowed since 7 September 2021 for use in farm animal diets in the EU do not correspond to the animal by-products that were used before the ban on their inclusion in farm animal diets. Processes have been modified and products now available for inclusion in animal diets may not have the same nutritional values as those included in commonly used tables with information on the composition and nutritional value of feed ingredients. Table values for meat and bone meal, feather meal and blood meal were established on basis of studies dating back 30 years and more. Actual processing conditions of PAPs are more intensive in terms of heat and pressure as compared to former methods, which might result in differences in protein digestibility between the former animal by-products and present PAPs. Moreover, former animal by-products as meat (and bone) meal were often based on multiple or unspecified species whereas present EU legislation requires that these products are of single species origin, e.g. porcine or poultry meal. Mixing of products from different species is not allowed (Commission Regulation (EU) 2021/1372). Therefore, Bikker and Davin (2020) conducted a study to determine the nutrient composition, ileal and total tract digestibility and nutritional value of poultry-based PAPs in growing pigs. The selected products were three poultry meals with varying protein and ash content (i.e. low-, medium- and high-ash poultry meal), feather meal (FM) and poultry blood meal (BM). The products were included in a basal diet and supplied to growing female pigs in two successive periods. The first period focused on the phosphorus digestibility, the second period aimed to determine the ileal protein and amino acid digestibility and the total tract digestibility of protein, fat, and energy.

b) Composition and digestibility values

In the study reported by Bikker and Davin (2020), high-ash poultry meal had a higher Ca and P content and Ca:P ratio, caused by a higher proportion of bone and connective tissues compared to medium and low-ash poultry meal (Table 4). The digestibility was higher in low- and medium-ash poultry meal compared to high-ash poultry meal, for crude fat and energy but not for CP. Thus, the higher ash content seemed to reduce fat and energy digestibility without negative impact on digestibility of protein and amino acids. Feather meal and blood meal were high in CP and low in other nutrients, although feather meal had a substantial fat content. The nutritional composition of these two meals was rather different from the older table values, particularly for the amino acid contents and the P concentration (Davin et al., 2019). Digestibility determined in three segments of the small intestine also indicated that protein from blood meal may be hydrolysed and absorbed more rapidly, largely in the proximal jejunum, than protein from feather meal, largely in the distal jejunum and ileum.

Composition and digestibility of poultry PAPs for pigs have now been included in the CVB table (CVB, 2020). In general, these results indicate that PAPs have a moderate to high nutritional value, but variation in composition and digestibility can be substantial and needs to be taken into account. This was also observed and reported by Kerr et al. (2017, 2019) in a survey of a large number of poultry by-products from commercial processing plants in the United States.

Table 4 *Composition (g/kg dry matter) and digestibility (%) in pigs of a selection of nutrients in processed animal proteins from poultry.*

	Poultry meal, high ash	Poultry meal, medium ash	Poultry meal, low ash	Feather meal	Blood meal
Moisture	44	65	66	62	40
Crude ash	336	133	125	14	26
Crude Protein	558	721	727	944	973
Crude Fat (hydr.)	100	124	127	71	6
Gross Energy, MJ	16.2	22.1	22.5	24.4	24.3
P	60	25	23	1.8	6.0
Ca	123	42	39	2.9	1.2
Lysine	29.7	46.1	45.1	21.3	80.4
Total tract digestibility,%					
CP	83	85	83	75	83
Crude fat	53	83	81	65	-
GE	72	83	81	74	76
P	68	68	62	-	-
Ileal digestibility					
Lysine	87	76	80	58	88

Adapted from Bikker and Davin, 2020.

c) Performance

In following studies, Davin et al. (2021) determined the effect of replacing SBM in the diets for weaned pigs and growing pigs with poultry PAPs, using the information on nutrient composition and digestibility described above. In pre-starter and starter diets, 7.5% SBM was replaced by 5% high-ash or low-ash poultry meal, 4% feather meal or 4% blood meal. Over the whole experimental period, growth performance was approximately 20-35 g/d lower on diets with high-ash poultry meal and feather meal compared to the other diets. This effect was largely mediated by a lower feed intake for these products in the starter phase. In addition, FCR was higher for pigs receiving these products in the pre-starter phase. This may suggest that the digestibility determined in growing pigs overestimated the digestibility of these products in newly weaned pigs. A lower digestibility for feather meal was confirmed by a relatively high concentration of ammonia in the small and large intestine in piglets sacrificed two weeks after weaning. In pig diets, Davin and Bikker (2021) determined the effect of replacing 7.5% SBM by 5% high- or low- ash poultry meal, or 4% feather meal. All dietary treatments had similar performance in the study period of 35 days from 25 to 55 kg body weight without any effect on faecal consistency.

d) Conclusion

These results indicate that low-ash poultry meal and blood meal can partly replace SBM in weaned pig diets without loss in performance, but feather meal and high-ash poultry meal may result in reduced feed intake and daily gain. In growing pig all PAPs can partly replace soybean meal as an inclusion level of at least 4-5% without negative effects on growth performance. The negative effects of feather meal were to some extent in line with results of Divakala et al. (2009) and Brotzge et al. (2014) using 7-10% feather meal without and with blood, respectively, to completely replace SBM in growing pig diets. With proper amino acid supplementation, the FCR on feather meal diets was similar to the control treatment but ADG and feed intake were 5-15% lower for feather meal with and without blood, respectively. Taken together, these results suggest that a high inclusion of feather meal may reduce palatability and feed intake and weaned pigs may be more sensitive to this effect than older pigs.

3 Influence on pig health and welfare aspects

3.1 Introduction

As mentioned in chapter 2 of this report, the diets of pigs in the future might differ from current diets in ingredient and nutrient composition related to the increased use of more circular ingredients and ingredients not fit for human consumption. Changing the diet by inserting or excluding feedstuffs that are more suitable in more circular pig production concepts, may come with challenges for animal health and welfare related to specific positive (functional) properties of feed ingredients or detrimental effects related to specific components (e.g. ANFs) present in circular ingredients. These challenges might also emerge from differences in nutrient composition of circular diets but might also be related to the feed form or structure. The scenarios regarding diet ingredient composition as described in paragraph 1.3 are the basis of the description of possible challenges and opportunities for future pig diets in relation to health and welfare of pigs. As described in the advisory report (Zienswijze Dierwaardige Veehouderij; RDA, 2021) by the Dutch Council on Animal Affairs, future animal husbandry systems should both be more circular as well as animal friendly. The Dutch Council on Animal affairs further describes that all animals should be recognized for their intrinsic value, which focusses on the opportunity to express natural behaviour. Behaviour will satisfy the animal's needs and result in a positive mental state. Behavioural needs are related to an animal's motivation to act a certain way. The animal's motivation is regulated by internal and external factors. Motivation drives the animal to behave in a way that it keeps healthy and balanced. Some behavioural needs are such that the motivation for them exists only in certain situations based on external factors, such as the need to avoid a predator. Other behavioural needs are regulated by internal motivating factors, such as the need to eat or, among pigs, the need to root (Council of Europe, 2004).
Next to governmental policies for the future development of Dutch animal husbandry, individual companies have similar targeted ambitions. Dutch initiatives such as Kipster in the poultry sector[5], aim for a more circular based animal husbandry, where also the welfare of the animal takes a more prominent place. Furthermore, societal concern is asking for welfare of farm animals to be improved without having a negative impact on climate change. Research of the last decades has focussed more on solely welfare and behaviour, without taking the impact of production concepts on environment and climate into account. Therefore, this research has been conducted with "standard", commonly used diets which may not be representative for more circular pig husbandry. However, if diets in the future change in ingredient composition, functionality of the diet related to health and behaviour could change as well. Such effects could vary in nature and be considered either positively or negatively depending on the exact mode of action of the constituent in the diet responsible for the effect. Examples are constituents in the diets that could act as prebiotics that support the stability and functionality of the gut microbiome or could be judged negatively in case of e.g. high concentrations of heavy metals present in a particular circular ingredient. Therefore, it remains important to review and research the consequences of feeding more circular diets on pig health and welfare.

To systematically assess the scenarios for their impact on pig health and welfare, a framework has been used. This framework is summarized in Table 5. The scenarios were assessed on seven elements related to the composition of circular feed ingredients; chemical nutritional composition (A), presence of chemical contaminations or accumulations (B), microbiological stability or presence of pathogens (C), presence of anti-nutritional factors (ANF's; D), prebiotic functionality (E), presence of bioactive compounds (F) and feed form (dry/liquid and structure) (G). It should be mentioned that the proposed framework does not consider all the complex effects and interactions which may occur in the animal as a consequence of the ingestion of a particular feed ingredient. It does, however, represent major elements in relation to specific positive and negative effects of animal feed ingredients apart from their strict nutritional value as presented in common references on nutritional value of feed ingredients (e.g. CVB, INRAE and NRC).

[5] Https://kipster.nl

In Table 5 different categories of functional or antinutritional constituents in feed ingredients have been linked to specific effects related to animal or organ health and functionality. Using this, each circular ingredient can be evaluated for its functional effects in relation to specific constituents. It should be noted that single circular ingredients do not contain all functional constituents mentioned in the diagram. In the scientific literature in most cases only attention is given to a limited number or often only one specific constituent. However, different specific constituents in a single ingredient or from different ingredients when combined in a circular diet could also cause interactive effects. This aspect has not been studied in the currently available literature but could a point of consideration in the design of future studies on the effects of circular diets for pigs.
In Table 6 an overview is given on the composition and characteristics of circular feed ingredients in relation to aspects of health and welfare, as considered in the present desk study.

Table 5 *Framework to assess effects of circular feed ingredients on pig health and welfare.*

Composition and characteristics categories		
A	Chemical nutritional composition (protein, fat, fibre, energy)	
B	Contaminants (chemical)	
C	Microbiological quality/presence of pathogens	
D	Anti-nutritional factors (ANF)	
E	Prebiotic functionality	
F	Bioactive compounds	
G	Form and structure	
Impact on	***Positive effects***	***Negative effects***
1) Growth performance	Discussed in chapter 2	Discussed in chapter 2
2) Gastro-intestinal tract		
- Nutrient digestibility	A	A (fibre)
- Gut barrier		C - D
- Gut microbiome	E, F	A (fibre), C, D
- Local immune system	E, F	B, D
- Faecal consistency		A (fibre), D
3) Systemic health		
- Organ/tissue functionality and metabolism		B, D
- Immune system	F	B
4) Clinical health		
- Clinical health status and mortality		B, D
5) Welfare		
- Behaviour	G	

Table 6 *Overview of composition and characteristics of circular feed ingredients in relation to health and welfare discussed in this review.*

	Chemical nutritional composition	**Contaminants (chemical)**	**Microbiological quality/ pathogens**	**Anti-nutritional factors (ANF)**	**Prebiotic functionality**	**Bioactive compounds**	**Form and structure**
Cereal grain by-products	X				x		X
Potato peels	X						X
Professional kitchen waste	X		X				
Rapeseed meal	X			X	X		
Fresh whey	X		X		X	X	X
Faba beans	X			X			
Lupins	X			X			
PAPs poultry	X					X	
Insect protein	X	X			X	X	
Algae	X	X			X	X	
Grass protein and clover	X			X			X

Most studies on circular ingredients which concern health and welfare, focus on gut health. An impaired health and functionality of the gut, often negatively influences performance of pigs, but also their welfare and wellbeing. One of the most critical periods within swine production is the weaning of piglets (Pluske et al., 1997, 2019; Canibe et al., 2022). Upon weaning, piglets undergo several changes, e.g., in environment and nutrition. Moreover, the piglets' immune system at this stage is not yet fully developed, which makes them more susceptible to digestive and respiratory diseases. Weaning is therefore often accompanied by signs of intestinal dysfunction and clinical disease, reflected in diarrhoea and reduced body weight gain. Due to the change to solid feed, weaned piglets experience strong structural and physiological changes in the digestive tract. For these reasons, many studies in pigs that focus on feed and feed ingredient functionality in relation to gut health are carried out with post-weaning piglets. As a result, the paragraphs below refer largely to studies with post-weaning piglets and to a lesser extent to studies done with growing-finishing pigs.

3.2 Assessment of the reduction of cereals

3.2.1 Inclusion of by-products of cereal, sugar and oil industry

a) Background

Co-products with low nutritional value (i.e., lower energy value or amino acid levels) from the human food industry can be used in pig diets to contribute to a more circular feed system. The inclusion of by-products cereal, starch, oil and sugar industries grain such as wheat bran, corn bran, sugar beet pulp, soybean hulls, distillers dried grains with soluble and wheat middlings affect the chemical composition of the diet and generally increases the fibre level (see also paragraph 2.1.1). As a matter of fact, the effects of high fibre levels inclusion on pig health and welfare have been a research topic for years, on which much investigation has been performed. For the present report, since these topics are not novel and most effects have been properly described, mostly reviews on the subject are summarized below.

b) Gut microbiome

The diet has a great impact on the gut microbiome and dietary constituents can cause both harmful or beneficial effects. Dietary fibres interact both with the intestinal mucosa and with the intestinal microbiota and have therefore an important role in the control of gut health (Lindberg, 2014) (Lindberg, 2014).

Dietary fibre is the main microbial energy provider in the large intestine, promotes the growth of health-promoting gut bacteria, and thus regulates the intestinal microbiome and promotes gut health, as reviewed by Li et al. (2021), Jha et al. (2019) and Lindberg (2014). Most of the bacteria degrading dietary fibres are beneficial to the pig, ferment fibres into organic acids which lower the pH of the intestinal lumen. Because of the lower pH, the proliferation of pathogenic bacteria is inhibited. However, the fibre source influences the effect on microbial composition and diversity (Lindberg, 2014). For example, weaned piglets fed alfalfa diets had an increase in relative abundance of *Firmicutes* and *Bacteroidetes* as compared to piglets which were fed a wheat bran diet (Mu et al., 2017). Furthermore, pea fibre diets increased *Lactobacillus* counts in pig colon, whereas soybean fibres increased the counts of *E. coli* (Chen et al., 2014b). Inclusion of insoluble dietary fibres in pig diets are proven to have an inhibitory effect on pathogen colonization in the pig gut, since they can stimulate intestinal peristalsis and thus reduce the colonization time of pathogenic bacteria. Some studies have reported a negative effect of insoluble fibres on the intestinal microbiota. In growing pigs, cellulose increased the *Enterobacteria* populations in the ileum, and inclusion of wheat bran in growing diets reduced the ratio of *Lactobacilli* to *Enterobacteria* (Li et al., 2021).
Apart from insoluble dietary fibres, also soluble dietary fibres have influence on the gut microbiome. Characteristic for insoluble fibres is their capacity to increase the passage rate of intestinal digesta, whereas soluble fibres increase viscosity and hydration properties (Lindberg, 2014; Jha et al., 2019). The inclusion of soluble or insoluble fibres, or also the ratio between the two fibres could shape the gut microbiome (Lindberg, 2014; Grzeskowiak et al., 2023). As reviewed by Li et al. (2021), effects of soluble dietary fibre fermentation can both be positive and negative. On the one hand, high viscous soluble fibres tend to aggravate the shedding of intestinal epithelial cells and decline of protein digestibility, which can increase the flow of undigested protein from the small intestine into the hindgut. An increase of protein in the hindgut could lead to increased protein fermentation and release of related fermentation products (amines) and the proliferation of pathogenic bacteria. On the other hand, low viscous soluble dietary fibres do not seem to negatively affect gut health. These fibres promote the proliferation of probiotics and could have a beneficial effect on the gut microbiome.
Reviewed by Grzeskowiak et al. (2023), feeding sows diets with a different ratio of soluble to insoluble fibre, resulted in differences in gut microbial community. Additionally, the intake of more soluble fibres led to higher antioxidant enzyme activity and in suppression of pro-inflammatory factors in both sows and their piglets. Furthermore, sows fed with guar gum as source of fermentable fibre and cellulose during gestation had elevated concentrations of faecal butyrate and propionate, as well as *Roseburia, Eubacterium-hallii* and *Bacteroides* bacteria. Inclusion of wheat bran and sugar beet pulp caused an enhanced intestinal barrier and a reduction of *Subdoligranulum* and *Mogibacterum* counts, but an increase in *Lactobacillus* count in gestation sows.
Dietary fibres could have major prebiotic effects. They are resistant to digestion by host enzymes, interfere with absorption and adsorption processes, some can be fermented by the microbiota within the gastro-intestinal tract and could stimulate the growth and/or activity of specific bacteria within the intestinal tract (Lindberg, 2014). A lot of research has investigated the influence of fibre on the microbiota and short chain fatty acid production with potentially positive or negative effects (see for example Zhao et al., 2019). However, the type of fibre is crucial for the possible effect by the properties hold by the fibres. As reviewed by Lindberg (2014), feeding guar gum, a soluble and viscous NSP increases the proliferation of *E. coli*, whereas feeding insoluble NSP reduces the occurrence of *E. coli*.
In weaned piglets, effects of dietary fibres on the intestinal microbiota are varying. Different fibre sources also seem to have different effects in weaned piglets. Grzeskowiak et al. (2023) reviewed that corn cob has been shown to favour lactobacilli and bifidobacteria in the stomach, whereas wheat bran has increased *E. coli* in the jejunal digesta, increased lactobacilli and bifibacteria in the gastric and jejunal digesta. Inclusion of 4% wheat bran stimulated the formation of short chain fatty acid formation, while also reducing *E. coli* counts in the digestive tract. However, other studies found smaller effects on the intestinal microbiome when fed diets with higher inclusion levels of fermented wheat bran.

c) Immune system

Effects on the local immune system in the gut are also depending on the source of fibre in the diet. Grzeskowiak et al. (2023) reviewed that chicory roots or corn cobs both showed reductions in intraepithelial lymphocytes in the jejunum of weaned piglets, whereas wheat bran or sugar beet pulp inclusion showed an increase.

Inclusion of high levels of wheat bran (10%) and pea fibres resulted in increased diamine oxidase activity and increased expression of transforming growth factor-alpha, trefoil factors and major histocompatibility complex in ileum tissue. Other studies showed no effect of lignocellulose inclusion on expression of immune-relevant genes in ileum, spleen, liver, or mesenteric lymph node tissues. While another study with 5% grape pomace observed a down-regulation of cytokines IL-1ß, IL-8, IL-6 and tumour necrosis factor-alpha, and an increase in serum levels of immunoglobulin G (Grzeskowiak et al., 2023).

d) Gut morphometry

When dietary fibres are fermented, short chain fatty acids are produced. These promote development of the mucosal epithelium and height of intestinal villi. Besides regulation of the exchange of nutrients, the intestinal mucosa also acts as a barrier to pathogenic bacteria and toxic compounds (Jha et al., 2019). Dietary fibres are considered anti-nutritive due to the increase of endogenous losses and consequently decrease in energy and nutrient digestion, which was supposed to be more prominent in young piglets than in growing and finishing pigs. However, moderate levels of fibres have been proven to increase gut size, length, volume, and morphological structure (Jha et al., 2019). Grzeskowiak et al. (2023) reviewed that feeding sows during gestation with diets having linearly increasing soluble to insoluble fibre ratios, resulted in a linear decrease in body weight at farrowing and body weight gain of the piglets. Furthermore, the crypt depth of the jejunum in the weaned piglets was linearly increased, whereas duodenal weight, jejunal villus height and villus height/crypt depth in new-born piglets linearly decreased. In growing pigs, as reviewed by Jha et al. (2019), inclusion of high levels of fibres resulted in an increase width of villi and depth of the crypts in both jejunum and ileum. Furthermore, high fibre inclusion also increased the rate of cell proliferation and crypt depth in the large intestine.

e) Clinical health

None of the studies reviewed in paragraph 2.1.1 reported any negative effect of cereal by-products on health or welfare of piglets or fattening pigs. Furthermore, inclusion in diets of fibres from by-products can be beneficial to prevent post-weaning diarrhoea in piglets. It seems that the particle size of the fibres is relevant to prevent diarrhoea. Coarsely ground wheat bran inclusion resulted in firmer faecal consistency after a pathogenic *E. coli* challenge as compared to finely ground wheat bran. These results were probably due to a higher binding of *E. coli* to the coarse fibre, as well as higher water-binding capacity of the intestinal digesta. Other studies show contradictory results: inclusion of 10% wheat bran has been associated with positive effects on diarrhoea and changes in morphology, gut microbiome composition and protective effects, whereas other studies including 5-10% wheat bran, soybean hulls or oat hulls show no effects (Review of Grzeskowiak et al., 2023).

f) Welfare

Pigs are often fed a nutrient- and energy-dense diet to ensure adequate growth. Within these diets, the fibre levels are often low, which could cause problems for pig welfare due to influences on behaviour. The integration of fibre components in these type of diets with a low physical structure, might require more processing and technical effort (i.e., pelleting) or lead to faster satiation in the pig consuming these diets. Although dietary fibre is not always considered an essential nutrient, various performance, behaviour, and health-related characteristics are affected, depending on the quantity and quality of the fibre source (Grzeskowiak et al., 2023). The natural feeding behaviour of pigs include rooting and uptake of intact, fibrous feedstuffs. Therefore, welfare-oriented feeding concepts, and most EU legislation often include the administration of dietary fibres in pig diets, as well as additional provision of roughages. Several effects of dietary fibre inclusions on behaviour have been reported, which directly affect pigs' welfare. For example, as reviewed by Grzeskowiak et al. (2023), group-housed sows tend to have aggressive interaction and fights with their pen-mates, while inclusion of fibres has lowered the occurrence of these unwanted social interactions. Different fibre sources could aid to less aggressive interactions in group-housed sows, such as grape pomace, ligno-cellulose, soybean hulls, resistant starch, and straw. Furthermore, fibres also seem to prevent the expression of sham-chewing and stereotypic behaviour when diets included sugar beet pulp, oat hulls or alfalfa meal. However, some studies also report no effects of high fibrous diets with wheat bran, sunflower meal, and sugar beet pulp during gestation on farrowing behaviour and reproduction. There are, however, positive consequences for piglets when a high fibrous diet is fed to sows during gestation. Some studies have shown higher growth rates and fewer skin lesions in piglets during the lactation period.

In fattening pigs, the dietary inclusion of fibre has little effect on feeding behaviour. For example, in their trial to reduce the proportion of cereals and eliminate maize and SBM, Wheatherup and Beatie (1997) found no differences in the time spent at the feeder or in the number of visits to feeder by pigs in any one of the four treatment diets without or with cereal co-products.
Low dietary fibre inclusions have been associated as a risk factor for tail biting in weaned piglets, and many studies have focussed on this topic with variable success. Reviewed by Kobek-Kjeldager et al. (2022), there are three main mechanisms whereby dietary fibre is thought to influence gut health and consequently tail biting. Fibres provide structure to the digesta, which influence feelings of satiety and controls the intake of feed as well as reduces the risk of gastric ulcers (1). By modulating digestive processes such as those that control transit time of the digesta, dietary fibres influence the blood concentrations of glucose and lipids (2). And lastly, by acting as an energy substrate for microbial fermentation and reduction of the formation of potentially toxic metabolites of microbial proteolytic activity (3).

g) Conclusions

Dietary fibres have numerous positive effects on health and welfare of pigs in all stages. Fibres can interact with aspects of the pig physiology, immunology, gut microbiome composition and functioning and pig behaviour. Furthermore, some transgenerational effects from sows to piglets have been proven in relation to feeding fibrous diets, which makes fibres an interesting constituent of pig diets. Fibres are, therefore, already extensively studied. The origin of the fibres, and the processing of the raw material in the case of a by-product, leads to variation in composition and properties of the fibres. The results discussed on post-weaning diarrhoea and pig welfare indicate the importance of both the chemical and physical characteristics of dietary fibres and their level in the diet.

3.2.2 Inclusion of wet by-products

a) Background

Providing the pigs with a liquid feed gives the opportunity to include liquid by-products and waste streams from the human food industry in pig diets. Therefore, liquid diets with by-products could fit well into a more circular feed system. Brooks et al. (2001) reviewed that liquid diets have potentially more advantages: less dust in the barn atmosphere leading to improvements to the environment and possibly pig health, improved pig performance and FCR, flexibility in raw material use, improved material handling by the combined automated function of mixing and distribution, increased accuracy of rationing, improved dry matter intake of difficult periods (weaners and lactating sows) and an improved intake at higher ambient temperatures.

b) Gut microbiome and digestive health

Feeding liquid diets could have effect on the gut microbiome composition in pigs. Hong et al. (2011) found influenced microbial populations in stomach and ileum due to a natural fermented liquid feed or the inclusion of rice distiller's residues in weaned piglet diets, while marginal effects were found in the colon. Especially the presences of *Lactobacillus* species was increased when the experimental diets were provided. The earlier mentioned review also mentions that liquid feeding could reduce the incidence of Salmonella, as has been shown by surveillance data. The authors explain this as an improvement of gut health due to liquid feeding, especially due to the acidity from some (fermented) by-products which were used such as acidified cheese whey (Brooks et al., 2001). Other beneficial microbial activity can be promoted, such as naturally occurring *Lactobacillus.* A study by Hong et al. (2009) tested the effects a naturally fermented liquid diet and a liquid diet with inclusion of rice distiller's residue on gut environment, the number of coliform and lactic acid bacteria and performance of weaned piglets. Piglets fed with either one of the experimental diets had higher concentrations of lactic acid bacteria in the stomach, ileum and mid-colon as compared to piglets fed the control diet. Furthermore, counts of lactic acid bacteria in stomach and ileum were also higher, while the number of *E. coli* and total coliforms along the gastro-intestinal tract was reduced. The effects, however, were most prominent in piglets fed the fermented diets, together with a lower pH in the digesta. These results indicate that the fermentation has a more prominent influence, probably due to the acidity (Hong et al., 2009). Lactic acid bacteria presences could have beneficial effects on gut health, but also stimulate systemic immune response. A study by Mizumachi et al. (2009) showed that a fermented liquid diet including probiotics resulted in increased levels of immunoglobulins M and G in sera. The authors, however, did not find any effects in total IgA levels in faeces and saliva.

Moreover, low levels of interferon-γ secretion and mitogen-induced proliferation were found in blood of pigs fed with the fermented liquid diet. Furthermore, the levels of proinflammatory cytokines interleukin-8 and tumour necrosis factor-α were lower when the fermented diet was provided. The authors suggest that fermented diets could enhance immune responses and prevent diseases in weaned piglets (Mizumachi et al., 2009).

Not all liquid diets are successful in influencing favourably gut microbiome. He et al. (2017) studied the effect of feeding pre- and post-weaned piglets with a *Bacillus subtilis* fermented diet in pelleted or liquid form on gut microbiome, gut metabolomic profiles, bile acid metabolism, proinflammatory cytokines and faecal consistency. The authors reported higher bacterial diversity, lower fungal diversity, lower concentrations of 3-hydroxypropionic acid, orotic acid, interleukin-6 and lactic acids in the piglets fed the fermented diet in pelleted form. Furthermore, the authors also reported a higher incidence of diarrhoea in piglets fed the liquid diet. From the result can be concluded that the liquid diet disturb the normal production of lactic acid, increased circulating interleukin-6 levels and resulted in more diarrhoea (He et al., 2017). Furthermore, also other less positive or negative effects on undesirable microbes could be a consequence of liquid diets. With whey or other liquid by-product feeding, gastrointestinal accidents revealed by sudden deaths have been reported in the past by several authors (Royer et al., 2004). According to Février and Chauvel (1976) it corresponds to a group of symptoms that liquid whey directly or indirectly promotes. These are mainly *Salmonella* enteritis, *E. coli* enteritis, *Streptococcus suis* septicaemia and *Clostridium perfringens* enterotoxaemia. These enterotoxaemia cases, frequently linked to overfeeding, concern typically the most vigorous pigs. They frequently correspond to the use of tank bottom deposits (not homogenised or never emptied) which are essentially made up of protein deposits (yeast cells). Royer et al. (2004) underlined that distension of the gastrointestinal tract (overload, high gas production, accumulation of liquid due to osmotic processes) can lead, as indicated by Häni et al. (1993), either to intestinal torsion, other to dilatation and/or overloading of the stomach, torsion of the spleen and/or stomach, tympany with rupture of the colon and peritonitis, all of which being part of the same disease complex in fattening pigs or sows. Feeding technique may be involved in the case of rapid intake of large quantities of feed, intake of air during greedy meals, increased excitement, and activity before or during ingestion, abrupt dietary adaptation ("osmotic diarrhoea"). Characteristics of feedstuffs may also play a role: fermentable substrates such as whey, air included in feed, digestive microflora change resulting from the diet (increase of clostridia when feeding whey, increase of yeast when taking antibiotics). Hygiene-related causes could be high micro-organism content or high yeast content in raw materials or liquid feed, errors in preparation and storage, insufficient hygiene of liquid feeding system. Drochner (1990) associated the symptoms of diarrhoea, tympany and sudden deaths to poor hygiene of by-products and/or liquid feed distributed in pig farms. Moreover, Buddle and Twomey (2002) emphasised the presence of highly fermentable raw materials (whey and molasses sugars, enzyme-treated starches) in the diet. The amount of undigested highly fermentable substrate that can quickly reach the large intestine is indeed the cause of excessive gas production, which can be increased if the intestinal flora is increased or unbalanced.

c) Conclusion

Using liquid by-products in liquid diets have clear benefits from a circular perspective. The influences on pig health, however, are dependent on handling and storage of the raw materials, as well as the equipment on farm. Fermentation of the by-products seems to have probiotic effects on the gut microbiome and in extent possibly on the immune system. However, monitoring is necessary to eliminate all risks of microbes, and the effects on welfare and behaviour when liquid feeds are provided.

3.2.3 Inclusion of kitchen waste

a) Background

Within a more circular food system approach, production animals should be fed with low-environmental impact diets. Kitchen waste, food left-overs from professional kitchens such as restaurants, hotels, could fit in such a food system since it recycles organic streams and important nutrients such as phosphorus (Myer et al., 1999). Kitchen waste could be a substitute for part of the cereal grains and plant protein sources used in animal feed (Georganas et al., 2020).

Due to the properties of the sources within kitchen waste, the mixture is often wet. To preserve kitchen waste, several methods are currently studied: heating, fermentation and drying. The method of preservation impacts the form and the way to provide the diet to pigs.
Historically, especially pigs have been fed left-overs from kitchens known as swill (cooked food waste) (Zu Ermgassen et al., 2016) which can be a high-quality feed. However, due to the foot-and-mouth disease epidemic in UK, feeding swill and kitchen waste has been prohibited in the EU. While in Asian countries, such as South Korea, Japan, Taiwan and Thailand, recycling of food left-overs in animal diets is promoted for decades (Menikpura et al., 2013). Kitchen waste can be a source for disease-causing bacteria and viruses and feeding uncooked meat wastes to pigs is a risk factor of diseases such as swine fever and foot-and-mouth disease, making kitchen waste a risky and hazardous ingredient for pig diets. Proper heating of kitchen waste inactivates viruses present and renders it safe for animal feed (Zu Ermgassen et al., 2016). This, however, requires strict regulation and registration of the kitchen waste processing in the diets. Other hazards could be micro-organisms, chemical, i.e. heavy metal or mycotoxin concentrations and physical, i.e. paper, metal and plastic (Georganas et al., 2022). Most of the available literature has focussed on environmental impact and global health, rather than on the effects on the pig itself. The small number of studies that discussed these aspects have been included in this review.

b) Effects on pig health

The quality of kitchen waste is subjected to a wide variation due to variability of the left-overs and consumer characteristics such as age, ethnic origin, and dietary habits (Georganas et al., 2020). However, since kitchen waste originate straight from food meant for human consumption, it has, depending on its composition, substantial nutritional value or and might contain bioactive compounds that provide health benefits. As reviewed by Georganas et al. (2020), kitchen waste contains variable levels of protein, essential amino acids, minerals (calcium, magnesium, phosphorous), starch and sugars, fat (including polyunsaturated fatty acids, monounsaturated fatty acids, saturated fatty acids) and, lesser studied, vitamins.

c) Effects on pig behaviour

Kitchen waste could be provided to pigs in several forms, depending on the source and processing of the ingredients. A study in which wet kitchen waste was fed to lactating sows, showed that the wet diet allowed sows to eat faster. On the other hand, the authors also reported lesser suckling time of the piglets (Prasanna et al., 2016). Since lactation is a challenging period for sows to retrieve enough energy and nutrients compared to the energy that is lost in milk production, less time spent on eating could be beneficial for their energy balance. However, the nutritional value and energy component of the diets should be similar, which can be challenging with inclusion of kitchen waste.

d) Conclusions

Feeding kitchen waste has theoretically high potential to serve as a dietary ingredient within pig production. Source variability in nutritional value and the methodology to preserve the ingredients are challenges to overcome before it can be used in practice. The effects of kitchen waste inclusions on health and behaviour are rarely studied. Hazards for both pig and human health are indicated, i.e. bacteria, viruses and other micro-organisms as well as concentrations of heavy metals, and pieces of paper, metal and plastic. Lastly, EU legislation currently does not allow kitchen waste as a pig diet ingredient. However, further research is necessary and ongoing to search for possibilities using kitchen waste in certain conditions, aiming to improve safe use in animal diets.

3.3 Assessment of the increased use of ingredients originating from EU

3.3.1 Inclusion of rapeseed meal

a) Background

As mentioned in paragraph 2.2.1, rapeseed meal is a main co-product with nutritional potential for pig diets. It is especially interesting to use rapeseed meal as a protein source, and thus to replace (part of) SBM of the diet. Higher inclusion of rapeseed meal could, however, result in higher levels of ANFs such as glucosinolates, phytates or tannins. Fermentation of rapeseed meal before mixing into the diet could be a method to reduce ANFs in the compound feed. However, fermentation could affect nutrient concentrations in the product as well as the palatability of the ingredient. Depending on further processing and the method of provision to the pigs, it could affect the feed intake.

b) Gut microbiome

Czech et al. (2021) studied the effect of fermented dried SBM and/or fermented dried RSM in weaning pig diets on performance, nutrient digestibility, gastrointestinal tract histology and gut microbiome composition (ileum and faeces). Focussing on the gut microbiome results, the piglets from the 6% fermented RSM and 2% fermented SBM group had a higher total bacterial count in ileum content. The total bacterial count in the faeces was higher in the control group than in the other groups. Inclusion of a fermented component seemed to affect the fungal count in ileum and total number of coliforms and *E. coli* bacteria in ileum which were all higher in the control group, except for the coliforms which was also increased in the group with 8% fermented SBM. The number of coliforms, *E. coli* and *Clostridium perfringens* in the faeces was also higher in the control group as compared to the groups receiving diets with fermented components. These results indicate an improvement of digestion and absorption when fermented components are used due to the positive effects on the gut morphometry. Furthermore, the gut microbiota composition was improved as well.
Satessa et al. (2020) studied the effect of fermented RSM in combination with one (*Ascophylum nodosum)* or two seaweed species (*Ascophylum nodosum* and *Saccharina latissimi*) versus control groups with and without zinc supplementation on gut microbiome maturation. Inclusion of fermented RSM with or without the inclusion of one or two seaweeds resulted in a more diverse colon microbiota. An increased richness and diversity of the gut microbiome are associated with a more stable gut microbiome community and could positively affect gut health. Furthermore, the Unweighted Unifrac distance metrics showed that fermented RSM inclusion could potentially have the same effect on the gut microbiome as compared to supplementation of zinc. The authors showed that the control group with zinc supplementation influenced the presence of numerous low abundant taxa and showed a similar tendency for the groups fed with fermented RSM (Satessa et al., 2020).
A study in growing pigs focussed on the effects of 20% RSM inclusion on the gut microbiome (Umu et al., 2020). Both composition and functioning of the microbiome were analysed by culturing of bacteria and 16S rRNA gene sequencing of the content from ileum, caecum, and colon. The diversity and composition of the gut microbiome generally did not differ due to the inclusion of RSM. Nevertheless, a relative abundance of a variety of bacterial groups and imputed functions of microbiome in the ileum and large intestine were altered in the group with RSM fed pigs. In the ileum of those pigs, the immune-inducing bacterial group *Mucispirillum* was more abundant, and in the large intestine the anti-inflammatory stimulating bacteria *Lachnospira* were more abundant. On the other hand, inclusion of RSM resulted in a reduction of *Lactobacillus* abundance, which is unfavourable due to the bacteria's positive effects on gut health around weaning. Furthermore, in the control group, a higher abundance of major amino acid fermenters and amylolytic bacteria were found. While in the RSM fed group, a higher abundance of putative short chain fatty acid producers was identified. The authors concluded that the inclusion of RSM in growing pigs has a beneficial effect on the gut microbiome. The inclusion resulted in an enhanced potential for carbohydrate and energy metabolism and a reduced potential for bacterial pathogenicity-related pathways. This indicates a potential protection from infections and improved immunological homeostasis via gut microbiome modulation. This is in contrast with an earlier study by Umu et al. (2018), in which RSM replaced part of the SBM in weaner pig diets. The authors reported no large differences in gut microbiota and suggested that RSM does not disturb the gut microbiome composition or gut functioning.

There was, however, a relative high abundance of short chain fatty acid producing phylotypes and colon-health related phylotypes found in the large intestine when RSM was fed. These findings suggest an anti-inflammatory stimulus effect of the RSM diet. Furthermore, the authors reported a relatively unaltered gut microbiome after episodes of diarrhoea, suggesting that RSM inclusion could aid to a more robust gut microbiome in weaning pigs (Umu et al., 2018).

c) Gut morphometry

The study performed by Czech et al. (2021) also explored the effects of fermented RSM on gut morphometry (ileum, caecum, colon). The group which received 6% fermented RSM and 2% fermented SBM, had an increase in length and width of the villi in the ileum, as compared to the other groups. The shortest villi were found in the control group and in the combination of high fermented SBM with low fermented RSM. Furthermore, the control group also had the narrowest villi. The deepest crypts in ileum tissue were found in the control group and the 8% fermented RSM group. In the caecum and colon tissue, inclusion of 8% fermented RSM reduced the depth and width of the crypts as compared to the control group. A reversed relationship has been found for the width of the caecum mucosa. The width of the colonic mucosa was also smaller in the control group piglets compared to all groups receiving diets with fermented components. Moreover, Satessa et al. (2020) studied also besides effects on the gut microbiome, the effects of fermented RSM in combination with one or two seaweed species on weaned piglet performance and intestinal development. Body weight and ADFI were improved for piglets fed diets with solely fermented RSM or fermented RSM in combination with one seaweed. Furthermore, the authors reported an increase in jejunal villi height in the control group with zinc supplementation and fermented RSM in combination with two seaweeds. Interestingly, the jejunal villi length was also increased in the groups receiving diets with solely fermented RSM and fermented RSM plus one seaweed, but this was only observed in male pigs. The jejunal crypt depth was increased in all groups with fermented RSM inclusion, except for the combination of fermented RSM and two seaweeds in male piglets. The villus-to-crypt ratio was increased in the control group without zinc and fermented RSM plus two seaweeds, with highest increase levels in males. Histopathological evaluation was only performed in the two control groups and the group receiving fermented RSM inclusion in the diet. The pig from the group with fermented RSM inclusion had more than an 8-fold higher number of gut-associated lymphoid tissue (GALT) structures in mid-jejunum tissue, but no differences were found in colon tissue. Furthermore, piglets fed with fermented RSM had signs of reductions in focal inflammation on mid-jejunal tissue and colon tissue.

d) Systemic health

Czech et al. (2020) studied the effect of dried fermented RSM on haematological and biochemical blood parameters. The authors fed sows with 4% dried fermented RSM as a replacement for SBM at the end of gestation, and 9% fermented RSM for 7 days in lactation, followed by 4% until the end of lactation. Blood was collected during both pregnancy and of sows and piglets during lactation, in which the mineral content (phosphorus, calcium, magnesium, copper, zinc, iron), red blood cell count (red blood cell count, haemoglobin, haematocrit), lipid parameters (total cholesterol, high density lipoprotein, triacylglycerols), selected enzymes (alkaline phosphatase, alanine aminotransferase, aspartate aminotransferase, lactate dehydrogenase, glutamyl transferase) and biochemical parameters (glucose, total protein, albumin and total iron-binding capacity) were measured. Including RSM resulted in increased levels of red blood cell count, haemoglobin, haematocrit, phosphorus, calcium, and iron levels in plasma of sows. Furthermore, inclusion reduced the plasma content of cholesterol and triacylglycerols in sows and piglets, as well as liver enzyme activity. These results could indicate a notable effect of RSM on sow and piglet metabolism and blood parameters. Satessa et al. (2020) found a reduction in the red blood cell, leucocyte, and neutrophil counts in pigs fed diets with inclusion of fermented RSM with one or two seaweeds. Blood biochemistry parameters were unaffected by inclusion of fermented RSM.

e) Health status

For piglets, factors other than the glucosinolate content as health status may interact with the incorporation of rapeseed meal. Royer and Gaudré (2008) observed that 15% RSM-based phase 2 feeds with low or high glucosinolate content (0.4 and 1.9 µmol/g feed, respectively), only significantly decreased feed intake (-8%) and growth (-6%) for piglets reared under optimal sanitary conditions, but not for piglets in the same trial whose health status was stressed by field sanitary conditions.

Accordingly, the same authors reported pooled results of 6 commercial farms for which phase 2 performance was not influenced by 12 % RSM level in piglet feed.
The study of Czech et al. (2021) observed the effect of fermented dried SBM and/or fermented dried RSM in weaning pig diets also on performance and diarrhoea. In all experimental diets, SBM has been replaced by either fermented RSM (8%), fermented SBM (8%) or a combination of fermented RSM and fermented SBM (6% and 2%; 2% and 6%). The authors reported an increased ADG in the groups with high inclusion of fermented SBM, both solely and in combination with 2% fermented RSM. These two groups also had lower mortality and a lower diarrhoea incidence.

f) Conclusions

Systemic research on the effect of RSM inclusion on gut health is lacking. From the few studies that have been reported, most research on health and welfare of pigs concerning RSM has focussed on the influence on gut health, especially on the gut microbiome composition and gut morphometry. The influence on welfare as described by behaviour, has had little attention. Overall, it can be concluded from the reviewed studies that the inclusion of RSM does not seem to have a vast influence on gut health. The gut microbiome composition can be affected by the inclusion of RSM, although most effects seem to be related to fermentation of RSM. It remains unclear if also gut microbiome functioning is affected due to the (fermented) RSM. The inclusion of RSM seems to positively influence the gut histology, resulting in increased villi height and crypt depths. Lastly, some indications on systemic health and clinical effects on diarrhoea incidence were found, however this is based on very few studies.

3.3.2 Inclusion of insects

a) Background

As mentioned in paragraph 2.2.3.1, insects are considered as a promising protein source in animal feed that may contribute to sustainability of animal production. Insects can convert organic biomass into high-quality protein. Furthermore, insects can be grown on waste streams and thus are not competing with arable land. The main idea is to replace ingredients that deliver protein such as soybean meal or fishmeal with insects. The last decades, legislation prohibited the use of insect based protein meal because of the general ban on the use of animal protein as feed material to minimise the risk of infectious (zoonotic) diseases. However, in anticipation on allowance in the future, research in the field of using insects for pig feed was conducted. Since 2022, EU legislation allows using insect based protein meal as a feedstuff for pigs and poultry, provided that these are fed with GMP+ certified feed. Veldkamp and Vernooij (2021) and Lu et al. (2022) found that limited literature is available on possible beneficial effects of insect products as feed ingredient on gut and systemic health of livestock animals. According to these authors, the presence of chitin, lauric acid and antimicrobial peptides in insects as potential functional constituents may have positive effects on intestinal health.

b) Potential risks

As mentioned earlier, performance of the pigs might be influenced by changes in the nutrient composition when insects are included in the diet. Furthermore, the insect species and life stage at harvest are important, as well as the processing technique from insect or larvae to feed ingredient. A possible risk in using insects as a feedstuff, could be high levels of chitin. Chitin is a polysaccharide with a structure similar to cellulose. It is however hypothesized that chitin could have beneficial effects on health parameters. Moreover, insects are rich in fat, especially the medium-chain fatty acid lauric acid. Medium-chain fatty acids are known for antimicrobial effects on the gut microbiome, while lauric acid is particularly active against Gram positive bacteria (Spranghers et al., 2018). Furthermore, the source of food used in the insect production is important as well. It is hypothesized that (pathogenic/toxic) contaminants from the food source could accumulate in the insects itself. However, current research is focussing on the digestibility and possible accumulations from food sources to test this hypothesis. The black soldier fly larvae (*Hermetia illucens;* BSF larvae) appear to be the most widely used in research, while the yellow mealworm (*Tenebrio molitor*; TM), housefly and other species have been studied as well. The effects of inclusion of insect products in pig diets on health parameters was reviewed by Veldkamp and Vernooij (2021).

The main message from the review indicates there are little to no effects on health parameters when BSF larvae or TM are used in pig diets (Veldkamp and Vernooij, 2021).

c) Gut microbiome

Some recent studies focussed on the effects of insects on the gut microbiome, and possible prebiotic function. Biasato et al. (2019) found effects from 2% inclusion of BSF larvae meal onwards at specific ileal and caecal bacterial populations and metabolic profiles, and on the expression of mucosal immune genes. The authors suggested a prebiotic effect, due to chitin levels. In a following study, BSF larvae meal utilisation positively influenced caecal microbiota and small intestine mucin dynamics of weaned piglets (Biasato et al., 2020).
Investigating deeper into the mechanisms of the potential health effects of the BSF larvae, Kar et al. (2021) replaced SBM with BSF larvae as single source of dietary protein. Compared to the control diet, the inclusion of BSF supported the modulate of the intestinal microbiome. The authors reported an increase of *Bifidobacterium* in the ileum, a genus known for positive health effects by e.g. probiotic functioning. The genera *Corynebacterium 1, Globicatella,* Oceanobacillus, and *Bacillus* were also increased in the small intestine. Furthermore, a decrease in *Streptococcus* was observed*,* together with an abundance of *Corynebacterium* and *Globicatella*, indicating an antimicrobial function of the diets with BSF larvae. These results indicate a possible effect on gut health. Furthermore, the authors found alpha-aminobutyric acid and taurine in the blood plasma, which are known to induce health beneficial effects.
Another study focussed on the effect of 4% or 8% BSF larvae as a dietary protein source in finishing pigs on colonic microbiota and bacterial metabolite production (Biasato et al., 2020). The authors reported an increase in abundance of *Lactobacillus, Pseudobutyrivibrio, Roseburia,* and *Faecalibacterium,* and a decrease in abundance of *Streptococcus* when 4% BSF larvae was included. Furthermore, also the number of *Lactobacillus, Roseburia,* and *Clostridium* were higher when 4% BSF larvae was included in the diet. Meanwhile, 8% BSF larvae inclusion increased the number of *Clostridium.* Furthermore, analyses of the colonic metabolites showed an increase in total short chain fatty acids, butyrate and isobutyrate concentrations when 4% BSF larvae was included in the diet, whereas only an increase in butyrate concentrations was found when 8% BSF larvae was included. products. Accordingly the diet inclusion of 2 or 4% BSF larval meal (in replacement of fishmeal) by Yu et al. (2020), increased the number of *Lactobacillus* and *Bifidobacterium* in the ileum and cecum, and decreased the number of *Escherichia coli* in weaned piglets.

d) Gut morphometry

Only a few studies focussed on the effects of insect inclusion on gut morphometry. Yu et al. (2019a) found an increase in small intestine relative weight and villus height in weaned piglets fed with 4% or 2% BSF larvae; indicating a promoting effect on gut development. Jin et al. (2021) induced weaned piglets with oral gavage of enterotoxigenic *E. coli* K88 and tested 2 inclusion levels of BSF larvae powder. When 4% or 8% BSF larvae was supplemented, less diarrhoea was observed, the integrity of ileum villi was improved. Furthermore, the expression of IL-10, Occludin and Claudin-3 in the intestinal mucosa were increased and the expression of *TNF-α* was decreased; all indicating on an improved immune performance. In contrast, Håkenåsen et al. (2021) found no effects on gut functioning or gut health, feeding different inclusion levels BSF larvae meal up to 19% in post-weaning diets. Spranghers et al. (2018) fed different inclusion levels of full-fat BSF larvae and defatted BSF larvae to weaned piglets. The full-fat BSF diets resulted in higher lauric acid concentrations, however, no effects were found on jejunum morphometry or microbiome composition.

e) Immune system

The study performed by Kar et al. (2021), in which 4% and 8% BSF larvae was included in diets of finishing pigs, showed effects on the intestinal immunity of the pig. Especially in the 4% diet, the authors reported down-regulated mRNA expression of *TLR4* and pro-inflammatory cytokines *IFN-γ,* while upregulating the expression of anti-inflammatory *IL-10* in the colonic mucosa. On the other hand, Crosbie et al. (2021) fed BSF larvae meal up to 50% replacement of the protein sources, without any effects on performance or immune response (immunoglobulins in blood plasma) or gut morphology. Then again, (Yu et al., 2019b) found higher neutrophil counts at high inclusion levels of BSF larvae (14.5% and 18.5%) and lower platelet counts (9%, 14.5% and 18.5%). The authors did not find any differences in red or white blood cell indices or other haematological parameters.

Nursing pigs fed with 3.5% BSF larvae inclusion showed an increase in haemoglobin concentration and higher haematocrit value, indicating possible immunological stress (Driemeyer, 2016). The studies focussing on weaned piglets also showed small or no effects on health parameters. The different studies used BSF larvae products ranging from 1 to 10% inclusion such as: oil, meal or the whole larvae; but also 1.5 – 10% inclusion of TM larvae. Meyer et al. (2020) found relative higher blood plasma concentrations of Ala, Asp, Glu, Pro, Ser, Tyr and Val, but a lower concentration of Asn with 10% inclusion, without providing a clear possible clear explanation for this observation as plasma levels of amino acids are highly regulated. Furthermore, plasma methionine sulfoxide was higher at 5 and 10% inclusion. Jin et al. (2016) fed different inclusion levels of TM and found a linear decrease in blood urea nitrogen and a linear increase in insulin-like growth factor. Another study found no effects on oxidative stress or activation of oxidative stress-sensitive signalling pathways in metabolic tissue of weaned piglets when fed with 5 or 10% TM; indicating TM as a safe protein source for pig diets (Ringseis et al., 2021). Biasato et al. (2019) included partially defatted BSF larvae at different inclusion levels. The only observed difference were the counts of monocytes and neutrophils with increasing levels of BSF larvae inclusion. No physical distress or inflammatory diseases were shown by the piglets. When BSF larvae oil was included in the diet, the cholesterol increased linearly with the inclusion level (Heugten et al., 2019).

f) Bioactive compounds

The bioactive properties of insect products may be categorized in three categories: antimicrobial peptides, fatty acids, and polysaccharides. Reviewed by Veldkamp et al. (2022b), those bioactive compounds demonstrate antimicrobial activities via different mechanisms. These mechanisms are membrane pore formation or destruction, impeding intracellular processes or pH, and supporting the immune system of the host. The review further mentioned the possible antioxidant capacity of insect-proteins to protect against oxidative tissue damage.

g) Effects on pig welfare

Besides possible health effects, live insects are considered as promising environmental enrichment for pigs. Ipema et al. (2021b) tested the interest of weaned pigs in live BSF larvae and the possibility to let the BSF larvae serve as environmental enrichment. They showed that pigs are willing to work for access to BSF larvae by rooting and pushing tubes. Furthermore, less oral manipulation of the pigs on pen mates was observed. This enhances natural behaviour and shows the suitability of using BSF larvae as enrichment material. In another study, Ipema et al. (2021a) tested the effect of live BSF larvae on behaviour directly after weaning. Piglets that were provided with BSF larvae scattered throughout the pen, showed more favourable behaviour such as floor-directed exploration and less unfavourable behaviour such as object-directed exploration, fighting and pig-directed oral manipulation as compared to piglets provided with wood shavings scattered throughout the pen. Interestingly, feed intake also decreased when BSF larvae were provided, however they did not find any differences in performance. Due to their earlier findings, Ipema et al. (2022) assessed the suitability of BSF larvae on weaning stress by increasing pre-weaning feed intake of the insects. The provision of larvae pre-weaning did not influence pre-weaning feed intake or post-weaning performance. However, they did find positive affect on the piglet behaviour post-weaning.

h) Conclusions

In conclusion, insects could potentially be an attractive ingredient in circular diets. Although legislation and production are currently limiting, both nutritional and functional properties of insects can be beneficial in a pig diet. The functional properties for gut health are limited. However, small suggested positive effects have been found on the gut microbiome and local immune system in gut tissue. The effect on welfare seems most promising when insects are provided intact and alive. While this might increase activity, it may be unpractical and expensive as compared to mixing intact insects or ingredients derived from insects into the diet. Studies on welfare and behaviour with insect inclusion in the diet are lacking. The number of studies that have been and are still being carried out on insects, shows the potential of insects as feed ingredient, although this needs further proof.

3.3.3 Inclusion of aquatic ingredients

Using aquatic sources in monogastric diets, could improve the sustainability of animal production systems. Aquatic sources are produced on surface water, ponds or other water sources and therefore do not compete for arable land. These aquatic sources can have a high protein content (as described in chapter 2.2.2), possibly replacing feedstuffs such as soybean meal in pig diets. The main aquatic sources of interest are the microalgae and the macroalgae. Microalgae are unicellular microorganisms with a wide genetic heterogeneity and with numerous varieties (Chaves, 2021). Due to this wide range in varieties, the composition of the microalgae varies significantly depending on species, production methodology and production circumstances. Macroalgae, or seaweeds, are macroscopic, multicellular aquatic plants that naturally grow in the littoral zone. This group comprises thousands of different species, varying in shape and composition (Makkar et al., 2016). Both micro- and macroalgae are considered interesting feedstuffs or supplements to pig diets due to their potential bioactive properties possibly affecting health characteristics.

3.3.3.1 Use of macroalgae

a) Background

Macroalgae or seaweeds occur in numerous varieties and with just as many properties. Seaweeds are highly variable in composition depending on the species, cultivation habitat, time of collection and external conditions such as water temperature, light concentration, and nutrients in the water. As indicated in paragraph 2.2.3.2, the seaweeds can roughly be divided into brown algae, red algae, and green algae, of which brown algae are studied the most. As reviewed by (Makkar et al., 2016), seaweeds contain small amounts of lipids, and most of those lipids are polyunsaturated n-3 and n-6 fatty acids. Furthermore, seaweeds can be protein-rich, however this protein could be an over-estimation due to the presence of a substantial concentration of non-protein nitrogen. Seaweeds may contain a broad range of bioactive compounds with prebiotic, antimicrobial, antioxidant, anti-inflammatory or immunomodulatory properties; e.g., phenolic compounds, carotenoids, tocopherols, polysaccharides, and peptides (Canibe et al., 2022). Next to possible bioactive compounds, seaweeds may potentially accumulate heavy metals (e.g. arsenic), iodine and other minerals which could compromise animal health when included in the diet. Feeding seaweeds in low amounts (1-2%) might aid potential benefits for pig health as suggested by (Makkar et al., 2016). Seaweeds could be included as a whole crop (dried), but also extracts of seaweed may be used to supplement pig diets. Compounds derived from seaweed such as laminarin and fucoidan are of special interest. They are water-soluble polysaccharides derived from brown algae. It is hypothesized that both compounds escape hydrolysis in the small intestine and are fermented in the colon by the microbiome, where it promotes growth of beneficial gut microbiota such as *Lactobacillus* and production of short chain fatty acids (Canibe et al., 2022).

b) Gut microbiome

Both seaweeds and seaweed extracts have been shown to have prebiotic effects and immune enhancing functions in pigs. Therefore, the inclusion of these products could potentially lower or replace antimicrobial use in pigs. A recent and extended review by Canibe et al. (2022) investigated the effects on postweaning diarrhoea in piglets from supplementation or inclusion of laminarin, fucoidan, their interaction, intact macroalgae and polysaccharides derived from green seaweeds. Laminarin is the main carbohydrate storage in brown algae. It can be supplemented directly to piglets, but also to sows during the gestation and lactation period to influence piglet health around weaning. The review showed that laminarin is associated with prebiotic and antimicrobial activities by altering the gut microbial composition and microbial fermentation, the intestinal morphology and barrier function, and immunomodulation. Fucoidan is a fucose-rich sulphated polysaccharide which is extracted from the cell wall of brown algae, mostly supplemented in the piglet diet. According to the review, the bioactive properties are antimicrobial, immunomodulatory, antioxidant and antiviral. Including both laminarin and fucoidan has shown positive effects in post-weaning diarrhoea of piglets when it is supplemented maternally or directly to the piglets post weaning. According to the review, the effect is less prominent than when solely laminarin or fucoidan is supplemented, which suggests different modes of action. The polysaccharides derived from green algae look promising on affecting post-weaning diarrhoea, however there is little information available, and more research is required.

Lastly, the review described that effects of intact seaweeds on postweaning diarrhoea were less promising than isolating the specific bioactive compounds.
A study by Bouwhuis et al. (2017a) focussed on weaned piglets, which were fed a diet supplemented with seaweed-derived polysaccharides and/or galacto-oligosaccharides after a *Salmonella Typhimurium* challenge. The supplementation with the seaweed-derived polysaccharides reduced both faecal and intestinal *S. Typhimurium* numbers. The galacto-oligosaccharides supplementation increased the *Lactobacillus* numbers in caecal and colonic digesta but had no effect on the *S. Typhimurium* numbers. Both supplementations reduced the gene expression of pro-inflammatory cytokines in colonic tissue after the challenge. Another study performed by the same authors tested laminarin, derived from seaweed supplemented to sows and/or piglets postweaning after an experimental challenge with *S. Typhimurium* (Bouwhuis et al., 2017b). Maternal supplementation resulted in a reduced faecal shedding of S. Typhimurium and reduced the faecal scores of pigs after the challenge. Furthermore, the maternal supplementation also resulted in an improved performance and increased VFA-production and Lactobacillus numbers in the colon.

c) Gut morphometry

Not many studies included the effects of macroalgae on the intestine morphometry. Bouwhuis et al. (2016) studied the effect on gut health parameters by supplementing the sow during lactation and/or the piglet postweaning with a seaweed extract after which the piglets were confronted with an enterotoxigenic *E. coli* challenge. These authors found that the postweaning seaweed extract supplementation reduced crypt depth, improved the villous height : crypt depth ratio and reduced the log gene copy numbers of the challenge associated enterotoxins in both caecal and colonic digesta. Furthermore, the authors also reported a reduced log gene copy numbers of enterotoxigenic *E. coli* in caecal and colonic digesta of the piglets, when seaweed extract was supplemented to both the sow and piglet. The authors suggested that seaweed extracts could affect abundance of enterotoxigenic *E. coli* in the hindgut, resulting in a positive influence on gut health.

d) Immune system

In their review, Makkar et al. (2016) also suggested that both seaweed products and intact seaweeds appear to influence pig health. Laminarin and fucoidan extracted from *Laminaria* species were found to improve piglet performance, in which laminarin was found as the main source for gut health and performance improvements. Intact, but unidentified seaweed fed for four days to pigs (0.8% inclusion) increased the IgA production in saliva and immune function (Katayama et al., 2011). Furthermore, an 1% inclusion of seaweed meal in piglet diets reduced the *E. coli* load in both stomach and small intestine and thus increased the *Lactobacilli/E. coli* ratio in the small intestine (Dierick et al., 2009). This indicates a greater resistance to intestinal disorders. Another study by the same authors did not find any differences in performance or gut health, due to low inclusion rates or the presence of a counteract to the prebiotic effects (Michiels et al., 2012).
The health promoting effects of seaweed have been researched in immunological studies. Bahar et al. (2012) studied the immunomodulating effects of two brown seaweed extracts in the colon using a bacterial lipopolysaccharide (LPS) *ex vivo* model. The authors tested the extracts on part of the pig colon that was stripped of its overlying muscle layer. They found that the pro-inflammatory response induced by the LPS was supressed by the extracts, by measuring a reduction in expression of IL-8, IL-6 an TNFA genes.

3.3.3.2 Use of microalgae

a) Background

The most studied microalgae in pig nutrition are *Chlorella vulgaris* and Spirulina. There are, however, numerous other microalgae species with different characteristics and functionalities. Furthermore, the cultivation circumstances, the moment of harvest and the preservation all have an influence on the composition of the end product (See 2.2.3.2). Microalgae are often dried for preservation; In addition, a fermentation step is also possible, which might improve flavour and enrichment (Yan et al., 2012). In general, microalgae are suggested to potentially affect health via several routes: immunomodulatory, antibiotic, prebiotic and clinical. Microalgae can be used in defatted or full-fat biomass form. As reviewed and studied in pilots by Gatrell et al. (2014), inclusion of microalgae does not seem to influence toxicity or clinical health status of pigs.

Microalgae contain high levels of essential omega-3 polyunsaturated fatty acids (n3-PUFA) such as docosahexaenoic acid (DHA) and eicosapentaenoic acid (EPA), which are well-known for their immune-modulating and anti-inflammatory properties, as reviewed by Lee et al. (2019a). It is hypothesized that these omega-3 fatty acids could support pigs combat all kind of health problems, such as decreased immunity, bacterial infections, and weaning diarrhoea.

b) Gut microbiome

The inclusion or supplementation of microalgae to the diet could have antimicrobial effects. Furbeyre et al. (2017) supplemented weaned piglet diets with 1% Spirulina or 1% Chlorella and studied the antimicrobial function. In their first trial focus was on performance and incidence of diarrhoea. The authors reported that diarrhoea incidence was reduced in pigs that received the Chlorella supplementation.
Microalgae can also have possible prebiotic properties. By promoting the intestinal health of the pig, i.e. by affecting the gut microbiome, the use of antimicrobial products could potentially be decreased. To explore the mode of action, Martins et al. (2022b) evaluated the impact of 5% Chlorella inclusion in diets supplemented or not with two exogenous carbohydrase mixtures on gut morphology, fermentation, and microbiota of weaned piglets. The authors reported that dietary inclusion of 5% Chlorella improved piglet gut health without impairing performance. The microalgae inclusion promoted compensatory development of gut mucosa and prebiotic effects. The viscosity of duodenum plus jejunum content was slightly increased compared to the control groups. Furthermore, the dietary microalga increased duodenum villus height and promoted a healthier gut microbiome with a higher abundance of *Colidextribacter, Oscillospira* and *Lactobacillus*. In a different study by the same authors, weaned piglets were fed with diets in which 10% Spirulina was included, with or without 0.01% lysozyme supplementation to aid further cell wall degradation (Martins et al., 2022a). The study aimed to assess the effect on intestinal function by combining proteomics, metabolomics, and histological studies. The incorporation of Spirulina and supplementation of lysozyme in this study was associated to intestinal proteomic changes. An increased protein synthesis was found, as well as an abundance of contractile apparatus proteins, related with increased nutrient availability. No differences were found between groups for the histology and metabolomics analysis. In another study, fermented Chlorella was supplemented to the diet of growing pigs (Yan et al., 2012). While the authors did not find any effect on performance, the faecal concentrations were higher in *lactobacillus* and lower in *E. coli* in pigs fed diets with Chlorella supplementation. The authors explain this shift in gut microbiome as a potential antimicrobial effect due to the development of less unwanted microbes and increase of beneficial microbes.

c) Gut morphology

A second trial within the same study by Furbeyre et al. (2017), supplementing weaned piglet diets with 1% Spirulina or 1% Chlorella, focussed on the determination of inflammatory status and intestinal morphology. In this second trial the authors showed greater villus height at the jejunum in pigs that received one of the two supplemented diets. In a following study by Furbeyre et al. (2018), Spirulina and Chlorella was orally administrated (385 mg/kg BW) to piglets for four weeks starting 14 days before weaning. The aim was to test the influence of the microalgae on gut morphology and functionality. The authors reported that the diarrhoea incidence was reduced by 50% between day 0 and 14 after weaning when Spirulina was administrated. Only little effect was found on gut morphology. Mucosal architecture was unaffected by the microalgae, while shorter ileal villi were measured in both microalgae groups. Furthermore, at 14 days post weaning, the IL-8 expression in the ileum was higher in piglets administrated with Spirulina, while IL-1β expression in the jejunum was higher in piglets that received Chlorella. The lack of effect on gut morphology was in agreement with by the results of Urriola et al. (2018), who fed different levels (1 – 20%) of a de-oiled microalgae extract replacing primarily corn, to weaned piglets. Although the gut morphology was unaffected, mortality tended to be lower in pigs fed diets with de-oiled microalgae and less medical treatments were required for individual pigs. The authors suggested there were health promoting effects which might be due to changes in the gut microbiome.

d) Immune system

The freshwater algae *C. vulgaris* has been recognized for having hypocholesterolamic, hepatoprotective, immunomodulatory and autoinflammatory properties (Abdelnour et al., 2019; Latif et al., 2021).

In finishing pigs, Coelho et al. (2022) studied the effects of 5% *C. vulgaris* incorporation in the diet on pig health and hepatic lipid metabolism using haematology characteristics, plasma metabolites, hepatic markers, and immunoglobulins as response parameters. The authors reported several effects on blood parameters of pigs fed with diets incorporating the microalgae. The microalgae showed an immunosuppressive effect, which could increase the pig susceptibility to infective diseases. Inclusion of *C. vulgaris* in the diet decreased the concentration of immunoglobulins IgA and IgG, the number of white blood cells, the percentage of lymphocytes, and the concentration of haemoglobin while it enhanced the percentage of granulocytes, and number of thrombocytes.
Bacterial infections within the sow during gestation, could alter immunological programming of the foetuses. Therefore, Lee et al. (2019b) performed a study to determine the effect of supplementing gestating sow diets with 3.1% microalgae and inducing an immune challenge in late gestation on piglet growth and immune responsiveness. They found increased PUFA levels in both sows and piglets, however the quality of the nursery diets seemed more affective for piglet health than maternal diet and the immune challenge.

3.3.3.3 Conclusions

The bioactive properties of both types of algae are promising to support pig health status. Both micro- and macroalgae contain similar properties which can be antimicrobial, prebiotic, and immunomodulatory. There are no studies performed on the effects on pig behaviour. It appears that microalgae can be supplemented as a whole, while for seaweeds it is more promising to extract the bioactive compounds. Laminarin seems to have most effects, and is best to use solely, not in combination with other compounds. It must be considered that the extraction requires resources and energy, which does not help to the more circular feed system.

3.3.4 Inclusion of grass products

a) Background

Grass or grass products, such as silage or clover, are considered roughages which have a dry matter content around 10-12% and are high in both protein and fibres. The protein, however, is locked within the cell walls, that are difficult to digest for non-ruminant species such as pigs. The pig is capable to partly digest forage fibres in the hindgut contributing to the energy supply via volatile fatty acids, but this does not contribute to the supply of amino acids (Andersson and Lindberg, 1997a, b).
Grass is an interesting crop within a circular food system approach, since it can be grown on land which is not suitable for other crops. It is possible to feed grass in several forms: whole crop fresh grass (long stems), ensiled, chopped, or (artificially) dried and processed within a diet. This may have a substantial influence on the potential effects on health and well-being of the pigs. As discussed in chapter 2.2.3, grass has nutritional potential and could be included in the diets with moderate loss in performance. Furthermore, grass is rich in undigestible fibres, which are known to positively influence satiety and potentially reduce the occurrence of detrimental behaviours such as ear and tail biting. Furthermore, roughages can support the microbiome in the gut and increase the motivation of the pig to explore and forage (Høøk Presto et al., 2009). Providing pigs with grass or grass products clover, could therefore have beneficial effects on pig welfare. Due to the high fibrous character, it can be compared to the provision of straw or other fibre-rich materials which are often used for bedding or enrichment. To reach these positive welfare effects, the grass needs to be provided whole or (coarsely) chopped to keep the fibres intact. This is opposite to the favourable form of provision from a nutritionally point of view, where grinding or processing is necessary to unlock the potential nutrients such as protein.

b) Behaviour

Not much studies have been performed on the influence of grass on pig health, welfare or behaviour. Furthermore, little information is given from performance or digestibility studies on possible effects of roughages on pig health and welfare. Presto Åkerfeldt et al. (2020) reported how provision of silage offered to pigs to express their natural foraging and exploratory behaviours. Pigs provided with intensively manipulated silage (20% DM inclusion) consumed more silage and spent more time on eating. Furthermore, the authors discussed that those pigs might be more satisfied for a longer time after feeding since less social interactions and less rooting was observed after feeding.

These results are in line with earlier findings by Presto et al. (2013), where growing/finishing pigs fed intact or chopped silage were more active compared to pigs fed with silage in pelleted diets or without silage. Furthermore, pigs fed intact silage had lower number of wounds from interactions with their pen-mates and tended to a lower response to social interactions. A study performed within an organic housing system studied behaviour of pigs provided with only the obligatory straw bedding or an additional roughage source in the form of grass clover or whole crop barley silage. The authors observed that pigs provided with additional grass silage rooted less in the straw bedding compared to pigs with no additional roughage source (Høøk Presto et al., 2009). The pigs provided with either additional roughage supply showed less aggressive behaviour in the lying area compared to the control group. There were no differences found in roughage intake between all groups. The results of this study indicate that an additional roughage provision in the form of grass silage could contribute to higher activity and less aggression in pigs. This is in contrast with another study in organic pigs with different types of roughages, where the grass/clover silage did not have any effect on rooting behaviour (Olsen et al., 2016).

c) Conclusion

From a welfare perspective grass and products, such as silage and clover, have a beneficial potential due to their fibrous character. The form in which the grass is provided is important for the effects and long structures seem most promising. Therefore, due to the form whole crop fresh grass and (chopped) silage have the highest potential. Using grass as a roughage has been linked to increases in rooting and exploratory behaviour, as well as a decrease in fighting and damages. However, not much research has been conducted in this area. The influences of roughage on health parameters are lacking.

3.3.5 Inclusion of processed animal proteins

a) Background

The inclusion of processed animal proteins, or bone and meat meal to pig diets is not new. However, due to EU legislation to protect public health against zoonotic diseases, using animal protein has been prohibited for decades. Only recently, using animal protein sources are allowed back into pig and poultry diets. To prevent cannibalism, it is only allowed to feed products of poultry origin to pigs and vice versa. Due to the ban on animal protein in pig diets, this field is quite new, and currently the number of published studies is low.

b) Health and welfare

The few available studies, focus primarily on the nutritional properties and digestibility rather than effects on health and welfare. In the previous century, the use of inadequately processed wasted food containing pig meat was the most likely cause of outbreaks of classical swine fever in the UK (Williams and Matthews, 1988) and the Netherlands (Elbers et al., 1999). The use of processed animal protein of poultry origin in the feed of porcine animals is re-authorised with strict requirements during the collection, transport and processing of those products, and regular sampling and analysis to be performed, in order to avoid any risk of cross-contamination and intra-species recycling (Commission Regulation EU 2021/1372). Therefore, it seems unlikely that present PAPs pose a risk of transmission of infectious diseases to pigs.
Early anecdotal evidence suggested that the use of animal by-products in pig diets might reduce the risk of unfavourable behaviour such as tail biting and cannibalism. This was not confirmed by registration of tail biting scores in studies in which PAPs replaced SBM in diets for weaned piglets (Davin et al., 2021) and growing pigs (Davin and Bikker, 2021) with undocked tails. The same hypothesis has been proposed in laying hens, where feather pecking and consequently cannibalism has been a behavioural problem for decades. A study performed by van Krimpen et al. (2011) tested the effect of animal versus vegetable protein on laying hen behaviour. The authors tested four different PAPs but did not find any effect of inclusion of PAPs on feather pecking behaviour or cannibalism.

c) Conclusion

The effect of inclusion of PAPs on health and welfare of pigs has rarely been studied, and therefore research questions remain. It seems that due to processing bioactive compounds are disappeared. The hypothesized effects on negative behaviour such as tail biting have not been confirmed yet.

4 Discussion and concluding remarks

The present report describes the effects of increasing the use of selected ingredients in pig diets to enhance the circularity of food production systems. The feed ingredients considered were selected according to two scenarios, the first related to the reduction of cereals grains in diets for pigs, the second related to the reduction or elimination of the use of protein sources from outside the EU, such as soybean meal. The effects were described from two perspectives. The first considered mainly the nutritional characteristics of selected ingredients and their effects as energy and protein sources in the diet on animal performance (feed intake, digestibility, average daily gain and feed conversion ratio). The second perspective considered the effects of inclusion of these ingredients on aspects of health and welfare of pigs.

This report based on published literature provided a large corpus of information. However, it appeared that the amount of results available on the effects of different feed materials at different inclusion levels on performance and aspects of health and welfare is highly variable depending on the category of feedstuffs considered. Some of these feed materials are very well known and also currently used in pig diets. However, there are more published experimental results for dry ingredients than for liquid by-products. This is a limitation of the search method applied in the present study which was based solely on available published scientific literature. Valuable additional information might be obtained via surveys or interviews with experts in pig feeding, especially in relation to the use of ingredients for liquid feeding of pigs.

Others ingredients are considered as novel protein sources which were only addressed in research on performance over the last decade (e.g. insects and aquatic protein sources). Generally, more quantitative information is available on the digestibility and nutritional value of the ingredients and their effects on growth performance than on (gut) health and welfare. Clearly, the latter information is less quantitative and very diverse in nature as it considers e.g. effects on the gut functionality, the gut microbiome, the local and systemic immune system, or specific organs. The relevance and application of results on health and welfare could be improved when trials are also performed under different environmental or challenge conditions as diet effects on animal health and welfare may be more variable than on the zootechnical performance. The latter makes it also difficult to derive straight conclusions on effects of different inclusion levels of circular feed ingredients on health and welfare of pigs under practical conditions.

In studies on the effects of the use of circular feed ingredients, it is important to consider how ingredients are included (i.e. at the expense of which ingredients in the reference diet) and whether the nutritional value of the ingredients have been properly determined or estimated. Part of the reviewed studies lack this fundamental prerequisite, making them less suitable for judging the effects of the inclusion of such ingredients in the diet on the growth performance. Also, in part of the studies feed ingredients were incompletely chemically or nutritionally characterised (e.g. with regard to the composition of the NSP fraction or levels of ANFs) which limits the application of results for using them in circular diets. Another limitation encountered related to the maximum inclusion level of the ingredient evaluated in the study. Frequently the highest inclusion level was below the level which could be of interest in more circular diets for future pig production, which could contain specific or total levels of particular feed ingredients substantially above currently used levels. A relevant point little addressed in research up to now are the possible (negative or maybe positive) interactions between the use of different circular feed ingredients simultaneously included in the diets. This includes for example diets with both alternative energy sources (as listed under scenario 1 in the present study), not being cereals, and alternative protein sources, not being soybean meal (e.g. as listed under scenario 2). In this scenario, voluntary feed intake as well as digestive capacity of the gut could be compromised. This is a topic which requires more attention in future research on feeding pigs in more circular production systems.

As conclusion, the most important constraints and opportunities for inclusion of circular ingredients in diets for pigs as observed in the present literature study are provided in Table 7. Effects are highly ingredient dependent and information for specific ingredients is far from complete.

The latter can be caused by the novelty of some of the ingredients, or the lack of urgency in the past to evaluate the effects of high inclusion levels of ingredients that are now considered of value for future more circular diets.

Table 7 *Summary of most important constraints and opportunities for inclusion of circular feed ingredients in diets for pigs.*

Ingredient	**Major constraint/opportunity, nutritional perspective**	**Major constraint/opportunity, Health and welfare perspective**
Cereal grain by-products	- High fibre contents (NSP and arabinoxylans) - (Enzyme) processing for improvement nutritional value / alleviating constraints	- Insoluble and fermentable fibre, gut health - Transgenerational effects of fibre - Prevention undesired behaviour
Potato peels and pulp	- High fibre - Few recent published data - Largely used	- Limited information [not included in present report]
Professional kitchen waste	- Highly variable composition	- Microbial stability - Presence of pathogens - Adverse (non-food) components
Rapeseed meal	- Fibre content - Origin of de-oiling plant - Processing and protein digestibility	- Glucosinolates - Small effects on gut health
Liquid diets	[not included in present report]	- Probiotic effects - Hygiene, development of undesired microbes in storage/distribution system
Faba beans	- Cultivar variation in nutritional value - No major constraints if nutritional value adequately considered - Limited options for processing	- No major effects described
Lupins	- Alkaloids, oligosaccharides, NSP - Feed intake for bitter varieties (high alkaloids) - Performance adequate if inclusion based on actual nutritional value	- Fermentable NSP, gut health
PAPs poultry	- No major constraints - Low digestibility feather meal - Potentially high Ca, P content	- Limited data - Bioactive compounds might be inactivated by processing
Insect protein	- Variable composition/origin - Limited data	- Potential functionality gut health - Accumulation of substrate components - Less injurious interactions, more rooting for intact and live insects
Algae	- Variable composition/origin - Limited data - Low digestibility of structural carbohydrates, e.g. marine sulphated polysaccharides	- Mineral accumulation - Short shelf live unless dried - Antimicrobial and prebiotic effects - Immunomodulatory effects - Bioactive compounds more profound in seaweeds
Grass products	- Low protein digestibility - Only suitable for low inclusion levels - Limited data	- Substrate for explorative behaviour

__Table 8__ Maximal inclusion levels of circular feed ingredients without negative impact on nutrient digestibility or performance in pigs.

Ingredient	Phase 1	Phase 2 piglets	Growing-Finishing Pigs	Other limits	References
Cereal grain by-products	- Wheat bran: 4%[a]	- Wheat middlings: 10-15%[c] - Millrun: 10-12.5%[d,e]	- Wheat bran: 15%[b]		- [a]Molist et al, 2011; [b]Sun et al, 2020 ; [c]De Jong et al, 2014 ; [d]Garcia et al, 2015e; [e]l'Anson et al, 2013.
Potato wet by-products			- Potato hash & pulp: 0%[a] - Fermented potato H & P: 5-20%[b,c] - Potato peels: 25%[d] - Wet by-products[#]: 35%[e]		- [a]Ncobela,et al, 2018 - [b]Li et al, 2011 ; [c]Thomas et al, 2018 - [d]Willequet et al, 1993 - [e]Scholten et al, 1987.
Professional kitchen waste			- Restaurant waste: 0%[a] // 60%[b] - Ecofeed: 12%[c] - Dried hotel residues: 8%[d]		- [a]Westendorf et al, 1998 ; [b]Myer et al, 1999 - [c]Takahashi et al, 2012 - [d]Giamouri et al, 2022.
Rapeseed meal	- RSM: 10-20%[a,b,c]	- RSM: 15-25%[a,c]	- RSM: 16-30%[c,d,e]	GLS: 2.2 µmol/g	- [a]Frandsen et al, 2018; [b]Sanjayan et al, 2014; [c]King et al, 2001 ; [d]Roth-Maier et al, 2004 ; [d]Royer and Quinsac, 2011.
Faba beans	- High tannins: 10%[a] - Low & medium tannins: 20%[a,b]	- Low & medium tannins: 20% [b,c]	- Low & medium tannins: 30-35%[c,d,e]	Tannins: <5-6 g/kg	- [a]Ivarsson and Neil, 2018; [b]Nyende et al, 2022; [c]Royer et al, 2010; [d]Smith et al, 2013; [e]White et al, 2015.
Lupins	- Blue L: 19-24%[a,b] - Yellow L.: 15%[b]	- Blue L: 15-20%[a,c] - Yellow L.: 16%[d] - White: L: 5%[c]	- Blue L: 20-25%[e,f] - Yellow L.: 20%[f]	Alkaloids <0.20 g/kg; NSP <200 g/kg	- [a]Sijmondsbergen et al, 2022. [b]Kim et al, 2008, 2012; [c]Cherrière et al, 2003; [d]Kasprowicz-Potocka et al, 2013; [e]Noblet et al, 1998; [f]Roth-Maier et al, 2004;
PAPs poultry	- High ash poultry meal: <5%[a] - Low-ash poultry meal: 5%[a] - Feather meal: <4%[a] - Blood meal: 4%[a]		- High ash poultry meal: 5%[b] - Low-ash poultry meal: 5%[b] - Feather meal: 4%[b]		- [a]Davin et al, 2021; [b]Davin and Bikker, 2021
Insect protein	- BSF larvae: 8-10%[a,b]	- BSF larvae: 8-10%[b] - TM meal: 5-6%[c,d]	- BSF larvae: 14-18%[e] - TM meal: 10%[f] - House fly larvae: 11%[g]		- [a$]Spranghers et al, 2018; [b$]Biasato et al, 2019$, [c$]Jin et al, 2016 ; [d$]Meyer et al, 2020 ; [e]Chia et al, 2021 ; [f]Yoo et al, 2019; [g]Fankwa et al, 2000.
Algae		- Macroalgae: no reference - Spirulina: 21%[a]	- Macroalgae: no reference - Spirulina: 13%[a,b]		- [a]Neumann et al, 2018; [b]Altmann et al, 2019.
Grass products		- protein concentrates from grass: no reference	- Alfalfa meal: G: 0%[a]// 7.5%[b]; F: 5%[a,b] // 15%[b] - Grass or alfalfa silage: 0%[d,e] - Red-clover/ryegrass bales: 5%[e £] - Alfalfa leaf meal: 0%[f,g]		- [a]Drique & Calvar, 2021; [b]Tacker & Haq, 2008; [c]Chen et al, 2014a; - [d]Bikker et al, 2014; [e]Drique et al, 2022. - [f]Renaudeau et al, 2020; [g]Calvar et al, 2020.

Abbreviations: RSM: rapeseed meal ; GLS: glucosinolates; NSP : non-starch polysaccharides ; BSF: Black Soldier fly, TM: Tenebrio molitor; G: Growing pigs; F: finishing pigs.

Within a row, results are referenced using letters.

#: including liquid starch, wey and peels (55% for finishers). $: quoted by Veldkamp and Vernooij (2021). £: red-clover and ryegrass wrapped in plastic bales was provided ad libitum to pigs 5% restricted.

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To explore the potential of nature to improve the quality of life

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