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REVIEW

PORK PRODUCTION SYSTEMS IN CHINA: A REVIEW OF THEIR DEVELOPMENT, CHALLENGES AND PROSPECTS IN GREEN PRODUCTION

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KEYWORDS

China, feed, pork production, sustainability

HIGHLIGHTS

- Large-scale industrial pork production enterprises are preferred in China in the future.
- Challenges to green pork production include emissions, feed shortage and residues.
- Potential solutions to green production include precise feeding and manure recycling.

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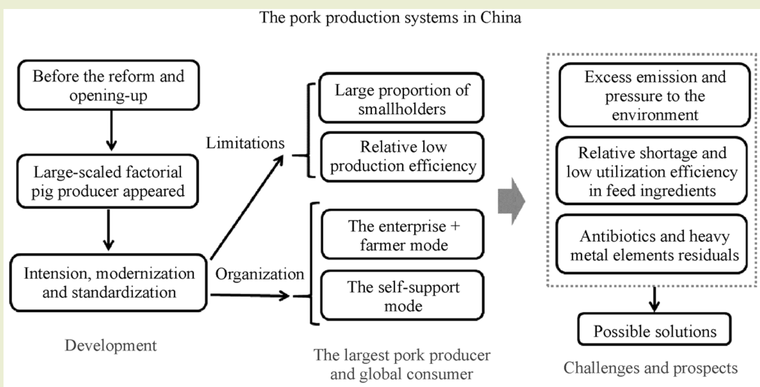
GRAPHICAL ABSTRACT



ABSTRACT

This paper reviews the changes in pork production in China, the largest pork producing and consuming nation in the world. The pork sector in China has changed dramatically since the 1990s, with large-scale intensive pork production systems replacing the former, exclusively family-based pork production systems. Modern breeding, feeding, vaccinating, and management technologies are widely used now. However, smallholders still account for a large proportion of the total production. The intensification and specialization of the pork sector is expected to continue in the future, but there is increasing awareness and pressure to develop more environmentally-sustainable production systems. The relative shortage of domestically produced feed, the low utilization efficiency of feed ingredients, the large emissions of nitrogen and phosphorus to the environment, the high use of antibiotics, and the presence of residual metals in manures are very large challenges for the pork sector nowadays. To solve these problems, techniques including new feed resource utilization, precise feeding, low-protein diets, alternatives to antibiotics and increased manure recycling are all important topics and research directions today. With new techniques and management approaches, it is possible to build more sustainable pork production systems in China.

1 OVERVIEW OF THE PORK PRODUCTION SECTOR IN CHINA

The pork production sector makes a vital contribution to the agricultural industry. With just over 18% of the global population, Chinese people consume nearly 50% of the total pork produced in the world (Fig. 1). The huge consumer demand for pork has greatly stimulated the pork production sector, especially in recent decades.

Swine slaughter exceeded 660 million head per year some ten years ago, equivalent to an annual pork production of > 50 Mt (Fig. 2)[2]. However, with the impact of African Swine Fever in 2019, both swine numbers and pork production declined dramatically, with annual swine slaughter falling to 540 million head, and annual pork production to 43 Mt[2]. In the first three quarters of 2020, this situation got even worse with the impact of COVID-19 with drops of 11.7% in swine stocks and 10.8% in pork production compared with 2019 (Fig. 2)[3]. Nevertheless, both the government and the industry have predicted a recovery of pork production after 2020, considering that pork consumption has continued to increase in recent years and has created substantial market potential. The per capita consumption of pork was about 20 kg in 2016 and nearly 23 kg in 2018, representing about 63% of the total meat consumption in China[4]. By 2029, total annual pork production is predicted to exceed 60 Mt[4].

Due to the rapid development of the pork production sector and poor management, incomplete regulation, and the spatial decoupling of crop and pork production systems, pork production has greatly increased environmental pollution, especially through the improper disposal of manures and slurries and waste of feed resources[5,6]. Annual pig manure production exceeded 60 Mt in 2017, while the comprehensive utilization rate of pig manure is > 50%[7]. The pork sector accounted for ~ 30% of total pollutants sourced from the animal husbandry industry, which is almost equivalent to the amount of pollutants originated from the whole industry[8]. The main regions of pig production are the southwestern and northern areas of China and south of the Huaihe River[9]. The top five provinces (Sichuan, Henan, Hunan, Shandong, and Yunnan) account for > 40% of the total pig manure production[9].

In 2018, the average feed conversion ratio of fattening pigs was approximately 2.6:1, with feed consumption exceeding 195 Mt (Fig. 2), among which the consumption of corn exceeded 110 Mt and that of soybean exceeded 50 Mt[2]. Crop residues were used as pig feed in the past but are now increasingly disregarded, and thereby contribute to environmental pollution and nutrient losses[6,10].

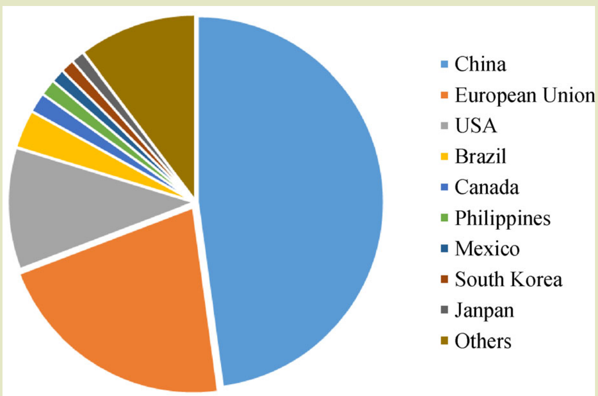


Fig. 1 Key pork producers in the world in 2018 (data sourced from FAO[1]).

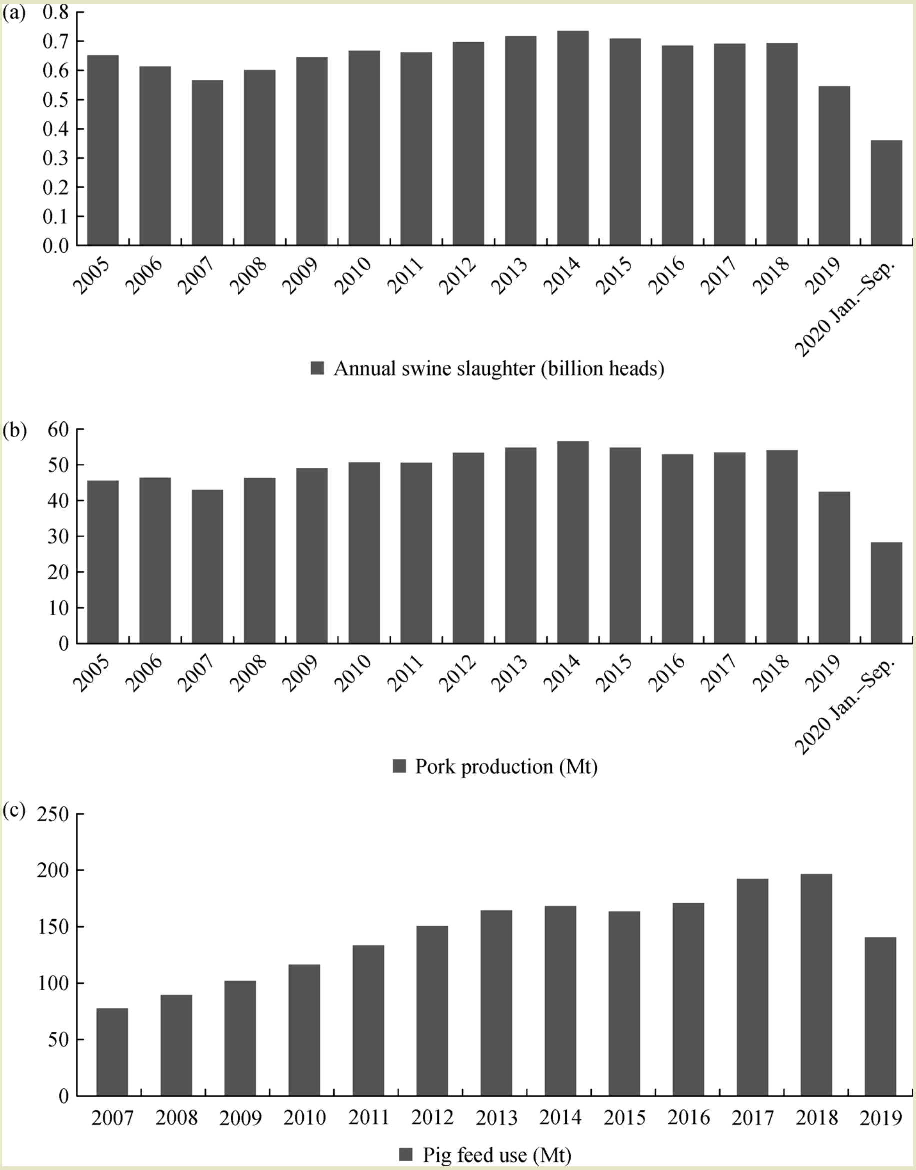


Fig. 2 Changes in annual swine slaughter (a) and pork production (b) in China over the last 15 years and annual pig feed use (c) over the last 13 years (data sourced from the National Bureau of Statistics[2]).

2 DEVELOPMENT OF THE PORK PRODUCTION SYSTEMS IN CHINA

The development of pork production systems is described below for three periods[11,12] (Fig. 3).

Before 1978, pork production was little developed and the pork supply was insufficient. The annual pork production nationwide was < 8 Mt, resulting in the pork supply to citizens being placed under a quota system with pork coupons as the certification for distribution. At that time, pork production relied on millions of families in the rural areas (smallholders, subsistence farming), with grass, roughage, and some wastes such as bran and dregs as the major feed. Major breeds were Yorkshire, Berkshire, and Soviet White. During this period, the urine and feces from pigs were re-used as fertilizers in crop production[13], indicating that the coupling of those two systems was common practice historically in China.

Large-scale factory pork production emerged after the reform

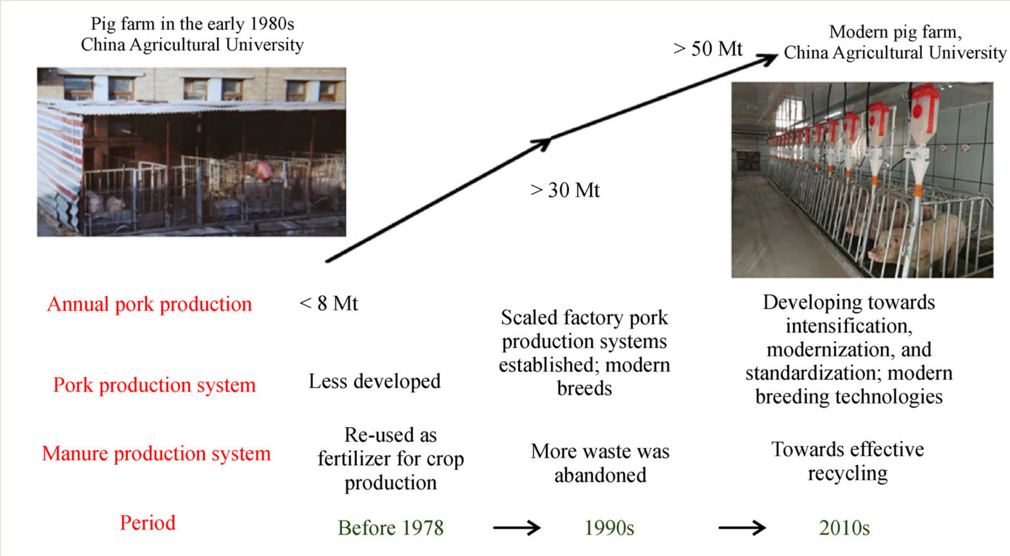


Fig. 3 Scheme of the development of the pork production systems in China.

and opening-up from the 1980s. Some pork producers in Guangdong Province started Sino-international joint venture companies, imported a complete set of equipment and technology from Europe and the USA, and initiated industrial pork production systems. With the implementation of the Urban Food Bases and the Vegetable Basket Project in the late 1980s, large-scale factory pork production systems were established in many cities and the development of the pork production sector was rapid. In 1997, national pork production reached 36 Mt, an increase of 58% compared to 1990, and the per capita consumption of pork reached 29 kg, which surpassed that in the USA[2,4]. In 1985, the first feeding standard for swine in China was issued and compound feed and premix and feed additives became widely used in swine diets. Meanwhile, more lean breeds such as Danish Landrace, British Yorkshire, and Duroc from the USA were imported. However, most producers contributed < 500 head of slaughtered swine annually during this period. During this period, cheap chemical fertilizers subsidized by the government became available to increase crop production, replacing pig manures and slurries[6]. The lack of sophisticated commercial technologies to transport and handle animal manures also contributed to the abandonment of the use of manures in crop production. Instead, manures and slurries were increasingly discharged and landfilled[6]. Hence, the modernization of the pig sector and the availability of cheap fertilizers have contributed to the decoupling between pig production and crop production.

With the expansion of large-scale pork production, the pork production sector was developing towards intensification, modernization, and standardization. Modern breeding technologies such as the use of molecular tools in breeding, and specialized feed products such as milk replacers, have been widely adopted to facilitate the development of pork production. However, a series of problems appeared in conjunction with factory pork production such as increased wastage of feed resources, rapid spread of infectious diseases, abuse of antibiotics, and food safety issues. In particular, environmental pollution caused by the neglect of pig manures and slurries has become a major threat to sustainable pig and crop production systems. At the same time, this has inspired the renewed exploration of manure treatment and recycling techniques[14]. Currently, anaerobic digestion is considered to be a main pathway for recycling manures and crop residues, with biogas, a renewable energy source, and digestates as major end products[6]. By the end of 2015, 42 million rural households used anaerobic digestion plants and 111 thousand large anaerobic digestion plants were subsidized by the government[6,15]. However, anaerobic digestion of pig slurries and crop residues is perceived as time- and labor-consuming, especially the emptying of the digesters and the subsequent handling and utilization of the biogas sludge (digestate). This holds especially for small-scale digesters and has resulted in many plants being abandoned by farmers[6,15]. From the practical and economic perspective, composting of the solid fraction (after liquid-solid separation of the pig slurries) is a more suitable approach to recycle the pig manure and crop residues at the farm and regional levels, with organic fertilizer as the major product.

Composting simultaneously reduces the mass and odor of the waste and eliminates most pathogenic microorganisms[16,17]. It was reported that in 2008, > 3000 composting factories were built to produce approximately 25 Mt of composted commercial organic fertilizers in China[13]. However, there is no ready and cost-effective and environmentally sound solution for the remaining liquid fraction.

In 2015, with the implementation of the new national environmental protection policy, the pork sector was placed under unprecedented restrictions. Many small and medium-sized producers left the sector and large-scale breeding enterprises expanded significantly (Fig. 4)[18]. By the end of 2017, the percentage of producers able to produce > 500 swine annually exceeded 45%[4]. The contribution of the top 10 mega pork producers accounted for 7.4% of production in 2017, whereas this proportion was 40% in the USA at that time[4]. In the list illustrating the top 15 global mega pork producers in 2020, there were five producers from China and they were in the top six (Table 1)[19]. The spread of African swine fever during 2018–2019 further impacted the structure of the pork production sector, with many small producers leaving the industry.

The way pig producers handle manures and slurries varies according to the scale of the farm. Taking Henan province as an example, 36.8% of small-sized producers (50–2000 head finished per annum) chose to directly discharge the slurries (liquid fraction) into the ditches outside the farm and re-use the manures (solid fraction) as fertilizers for crop production[20]. The percentage that have built anaerobic digestion plants and can handle the biogas sludge account for 18%. In contrast, 70% of the medium-scale (2000–5000 head) producers and large-scale (> 5000 head) producers use anaerobic digestion, mainly because of government incentives[20].

3 ORGANIZATION OF MODERN PORK PRODUCTION SYSTEMS IN CHINA

The structure and major components of modern pork production systems can be divided into the following parts: feed production, feed processing, sow production, nursery pig production, growing and finishing swine, abattoir operations, and manure and waste management (Fig. 5), and is the same for modern pork production systems all over the world[21–25].

Large-scale modern pork production systems in China can be divided into two categories: the enterprise plus farmer model and the self-support model[21] (Fig. 6). Also, with the encouragement of the government in recent years, pork production cooperatives have developed rapidly and a third kind of pork production model has emerged. Nowadays, the enterprise plus farmer model is most common; this model can rapidly facilitate an increase in the scale of production. In this contract-system model, farmers are responsible for the fattening process only, and the enterprise or the mega pork producer will provide the piglets, feed, and vaccines, as well as professional guidance. After the completion of fattening, the enterprise will collect the finished swine, undertake the marketing, and settle with the cooperating farmers according to the contract and market prices.

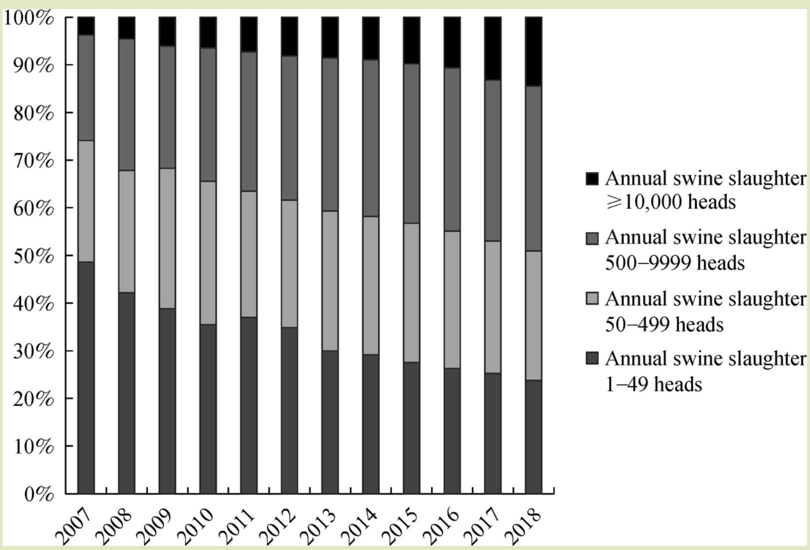


Fig. 4 Changes inpig producer scales in China from 2007–2018 (data sourced from Ministry of Agriculture and Rural Affairs of China[18]).

Table 1 Top 15 global mega pork producers in 2020 (data sourced from the National Hog Farmer[19])

Rank	Producer	Country	Sows owned in 2020 (1000 head)
1	Wens	China	1300
2	Muyuan	China	1283
3	Smithfield Foods	USA	1241
4	CP Foods	China	1150
5	New Hope Group	China	500
6	Zhengbang Group	China	500
7	Triumph Foods	USA	492
8	BRF	Brazil	389
9	Pipestone Veterinary Services	USA	385
10	Seaboard Foods	USA	345
11	COFCO Group	China	250
12	Cooperal	France	245
13	Iowa Select Farms	USA	243
14	Seara Foods	Brazil	213
15	Vall Company Group	Spain	213

Wens, the leading domestic pork producer (Table 1), established the enterprise plus farmer model and is one of the most successful enterprises in this sector. The other large Chinese pig producers taking this organization model include CP foods, New Hope Group, Zhengbang Group, and Twins Group. By comparison, the self-support model is a system in which enterprises are responsible for the entire process including inputs and marketing; Muyuan is a main example of this model. Other large pig producers in China such as COFCO Group also have this organization model.

The fact that small-scale (family-based) production is important in China is similar to Europe but different from North America and Brazil. Three periods may be distinguished in the development of pork production systems in the USA[21]. The first was between the 1970s and 1980s in which the sector experienced a sharp decrease in the number of producers. At the end of the 1970s there were nearly 650 thousand pork producers, 78% of which had < 100 head[21]. By 1989, the total number of producers had decreased to about 300 thousand, with numerous small-scale producers leaving the industry. The second period was in the 1990s during which large-scale farms with > 5000 head began to emerge and expanded rapidly. By 2000, the number of producers had further declined to 86 thousand, with more than 2000 farms able to annually produce more than 5000 slaughtered swine[21]. This could be attributed to the innovation and application of technologies in animal genetics, animal nutrition, feeding equipment, veterinary services, and organization and management of production systems. Professional fattening farms also appeared during this period which accounted for 80% of the total pork producers by 2004[21]. After entering the 21th century, pork production in the USA stepped into a new phase with the scaling process slowing and the swine population stabilizing. Nevertheless, the number of large-scale swine farms was still steadily rising, driven mainly by the integration of slaughter and processing enterprises. By 2010, the top four slaughter and processing companies run by

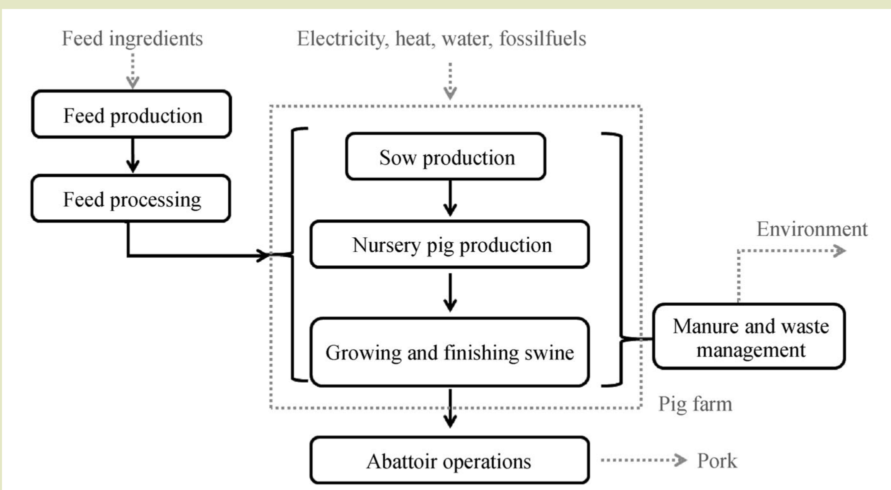


Fig. 5 Scheme of a modern pork production system illustrated through life-cycle analysis.

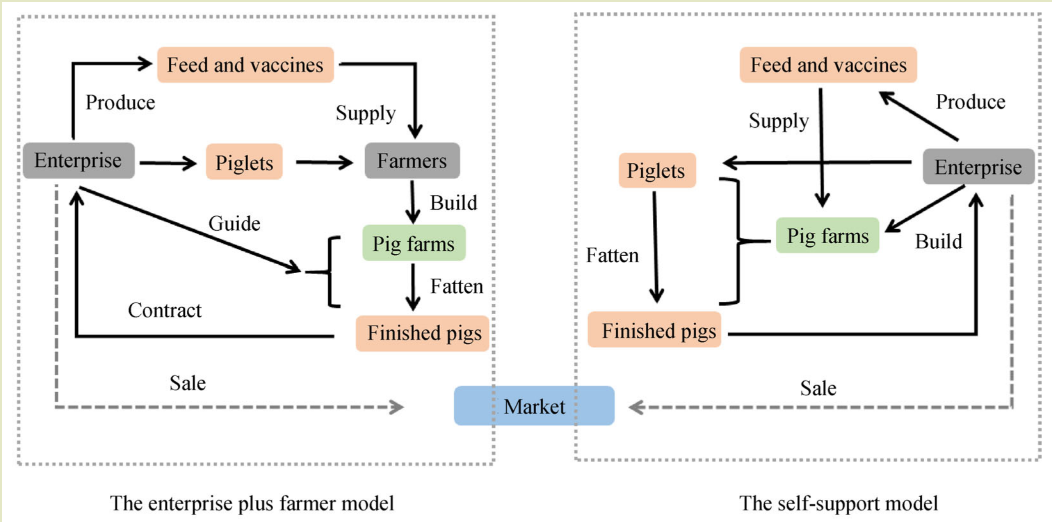


Fig. 6 Schemes of two main organization models of large-scale modern pork production systems in China, namely the enterprise plus farmer model and the self-support model.

Smithfield occupied nearly 70% of the pork slaughter and processing market[21]. This process is likely to continue in the future and the experience in the USA and some other countries will act as a valuable reference for China.

4 CHALLENGES AND PROSPECTS IN GREEN PORK PRODUCTION

As mentioned above, the number of smallholders (usually defined as producers with < 500 head of slaughtered swine annually) still account for half the total number of pork producers in China. These smallholders have a relatively high resource use and low production efficiency. This pattern of smallholders next to large-scale industrial pork production is expected to remain in the near future, leading to the necessity to overcome the consequent challenges and to develop an environmentally and resources-use friendly and more sustainable production system.

4.1 Need to reduce emissions and pressure on the environment

According to recent life-cycle assessment studies, feed production causes the majority of the environmental impacts in the pork production system, mainly due to the associated greenhouse gas emissions and non-renewable energy and resource use[26]. Manure management is associated with high acidification and eutrophication potentials as a result of the discharge of manure nitrogen and phosphorus to surface waters[26,27].

To alleviate the environmental pressure created by pork production, strategies such as increasing the inclusion of co-products in diets, low-protein diets combined with the use of synthetic amino acids, and application of dietary enzymes to promote the digestion of feed ingredients are all possible solutions[26,27]. Additionally, the development of a more circular agriculture through the integration of pork and crop production is an effective approach to handle the manure and waste created by swine; this can ultimately help to reduce the emissions and pressure to the environment created by pork production[28].

4.2 Relative shortage and low utilization efficiency of feed ingredients

The increasing global human population leads to a rising demand for food, including animal-sourced food. As a result, more studies are raising concerns about the conflict between the increasing amounts of crops (cereals and oilseeds in particular) used to feed livestock that could be used to feed people directly[29]. On average worldwide, about 1.2 m^3 of water is needed to produce 1 kg of grain used for animal feed, indicating that livestock fed compound diets indirectly consume large quantities of water[30]. In 2018, a total of 116 Mt of cereal and oilseed crops were imported, comprising 88 Mt soybean, 6.8 Mt barley, 3.7 Mt sorghum, 3.5 Mt maize, 3.1 Mt wheat, and 3.1 Mt rice, > 70% of which was used for animal feed[2]. This reflects the relative shortage of feed ingredients in China. Further, the average feed use efficiency in pork production and the average piglets born per sow per year are still 15% and 30%, respectively, lower in China than in Europe or North America[21].

To overcome the relative shortage of feed ingredients and increase the feed use efficiency in pork production, more studies focusing on exploiting alternative feed resources such as agricultural byproducts are needed[31]. Understanding the nutritive value and developing economic processing, such as biological fermentation, are important for alternative feed utilization. The development of precision nutrition in pork production is another important area of study in recent years, which could lead to increased feed use efficiency for current feed ingredients, and relieve the competition between humans and livestock for food resources, and also reduce the emissions to the environment[32]. The theoretical foundation to develop precision nutrition relies on accurate evaluation of the available nutrient value of feed ingredients and accurate determination of the nutrient requirements of swine at different stages of growth under different environmental conditions. With the implementation of smart equipment in pork production, for instance, the Internet of Things devices, including smart sensors for data collection and precision feeders for automatic management, precision nutrition is likely to be realized in the near future.

4.3 Antibiotics and metal residues

Antibiotics have been used in swine feed as a growth promoter, and copper and zinc have been added in high amounts especially to piglet diets to maintain intestinal health[33]. However, the adverse effects of the use of antibiotics and metals in pork production have raised serious concerns because antibiotics and metals in animal feed will enter the food chain and have direct impacts on agroecosystems and the environment[33]. Particularly, the abuse of antibiotics during livestock production can cause serious antibiotic residues in animals, which then flow into to humans along the food chain, resulting in risks of antibiotic resistance. Antibiotics as growth promoters were already banned in some European countries before 2010 (e.g., in the Netherlands in 2006) and in the USA using antibiotics as growth promoters was prohibited in 2017. In 2017, the Chinese Ministry of Agriculture and Rural Affairs has officially set an upper limit of zinc and copper use in feed additives and has officially banned the use of antibiotics as feed additives from July 1, 2020[4], making great progress on reducing the levels of antibiotics and metals used in livestock production.

As a result, there is an urgent need to find safe and effective alternatives to antibiotics and metals that will allow pork producers to remain competitive. Some potentially-effective alternative products are now being marketed including plant-sourced essential oils, Chinese herbal extracts, organic acids, probiotics, and antibacterial peptides[33–35].

4.4 Other challenges for sustainable pork production

Other challenges such as unstable pork price, infectious diseases, and sow reproductive diseases have always represented major threats to the development of pork production. Since 2018, African Swine Fever has dramatically reduced the swine population in China and in some other Asian and also European countries, directly leading to an increased retail price for pork. It seems that African Swine Fever cannot be alleviated and eliminated within a short time in affected countries[36]. Therefore, more action is needed to control the occurrence and spread of pathogens, for instance, strengthening monitoring and accelerating vaccine development and application. Moreover, the government should strengthen the guidance and training of pig producers, especially small-scale producers. Further, market intervention may be needed to stabilize pork production and reduce pork price fluctuations. To better control sow reproductive diseases such as Porcine Reproductive and Respiratory Syndrome, which can damage the productive performance of sows and cause great economic losses, approaches including antibiotic therapy, prophylaxis, and immunization programs should be taken into account[37].

5 CONCLUSIONS

Pork production has developed rapidly in China over the last 30 years. China has become the largest pork producer and consumer in the world. However, nearly 50% of the pork producers are smallholders with relatively low production efficiency leading to significant pressure on the environment through emissions of nutrients, antibiotic residues and copper and zinc. Therefore, China needs to develop environmentally-friendly and economically more sustainable production systems in which medium- and large-scale industrial pork production enterprises should be the preferred organization forms in the future. With these challenges, exploitation of alternative feed resources, precise feeding, low-protein diets, alternatives to antibiotics and increased manure recycling are all important topics and research areas. The target is to develop pork production systems which provide sustainable and healthy pork products to consumers.

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Compliance with ethics guidelines

Shuai Zhang, Xin Wu, Dandan Han, Yong Hou, Jianzhuang Tan, Sung Woo Kim, Defa Li, Yulong Yin, and Junjun Wang declare that they have no conflicts of interest or financial conflicts to disclose. This article does not contain any studies with human or animal subjects performed by any of the authors.

REFERENCES

1. Food and Agriculture Organization (FAO). FAOSTAT: livestock processed. Available at FAO website on August 1, 2020
2. National Bureau of Statistics of China (NBSC). Annual data: agriculture. Available at NBSC website on August 1, 2020
3. National Development and Reform Commission (NDRC). Routine press conference in October. Available at NDRC website on December 30, 2020
4. China Agriculture Outlook (CAO). China agriculture outlook report (2020–2029). Available at CAO website on January 19, 2021
5. Hou Y, Bai Z H, Lesschen J P, Staritsky I G, Sikirica N, Ma L, Velthof G L, Oenema O. Feed use and nitrogen excretion of livestock in EU-27. *Agriculture, Ecosystems & Environment*, 2016, **218**: 232–244
6. Jia W, Qin W, Zhang Q, Wang X, Ma Y, Chen Q. Evaluation of crop residues and manure production and their geographical distribution in China. *Journal of Cleaner Production,* 2018, **188**: 954–965
7. Ministry of Agriculture and Rural Affairs of the People's Republic of China (MARAC). National pig production and development plan (2016–2020). Available at MARAC website on January 19, 2021
8. Peng X Y. Study on biogas technology adoption behavior and green subsidy policy of livestock farming pollution prevention: evidence from specialized pig breeding households. Dissertation for the Doctoral Degree. Beijing: *Chinese Academy of Agricultural Sciences*, 2007 (in Chinese)
9. Wu S H, Liu H B, Huang H K, Lei Q L, Wang H Y, Zhai L M, Liu S, Zhang Y, Hu Y. Analysis on the amount and utilization of manure in livestock and poultry breeding in China. *Strategic Study of CAE,* 2018, **20**(5): 103–111 (in Chinese)
10. Wei S, Bai Z H, Qin W, Xia L J, Oenema O, Jiang R F, Ma L. Environmental, economic and social analysis of peri-urban pig production. *Journal of Cleaner Production,* 2016, **129**: 596–607
11. Pan Y C. Take the development path of pig industry with 'Chinese characteristics'. *Chinese Journal of Animal Science,* 2017, **53**(9): 165–168 (in Chinese)
12. Xiong Y Z. The development path of pig industry in China. *Today Animal Husbandry and Veterinary Medicine,* 2007, **11**: 1–4 (in Chinese)
13. Yang Y L, Zhang P D, Zhang W L, Tian Y S, Zheng Y H, Wang L S. Quantitative appraisal and potential analysis for primary biomass resources for energy utilization in China. *Renewable &* Sustainable Energy Reviews, 2010, **14**(9): 3050–3058
14. Westerman P W, Bicudo J R. Management considerations for organic waste use in agriculture. *Bioresource Technology,* 2005, **96**(2): 215–221
15. National Development and Reform Commission (NDRC) and Ministry of Agriculture and Rural Affairs of China. (MARAC). National rural biogas development planning in the 13th five-year. Available at NDRC website on January 19, 2021
16. Onwosi C O, Igbokwe V C, Odimba J N, Eke I E, Nwankwoala M O, Iroh I N, Ezeogu L I. Composting technology in waste stabilization: on the methods, challenges and future prospects. *Journal of Environmental Management,* 2017, **190**: 140–157
17. Bernal M P, Alburquerque J A, Moral R. Composting of animal manures and chemical criteria for compost maturity assessment. A review. *Bioresource Technology,* 2009, **100**(22): 5444–5453
18. China animal husbandry and veterinary yearbook 2007–2018. Beijing: *China Agriculture Press*, 2007–2018 (in Chinese)
19. National Hog Farmer (NHF). Top stories. Available at the NHF website on August 1, 2020
20. Chou H G, Chen F F, Wang Y N, Li Y F, Tang X Y, Yang C. Analysis of the cost of comprehensive use of pig manure and subsidy policy: take Henan Province as an example. Renmin University of China, Scool of Agricultural Economics and Rural Development, 2016. Available at the GREENPEACE website on December 30, 2020
21. Liu W T, Gu L W. A comparative study on pig industry between China and the United States. *Chinese Journal of Animal Science,* 2016, **52**(6): 3–7 (in Chinese)
22. Mackenzie S G, Leinonen I, Ferguson N, Kyriazakis I. Accounting for uncertainty in the quantification of the

environmental impacts of Canadian pig farming systems. *Journal of Animal Science,* 2015, **93**(6): 3130–3143
23. Ali B M, van Zanten H H E, Berentsen P, Bastiaansen J W M, Bikker P, Lansink A O. Environmental and economic impacts of using co-products in the diets of finishing pigs in Brazil. *Journal of Cleaner Production,* 2017, **162**: 247–259
24. Noya I, Villanueva-Rey P, González-García S, Fernandez M D, Rodriguez M R, Moreira M T. Life cycle assessment of pig production: a case study in Galicia. *Journal of Cleaner Production,* 2017, **142**: 4327–4338
25. Wang X L, Dadouma A, Chen Y Q, Sui P, Gao W S, Jia L H. Sustainability evaluation of the large-scale pig farming system in North China: an emergy analysis based on life cycle assessment. *Journal of Cleaner Production,* 2015, **102**: 144–164
26. Mackenzie S G, Leinonen I, Ferguson N, Kyriazakis I. Can the environmental impact of pig systems be reduced by utilising co-products as feed? *Journal of Cleaner Production,* 2016, **115**: 172–181
27. Mosnier E, van der Werf H M G, Boissy J, Dourmad J Y. Evaluation of the environmental implications of the incorporation of feed-use amino acids in the manufacturing of pig and broiler feeds using Life Cycle Assessment. *Animal,* 2011, **5**(12): 1972–1983
28. Bouwman L, Goldewijk K K, Van Der Hoek K W, Beusen A H W, Van Vuuren D P, Willems J, Rufino M C, Stehfest E. Exploring global changes in nitrogen and phosphorus cycles in agriculture induced by livestock production over the 1900–2050 period. *Proceedings of the National Academy of Sciences of the United States of America,* 2013, **110**(52): 20882–20887
29. Le Cotty T, Dorin B. A global foresight on food crop needs for livestock. *Animal,* 2012, **6**(9): 1528–1536
30. Faust D R, Kumar S, Archer D W, Hendrickson J R, Kronberg S L, Liebig M A. Integrated crop-livestock systems and water quality in the northern great plains: review of current practices and future research needs. *Journal of Environmental Quality,* 2018, **47**(1): 1–15
31. Tan B, Yin Y. Environmental sustainability analysis and nutritional strategies of animal production in China. *Annual Review of Animal Biosciences,* 2017, **5**(1): 171–184
32. Andretta I, Hauschild L, Kipper M, Pires P G S, Pomar C. Environmental impacts of precision feeding programs applied in pig production. *Animal,* 2018, **12**(9): 1990–1998
33. Wu Y, Zhao J, Xu C, Ma N, He T, Zhao J, Ma X, Thacker P A. Progress towards pig nutrition in the last 27 years. *Journal of the Science of Food and Agriculture,* 2020, **100**(14): 5102–5110
34. Wang S, Zeng X, Yang Q, Qiao S. Antimicrobial peptides as potential alternatives to antibiotics in food animal industry. *International Journal of Molecular Sciences,* 2016, **17**(5): 603
35. Liao S F, Nyachoti M. Using probiotics to improve swine gut health and nutrient utilization. *Animal Nutrition,* 2017, **3**(4): 331–343
36. Dixon L K, Sun H, Roberts H. African swine fever. *Antiviral Research,* 2019, **165**: 34–41
37. Pozzi P, Loris A. Reproductive diseases in sows (*Sus scrofa* domestica): a review. *Israel Journal of Veterinary Medicine,* 2012, **67**(1): 24–33