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Review

Main contributions of INIFAP research to swine nutrition in Mexico: challenges and perspectives

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Abstract:

This review is a retrospective of the research activities carried out in swine nutrition by INIFAP researchers during the 35 years of the Institute's existence. The main product of this activity was to lay the foundations for a better feeding of the breeding herd and pigs for slaughter, focusing on solving the particular problems of Mexican swine farming, with respect to the raw materials that are utilized in pig feeding, as well as the evaluation and improvement of the carcass quality, and the enrichment of meat with metabolites that increase its shelf life and improve its organoleptic properties. It also reflects on the challenges that swine nutrition will face in this century, proposing the areas that will have to be researched in order to guarantee the sustainability of the sector, and the actions that the program's researchers and INIFAP will have to take in order to adequately respond to the challenges faced by Mexican swine production.

Key words: Swine nutrition, Challenges, Contributions, INIFAP.

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Introduction

Research in swine nutrition is important, since this species is characterized by its high prolificacy, short production cycle and high feed efficiency ―characteristics that have made it the most consumed meat in the world, representing 36 % of the market[1], and the second at the national level, representing 26 % of the country's meat consumption[2]. In Mexico, livestock research began in 1947, with the creation of the Livestock Institute (Instituto Pecuario) under the Ministry of Agriculture and Livestock (Secretaría de Agricultura y Ganadería); in 1962, it became the National Livestock Research Center (Centro Nacional de Investigaciones Pecuarias, CNIP). In 1968, this became the National Institute of Livestock Research (Instituto Nacional de Investigaciones Pecuarias, INIP), which, in 1985, merged with the Institutes of Agricultural and Forestry Research, giving rise to the National Institute for Research on Forestry, Agriculture, and Livestock (Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias, INIFAP). The first four articles on swine nutrition appeared in 1966; were published in issue No. 7 of *Técnica Pecuaria en México* (Livestock Technology in Mexico), a journal created in 1963 by CNIP, which in 2010 was transformed into *Revista Mexicana de Ciencias Pecuarias* (Mexican Journal of Livestock Sciences). From that time to date, the Institute's staff has conducted research that responds to the needs of the national swine industry, either by generating the necessary technology for the use of raw materials in the different production phases or by studying the impact of the feed on the quality of the product, as well as the impact of feeding on reproductive efficiency and productivity of the breeding herd. Throughout this period, INIFAP's research has contributed to the development of the national swine industry and its value chain. This manuscript summarizes INIFAP's main contributions to swine nutrition and the medium and long-term challenges faced by research across the world and particularly in Mexico. For the selection of the material, it is considered what was generated from 1985 to date by INIFAP researchers, in both printed and digital material, giving preference to published scientific articles and, in the second place, to publications in theses and conferences. The information was organized into breeding herd and slaughter pig nutrition, from weaning to finishing, as well as carcass yield and meat quality.

Breeding herd

Litter size, the number of farrowings per sow per year and the number of pigs produced during the productive life of the sow are the parameters that establish the basis for the productivity and profitability of a pig farm. Scientific and technological advances in the disciplines of genetics, nutrition, reproduction, and animal health have made it possible to increase these variables over the last 35 yr.

Current situation

In most of the technified farms, 30 pigs per sow are expected to be weaned every year, and each sow is expected to produce more than 70 pigs for slaughter throughout her productive life. In the case of Denmark in particular, the total number of piglets weaned per litter increased from 9.9 in 1996 to 12.2 in 2009(3), while a more recent report mentions that the number of piglets weaned per litter for this country in 2017, was 14.6, which is equivalent to 33.3 piglets weaned per sow per year(4).

The statistical evaluation of swine production in Mexico is oriented toward the inventory of pigs, production by state, imports and exports, costs of inputs and raw materials, price of live pigs and primal cuts. The few herd productivity analysis data available in Mexico are isolated reports from farms where detailed records of herd performance are available. When analyzing data for first and second farrowing sows of four commercial farms, Ek-Mex *et al*(5) found variation in the number of piglets born alive per sow per year, ranging between 17.4 and 27.2 piglets. On the other hand, Pérez Casillas(6) presented data from four commercial farms where the average number of total piglets born was 14.96; piglets born alive 13.59, and piglets weaned 11.58 ―values similar to those reported by PigChamp in 2019, for U.S. farms.

Issues

Although the increase in reproductive efficiency has meant greater profitability for swine farms, it also represents new challenges, among which are the development of precision feed and feeding schemes that allow expressing the genetic potential in the different physiological stages, improving their permanence in the herd, and maintaining the sustainability of swine farms.

Inadequate nutrient intake can influence reproductive response in several ways; it may disrupt the ovulation process and delay the onset of puberty in gilts. Overfeeding during gestation causes excessive weight gain, interferes with normal mammary gland development, and has a negative impact on milk production and voluntary feed intake during lactation. The increase in litter size and, consequently, in the demand for milk production, results in a nutritional deficit for the lactating sow, which can lengthen the duration of the weaning-estrus interval, reduce the ovulatory rate and the quality of the oocytes released, as well as the development of the corpora luteae, during the first post-weaning estrus. This is likely to result in a reduction of the ability of the embryos to develop and survive, negatively impacting litter size at the subsequent parturition. These issues are a major cause of culling, particularly in gilts, because they make it difficult to maintain the integrity of farrowing groups in the farm and induce a reduction in the number of piglets produced annually per sow(7).

Pubertal sow feeding

The feeding of replacement sows during their growth influences the age at which they start their reproductive life (puberty) and the number of eggs released (ovulation rate) during the first estrous cycles, as well as the conformation of their bone, muscle and fat structure. According to research by INIFAP, the feeding of replacement sows should start at 75 kg/120 days of age, limiting daily weight gain to 700 g/d, for which energy intake should be restricted to 8 Mcal of ME/d, using a feed with 0.78 % of digestible lysine and a protein level of no more than 17 %(8).

Cyclic sow feeding

Nutrition influences the reproductive function of sows, particularly affecting the ovulation rate, but there is little information on the specific effect of an energy or protein deficit on embryo survival. Mejía-Guadarrama *et al*(9) reported that protein restriction in cycling nulliparous sows decreases plasma urea concentrations without affecting ovulation rate. Increased maternal muscle mass at delivery cushions the negative impact of moderate protein restriction on milk production[10]; however, when this restriction is severe, there are repercussions on reproduction[11-13].

Feeding of the pregnant sow

Globally, the competition between animal production and human beings for basic grains is worrisome; therefore, one of the lines of research that INIFAP has developed is the use of alternative ingredients and nutritional strategies that guarantee the provision of adequate nutrients to the pregnant sow, taking advantage of industry by-products and local inputs, both conventional and non-conventional. Dehydrated alfalfa and corn, sorghum or grass silage can be used as the complete ration for the pregnant sow; likewise, the substitution of 33.3 % of sorghum with cassava plant meal can be used as a complete ration[14] or the addition of 3 kg/d of cassava silage[15] improve sow weight gain during the last third of gestation, provided that they are fortified with vitamins, minerals and protein supplements[16-18], to ensure that, in the last third of gestation, the energy requirement will be met. Regarding the use of molasses as an energy source, Ángeles and Cuarón[19] report longer sow lifespan and improved productivity due to the use of ketogenic substrates.

By evaluating the addition of different sources and levels of soluble and insoluble fiber to the diet of pregnant sows, the fiber composition was shown to differentially affect energy digestibility and the dietary nitrogen levels[20]; therefore, it is important to know what type of fiber is being used. The 78 % of the variation in the digestibility of energy in a diet could be explained by the intake of soluble and insoluble fiber: AED= 88.74+0.083(SF)- 0.02(ISF); (P<0.01; R^2=0.78), where: AED is the apparent energy digestibility, SF is the soluble fiber intake in grams, and ISF is the insoluble fiber intake in grams. Rentería *et al*[20] proved that the inclusion of insoluble fiber decreased apparent energy digestibility by 0.2 % and apparent nitrogen digestibility by 0.1 % at an insoluble fiber intake of 250 g/d equivalent to 13.5 % insoluble fiber in the diet[21]. It was also shown that soluble fiber intake did not affect nitrogen digestibility, while energy digestibility was positively related to soluble fiber intake. This means that it is possible to include high levels of fiber in the diet of pregnant sows without compromising their productivity, provided that the influence of fiber on nutrient digestibility is considered in the formulation of the diet and in the calculation of the daily ration[22]. Besides, the inclusion of fiber in the diet of the pregnant sow helps to mitigate the impact of the dietary restriction to which she is subjected and improves feed intake in lactation.

Feeding of the lactating sow

In general, a decrease in energy intake during lactation does not affect milk production, which is maintained thanks to the mobilization of maternal body reserves[23]. However, if energy restriction is particularly severe (6.5 *vs* 16.5 Mcal ME/day), litter growth is reduced[24].

For the lactating sow, the amino acid intake is calculated according to the lysine intake, which is the first limiting amino acid. Protein intakes are expressed as the amount of crude protein or lysine provided in the feed. Litters of sows subjected to protein restriction during lactation (300-400 g of protein vs. 700-900 g/d), showed a reduction in their growth rate[25], especially from the third week of lactation onwards[26]. The decrease in litter growth rate is due to a reduction in the amount of milk produced, as well as to a low export of protein and lipids in the milk of rationed sows[27]. However, other authors[10] observed no significant effects of severe protein restriction (350 to 410 g protein *vs* 830 g/d) on litter growth and milk composition. These contrasting results could be explained by differences in the state of the body reserves of the sows at the beginning of lactation, since a greater maternal muscle mass at farrowing cushions the negative impact of protein restriction on milk production[10-12]. Milk production depends on the quantity and quality of feed consumed during lactation, as well as on the sows' ability to mobilize their body reserves. The level of lysine intake and metabolizable energy interact to influence milk production[28].

Research conducted by INIFAP on lactating sows has been aimed at improving the consumption of energy, amino acids, vitamins and minerals, which are essential in this phase, as well as developing feeding programs and techniques that promote daily feed consumption to minimize excessive loss of weight, protein and body fat, in order to improve reproductive parameters and reduce the high rate of culling[8]. Research conducted at INIFAP shows that the addition to the diet of sucrose, molasses[19,29,30], molasses-cassava plant[15], or chromium picolinate[31,32] can contribute to partially diminish the problem of low voluntary feed intake and reduced litter size at the next parturition, provided that the lysine level of the diet is taken into account[33-35]; however, the best strategy to avoid this problem is to avoid overfeeding the sow during gestation. The digestible lysine demand for the highest productivity is 49 to 56 g/d[21]. When the dietary lysine concentration (0.85 to 1.05 %) was evaluated in sows during their first lactation, litter weight gains in excess of 2.5 kg/day (21-d weaning litter weight ≥67 kg) were reported when the digestible lysine intake was 45 g/d, and the response increased to a digestible lysine intake of 66.2 g/d[21].

With respect to mineral intake in lactating sows, selenium has been researched as an important mineral (0.2 to 0.3 ppm) because of its relation to production, the use of "organic" selenium is recommended due to its better distribution in peripheral tissues[36]. With respect to vitamin intake, it was observed that the inclusion of β-carotene (250 mg/kg) before the first service and during lactation increases embryonic survival[8], and the use of 4 mg/kg of 25-OH-cholecalciferol contributes to structural robustness and cell differentiation in reproductive activity[8].

Restarting sexual activity at weaning

Nutritional restriction during lactation can influence the post-weaning reproductive performance of the sow, inducing, firstly, an increase in the weaning-estrus interval, and in the case that the sow becomes pregnant, an increase in embryonic mortality and a decrease in litter size at the subsequent farrowing(28). Several authors report a 39 % decrease in the number of preovulatory follicles (≥ 7 mm in diameter) during the 3 to 4 d after weaning in gilts subjected exclusively to protein restriction (approximately 460 g/d), suggesting that the ovulatory rate of these sows may be negatively affected(37). For their part, Mejia-Guadarrama(10,11) and Quesnel(12) established that a protein deficit during lactation does not affect embryonic survival, but it does decrease the ovulatory rate at the first post-weaning estrus in gilts, in contrast to the findings of other authors(38). This discordance is probably explained, at least partially, by the difference in the ovulatory capacity of the sows used in these studies, 20 eggs or more *vs* 12-15 eggs, which could accentuate the negative impact of the protein deficit on the ovulatory rate in sows with a high ovulatory potential.

Nutrition of pigs for slaughtering

Piglet feeding

Current situation

Weaning is one of the most stressful events in the life of the pig, predisposing it to digestive disorders in the short and medium term and negatively affecting its productivity and survival; at this stage, mortality levels of 6 to 20 % are reported(39). This mortality is linked to different stress factors associated with weaning, such as change of feed or environment, separation from the mother, interaction with piglets from other litters, and the presence of pathogens. The change of feed is relevant because, by replacing milk with a solid feed from different sources and with different proportions of nutrients derived from cereal grains and oilseed pastes, which contain starches and complex proteins, the piglet does not digest it fully because its digestive capacity has not yet reached sufficient maturity to assimilate the nutrients. In addition, sometimes these ingredients may contain antigens or anti-nutritional factors, which cause lower digestibility of the solid feed, resulting in mechanical or infectious diarrhea(40,41).

At weaning, piglets are exposed to different types of pathogens, some of which are part of the normal microbiota of the digestive tract. Likewise, the immune system associated with the intestinal mucosa (innate and adaptive) is immature in piglets weaned at 21 to 28 d of age, due to the changes undergone by the surface of the intestinal mucosa as a result of weaning. At this stage, cortisol concentrations in the blood are also elevated, causing additional immunosuppression(42,43). This is why young pigs are susceptible to a number of bacterial diseases, including colibacillosis, caused by enterotoxigenic *Escherichia (E). coli* serotypes, and salmonellosis, caused by *Salmonella* spp(44).

On the other hand, piglets exhibit a low and erratic feed intake, which causes delayed or total suspension of stomach motility, congestion of the intestinal blood vessels affecting their lining with hemorrhages and ulcerations, edema and inflammation with the presence of immature epithelial cells on the absorption surface. This leads to the deterioration of the protective function of the intestinal mucosa, because the protein matrix found in the intercellular spaces is weakened by the inflammation of the intestine, increasing the permeability of the epithelium(40,41).

After a few hours of fasting and starvation, piglets may consume feed in quantities above their digestion capacity, which together with changes in mucosal permeability may lead to incomplete digestion of feed, causing osmotic and pH changes in the intestine which induce increased secretions into the intestinal lumen and result in increased motility and the presence of diarrhea. Also, undigested feed components can serve as a substrate for the growth of pathogenic microorganisms, increasing the incidence and severity of diarrhea, which can be reflected in growth retardation in the piglets(45).

The duration and magnitude of growth depression caused by the above factors can vary from 7 to 14 d, depending on the age and physical condition of the piglet at weaning, the quality of the feed, the feeding program, and the environmental and sanitary management. Although most piglets manage to overcome the recession and continue to grow, there is evidence that pigs that are stunted at this stage have larger amounts of subcutaneous fat deposits and lower amounts of protein in the carcass at later stages than pigs that were not affected in their growth. It follows that post-weaning productive capacity is affected by the magnitude of the reduction in post-weaning growth rate.

From the nutritional point of view, in order to shorten post-weaning growth retardation, it is necessary to formulate diets with highly digestible ingredients, and with the appropriate nutrients for the weight and age of the animals, to design a feeding program that considers the digestive development of the piglet, as well as the use of feed additives that favor the integrity of the mucosa. This results in better feed utilization and consequently better piglet productive performance.

Intestinal health

In pigs, intestinal health and the criteria defining it have not been fully elucidated[45,46]. The usual focus on intestinal health has been on the prevention of infectious diseases, as well as on improving animal productivity, which includes nutrient utilization and productive performance[47]. Studies on intestinal health have evaluated different components of the intestinal barrier, especially the mucosal epithelium, the components of the immune system and the microbiota, which are interdependent and, together with dietary factors, have a determining influence on the morphological and functional development of the digestive tract.

The low feed intake due to weaning causes the morphological and functional changes in the intestine described above, as well as the shortening of the villi, hyperplasia of the crypts, increased mitosis, and recycling of epithelial cells, reducing brush border enzymatic activity and absorptive capacity. The aforementioned histological damage causes increased paracellular permeability, with increased transport of antigens to the lamina propria, leading to inflammation. Adequate feed intake after weaning prevents the loss of the barrier function of the tight junctions located in the intercellular spaces, indicating the importance of the presence of nutrients inside the intestine to maintain the protective function of the epithelium[44,47]. The loss of intestinal integrity also reduces the development of innate immune activity by limiting its antigen-presenting capacity, as well as the release of cytokines and chemokines that regulate the local immune response[48,49].

Although the enterocyte monolayer represents approximately 80 % of the epithelial cells, the remaining 20 % of the intestinal epithelium performs other important tasks and consists of: goblet cells that secrete mucins, Panneth cells that produce defensins, M cells that are part of the enteric immune system, and endocrine cells that release hormones and neuropeptides. In studies of intestinal health, mucin production and function have played a relevant role because changes in the amount or composition of mucus can lead to impaired nutrient absorption or a reduction in the protective function of mucins[50]. Intestinal mucin 2 (MUC2), one of the major gel-forming mucins, represents the primary component of the mucus layer barrier, is a site where secretory IgA resides and is the first line of defense that limits epithelial contact or penetration of microbiota and other potentially dangerous antigens into the body[51]. Changes in mucin secretion and the resulting inflammatory response at weaning increase the susceptibility of the piglet to bacterial infections.

The immune system of the weaned pig is immature; therefore, its response to the presence of antigens and pathogens is deficient. Examples of this are seen in the limited function of B and T lymphocytes during the first weeks of life, and the poor antigen-specific responses in pigs less than six weeks old compared to older animals. T lymphocytes are divided into CD4 (helper) and CD8 (cytotoxic), whose function is to establish and maximize the capabilities of the immune system; CD4 cells appear in the intestinal mucosa between the third and fourth week of life, while CD8 T cells begin to appear in the epithelium at the age of four to six weeks. In pigs at weaning, CD4+ and CD8+ T lymphocytes are increased, and the expression of pro-inflammatory cytokines (TNF-α, IL-1β, IL-6 and IL-8) is more prominent in the jejunum two days after weaning, due to transient intestinal inflammation.

The intestinal microbiota in pigs is very dynamic and subject to change over time, especially in early life. In the newborn pig, the microbiota is modulated by sow's milk, and contains a higher abundance of lactic acid type bacteria[39,52]. However, at weaning, opportunistic pathogens have been reported to be present in the small and large intestine of piglets, and, during this critical period, this reservoir of pathogens can trigger infections leading to severe diarrhea[53]. Immediately after weaning, the relative abundance of Lactobacilli is reduced, and other types of bacteria proliferate such as *Clostridium* spp., *Prevotella* spp., *Proteobacteriaceae*, and *E. coli*, resulting in a loss of microbial diversity as a consequence of the cessation of milk intake and the initiation of solid feed intake[39,52]. The composition and diversity of the intestinal microbiota of pigs after weaning can be modified by the levels and sources of proteins, sugars or dietary fibers present in the starter feed, in addition to management, environmental and sanitary status of the farm[44,45,54].

Therefore, in order to avoid severe alterations in the integrity of the mucosa, the immune response capacity and the intestinal microbiota, it is necessary to design special diets that will provide the amounts and proportions of nutrients appropriate to the age and weight of the pigs at weaning, including highly digestible ingredients but also conventional ingredients that favor an adequate maturation of the digestive epithelium, and that facilitate the transition to the use of less complex diets. Also, at this stage, additives can be included in the diet to improve nutrient assimilation, increase the speed and effectiveness of the immune response, as well as to modulate changes in the dynamics of microbial populations during the period of milk consumption to solid feed change. Nevertheless, these recommendations will be successful to the extent that they are accompanied by feeding strategies and programs that ensure adequate food intake in the pre- and post-weaning stages.

Contributions by INIFAP

The relevance of maintaining high feed intakes at weaning through strategies that induce the maturation of digestive capacities in a gradual manner, and based on the presence of adequate substrates, is given priority, to the induction of early maturation of digestive enzymatic activity by pharmacological means[55,56]. For this reason, different strategies have been evaluated to induce early solid feed intake in lactating piglets and in the immediate post-weaning period. During lactation, the introduction of a pre starter feed, starting at 14 d of age, serves as a stimulus for pigs to become sensitized to the odor and texture of feed other than milk. Although solid feed intake is low and variable in suckling piglets, the use of ingredients such as molasses and oil, especially if they are also used in sow feeds, can be a good way to reduce the amount of solid feed intake by sows[57], in addition to milk by-products, can facilitate and accelerate feed recognition at weaning. Also during lactation and the first days immediately after weaning, it is recommended to offer feed in small quantities, but frequently, in order to simulate the suckling habits of piglets that on average suckle every 50 minutes[58]. The greatest benefit of feeding "little and often" at weaning is observed during the first week post-weaning and, in particular, it is an effective practice in the adaptation to the consumption of simple diets[59,60].

In order to design feeds that provide the appropriate amounts and proportions of nutrients for the age and weight of the pigs at weaning, a methodology for ileal cannulation of pigs was developed to evaluate ileal digestibility, as well as the impact of different ingredients on endogenous nutrient losses[61]. This methodology has been used to determine the ileal digestibility of dry matter, protein and energy of ingredients such as beef tallow and coconut oil[62], and different sources of lactose[63], cereals such as oats, corn and sorghums high and low in tannins[64], protein sources such as soybean concentrate, soy isolate and whey[65], and sesame[66]. Apparent ileal digestibility of amino acids has been obtained in soybean meal and sesame meal[66,67] canola meal[68], casein[69, and sorghum[70]. In addition, endogenous ileal losses of nitrogen and amino acids have been determined using casein as a reference[69,71]. Post-weaning morphophysiological changes, such as villus histology and digestive enzyme activity, associated with the use of different feed ingredients such as cereals, including corn, oats and sorghum hybrids[72], low and high tannin sorghums[73], protein sources such as sesame and soybean meal[74], and soy concentrate, soy isolate and whey[75] have also been evaluated.

Another important area of study is the addition of probiotics and prebiotics to feeds, and the design of these. The use of low protein diets combined with *Bacillus (B). subtilis* and *B. licheniformis* in pigs at weaning allowed changing the fermentative pattern of the intestinal microbiota increasing the concentration of acetic, propionic and butyric acid, and reducing the concentration of ammonia in the small intestine and cecum, reducing the incidence and severity of diarrhea, and improving the productive parameters compared to pigs that received high protein diets plus antibiotic [76]. The addition of benzoic acid and a mixture of *B. subtilis* and *B. licheniformis* administered to piglets at weaning maintained productive parameters, reduced coliform counts, and ammonia release in wastewater, compared to responses of pigs at weaning fed diets containing antibiotics[77]. Supplementation with *Saccharomyces (S.) cerevisiae*, and *S. boulardii* improved villus height and reduced pro-inflammatory cytosine concentrations in the intestinal epithelium; control of intestinal inflammation and mucosal preservation was more effective with the use of *S. boulardii* in weaning piglets[52,78]. Also, the use of potato protein concentrate in piglets consuming antibiotic-free diets reduced the severity of diarrhea and maintained productive parameters compared to piglets that received antibiotic-added feed[79].

Feeding of growing-finishing pigs

Current situation

Modern swine feed formulation, as far as macronutrient intake is concerned, is based on the use of three concepts developed in the second half of last century. The first is ideal protein, which refers to a protein in which all essential amino acids are co-limiting to the pig's productive performance. That is, the supply of amino acids coincides exactly with their requirement and is based on the first limiting amino acid, which in pigs is lysine. This theoretical concept was challenged experimentally by the English group of Reading[80]. Currently, it has been modified by several researchers, refining the profile for the different production stages. The second is the use in the formulation of rations of the net energy content of raw materials, optimizing the use of nutrients by the animal by reducing the use of dietary protein as a source of energy; the development of this concept was carried out by Noblet and his team at INRA[81]. The third is the use of nutrient digestibility.

Ileal digestibility of amino acids had its apogee in the last quarter of the last century[82] and the type of coefficient chosen to be use in formulation was the standardized ileal digestibility coefficient, which has two essential characteristics: the first is its additivity, an essential aspect when formulating a ration, since it allows the best estimation of the amount of the amino acid that will be metabolically used by the animal. The other characteristic is that its value is not influenced by the protein level of the diet used in its determination, an important aspect especially for cereals and low-protein raw materials. The use of digestible phosphorus content in the formulation of rations begins with the commercial use of the enzyme phytase, since its use allows reducing the use of mineral phosphorus in the diet[83]; the practical implementation of this concept has been carried out by various research groups. At the beginning of this century, these three formulation principles were integrated into models capable of predicting nutritional requirements[84,85], this has allowed the approach to "Precision Nutrition", a concept that applies the results of research in nutrition and related sciences, using large databases through computer science to predict and provide the nutrient requirements as accurately as possible, seeking a safe and high quality efficient production, in addition to ensuring the least possible impact on the environment.

The joint use of these concepts opened up the possibility of using new raw materials and by-products of the industry, since it potentiates their use by estimating both their nutritional contribution and their effect on the growth and conformation of the pig carcass.

Contributions by INIFAP

The Swine Nutrition research program first compiled data on the standardized ileal digestibility coefficients of various raw materials(86); but later INIFAP contributed to the methodology for the study of ileal digestibility of amino acids(61), as well as to the estimation of endogenous basal losses of nitrogen and amino acids in both piglets and growing pigs(69,71) which made it possible to generate information on the standardized ileal digestibility coefficients of the amino acids of the main cereals used in Mexico —sorghum(87-89), corn(90) —, and from various protein sources: sesame meal(67), safflower meal(91), canola meal(68,92), gluten feed(90). Regarding the use of digestible phosphorus, INIFAP has conducted research on the impact of the use of the enzyme phytase on the increase in phosphorus digestibility of various raw materials(66,93,94). Studies were also carried out on the use of crystalline amino acids(95-98) and on the nutritional adequacy to be achieved when using metabolic modulators(99-101); all the aforementioned research was focused on generating the necessary information to optimize the use of the most widely used raw materials in the country, which in some cases are scarcely researched at the international level.

Regarding the use of dietary energy, INIFAP's contribution consisted of studies of metabolizable energy balances(102,103). Currently, the Institute has respiratory chambers to determine the Net Energy content of diets in pigs, which opens the possibility of conducting studies on this subject.

Carcass conformation and meat quality

The generation of pig carcasses with a good conformation and quality begins with the selection of parents(104), of proper handling from weaning to finishing, including proper procedures during slaughter and post-mortem meat handling. In this regard, in some countries there are grading systems for pig carcasses, such as the USDA Pork Carcass Grading System, in the US; the Pork Carcass Classification and Grading, in Canada; (EC) REGULATION No 1249/2008, in the European Union, and the Mexican Norm (NMX-FF-081-SCFI-2003) for the evaluation of Pork Meat in Carcass-Quality of Meat-Classification, in Mexico(105). The purpose of these systems is to facilitate trade and provide producers with a system to grading and paying a fair price for the carcass.

The generation of the NMX norm(106) was the beginning of the objective evaluation of pork carcasses in Mexico. In general, grading systems require the evaluation of complete strains, through the subjective and objective evaluation of the primary cuts (after dissection), and their correlation with the kilograms produced as live or carcass weight (amount of lean meat) to generate mathematical models[107]. Such factors as fat-free lean, fat content, ultrasonography measurements in the dorsal region, and hot carcass weight have been included in the models[108].

In the 1990s, information was generated on the quality of meat obtained from pure breeds and from certain crossbreeds[109]. In these studies, the Duroc breed predominantly showed greater productive potential (daily weight gain) and meat quality (lower back fat thickness, greater infiltrated fat, lower resistance to cutting, greater juiciness and tenderness), which is why it is currently one of the most commonly used breeds in terminal crossbreeding.

However, the evaluation of meat quality at the industrial level is complicated by the fact that, when looking for the least damage to carcasses and primal cuts, measurements are taken at sites that are not representative of the existing variability, and therefore they lead to deficient studies, for example, when evaluating the ventral surface of the loins, for which the correct procedure should be to make a transverse cut to the muscle at the P2 point, at the level of the tenth rib. INIFAP's National Center for Disciplinary Research in *Animal Physiology and Improvement* (CENID Fisiología y Mejoramiento Animal) has generated a series of technical-scientific documents to help perform objective evaluations, which can be requested at the following e-mail address: lopez.lhumberto@inifap.gob.mx

There are studies that reviewed the key aspects for producing quality pork, taking into account the interaction of metabolic pathways (gluconeogenesis, glycogenolysis, beta-oxidation and adipogenesis) and endogenous-exogenous antioxidant systems in the animal[110-112]. Specifically, the impact of micronutrients and the ante-mortem (fasting, handling), slaughter (desensitization) and post-mortem procedures[113] will have an effect on meat quality. During the transformation of muscle to meat, anaerobic glycolysis plays a fundamental role; therefore, the study of the glycolytic potential[114] is crucial to explain the final pH of the meat and its relationship, in populations with the Halothane and Rendement Napole genes[104,115], with a high susceptibility to generate pale soft exudative (PSE) meat and sour meat in pigs, respectively. Meat with the PSE condition is characterized by low pH (<5.5), low water holding capacity (WHC) and a pale color as a consequence of surface dewetting. WHC is a property that describes the technological aptitude of the meat and PSE meat is a direct consequence of an oxidative imbalance at membrane level[116]. In order to ensure a high WHC, several lines of research were generated at the CENID Fisiología y Mejoramiento Animal, in which trace minerals[117], functioning as cofactors of endogenous antioxidant enzymes —selenium in glutathione peroxidase (Gpx); iron in catalase, and copper in superoxide dismutase—, partially reduced the damage caused by oxidative stress by reducing drip weight loss and improving the color. However, the pro-oxidant factors could be greater, and, therefore, alternatives were sought, using vitamin E (exogenous antioxidant) to supplement the diet. Vitamin E significantly reduces oxidation reactions measured mainly by the TBARS (2-Thiobarbituric Acid Reactive Substances) technique, which affect meat color and shelf life[117,118]. The use of adequate levels of trace minerals and vitamin E has been shown to have positive effects on meat quality[119].

In Mexico, research conducted at the CENID Fisiología y Mejoramiento Animal, recommends reducing the dose of trace minerals from chelated sources[120] and administering 120 IU of vitamin E (alpha-tocopherol acetate) per kilogram of feed in the last 42 d of fattening[121,122], a dosage without detriment to meat productivity and quality. Other micronutrients of benefit have been found as well; such is the case of 25-hydroxycholecalciferol, a secondary metabolite of vitamin D3 with lower toxicity, which, when added to the diet, affects muscle hyperplasia during embryo development with possible effects on meat quality[123]; it also reduces leg issues in pigs of average to high weight, favoring productive performance by lessening the number of low-yielding animals, with positive effects on meat color, WHC, and meat texture[124,125].

Enrichment of meat

Meat enrichment is a finite quality, intrinsic to genetics and to the anatomical region, but strongly influenced by nutrition, especially during the finishing stage. The widely studied molecules for enriching meat are long-chain fatty acids, vitamins (mainly fat-soluble) and trace minerals. In addition, through surveys and some sampling in the last decade, the National Health and Nutrition Survey ENSANUT[126] has identified among the Mexican population vitamin and mineral deficiencies for which animal products are the recommended solution.

Today, obtaining foods of animal origin enriched with good quality fats, such as long-chain omega 3 and 6 fatty acids, is necessary for human nutrition. In pork, the lipid profile deposited in the meat and fat will differentiate products enriched with these fatty acids from those not enriched[127]. The use of highly oxidizable lipids together with other pro-oxidant factors, such as high concentration of certain minerals, can cause a delay in pig growth[128]; therefore, low doses of minerals are recommended, which can be attained by using chelated sources[120].

In this regard, INIFAP's research on pork fortification in recent years has focused on the modification of the lipid profile (linoleic, linolenic, docosahexaenoic acid)[129-131], concentration of vitamins (25-OHD3 and vitamin E)[125,132,133] and trace minerals (Se, Zn, Cu, Mn, Mg, and Fe)[134,135].

Impacts of INIFAP

It is difficult to quantify the impact that INIFAP has had on swine production and on Mexican society through research in swine nutrition, since the improvements in production observed in the last 35 yr are the result of several factors such as genetics, feeding-nutrition, reproduction, health and management. However, it is worth noting that INIFAP's research generated the first Mexican carcass quality standard and quality criteria for pork produced in Mexico. It also generated information on non-conventional ingredients and the digestibility of several of the most commonly used raw materials in the country, which has allowed their inclusion in swine feeds. However, it is considered that the greatest impact has been achieved through the agreement with the National Autonomous University of Mexico (Universidad Nacional Autónoma de México, UNAM), in which more than 170 nutritionists have been trained and are currently working in the industry, and specialized training courses have been provided to a large number of agents of change; in addition to the leading role that its researchers have played and continue to play in the trade associations that affect the sector, such as the Mexican Association of Animal Nutrition Specialists (Asociación Mexicana de Especialistas en Nutrición Animal, AMENA) and the Mexican Association of Veterinarians Specialists in Swine (Asociación Mexicana de Veterinarios Especialistas en Cerdos, AMVEC).

Challenges

The current world population is almost 7.5 billion, and it is expected that by 2050 there will be more than 9 billion people; therefore, FAO estimates that the world will have to produce approximately 60 to 70 % more food in the next 30 yr. It is also predicted that animal protein production should increase at least threefold and meat production should double by 2050[136]. Thus, the challenge for animal production in general and pig farming in particular in the 21st century will be to sustainably produce food of animal origin in adequate quantity and quality. The challenge will be to produce that amount of food with diminishing resources year after year, and in a sustainable manner. Therefore, the issues that become relevant and need to be researched are:

The use of alternative ingredients: The incorporation of cereals and protein sources in animal nutrition, which are also consumed by humans, generates increasing pressure on the livestock industry to create or use raw materials that do not compete directly with humans. This situation favors the use of by-products and new products such as protein sources from larvae, worms, algae, etc. The rational use of these raw materials will depend on the generation of information through research on the composition and digestibility of their protein, phosphorus and net energy intake, as well as on the knowledge of their anti-nutritional or toxic factors.

Nutritional requirements: Selection and continuous genetic improvement produce animals with higher growth speed and animals with a higher growth rate and protein deposition capacity, traits that modify their nutritional requirements. This area of research has traditionally been carried out in developed countries, where pig farming takes place in closed facilities with controlled climate, which means that the knowledge generated for these conditions is not necessarily repeatable in the country, given that in Mexico the growth-fattening phase is carried out in open facilities, with important climatic variations in certain seasons of the year, which are capable of modifying the productive behavior of the animals. For this reason, research will be required in this aspect in order to be able to adapt the nutritional requirements to the environmental situation of the country.

Intestinal health: Weaning is associated with social, environmental and nutritional stress factors, which can lead to reduced digestive capacity and stunted growth of piglets. Antibiotics have been used in sub-therapeutic doses in starter diets to reduce the occurrence of severe diarrhea and the negative impact of weaning. However, their use as growth promoters has been banned, as they favor the presence of antibiotic-resistant bacteria. Therefore, it is necessary to have alternatives to its use in the weaning phase when animals are more susceptible(79).

Climate impact mitigation: Pig production is estimated to issue 668 million tons of CO_2-eq/yr, or 9 % of total livestock emissions(137). Theoretically, this amount can be reduced by improving feed efficiency through the use of the above formulation criteria (ideal protein, net energy, digestible amino acids, and phosphorus) and translating them into precision nutrition. Studies show that the use of these concepts in the formulation of the diet and feeding program can reduce by up to 22 % the excretion of nitrogen, which is the main pollutant in swine excreta, and from which nitrates, ammonia and nitrous oxide — the main greenhouse gas produced by pig farming— are formed.

New approaches to nutrition: The metabolic interaction between nutrients and how they affect the expression of specific genes that can influence feed intake, preferential use of nutrients towards protein deposition, and the metabolic interaction between nutrients and protein deposition have become increasingly important. From a nutritional point of view, the impact of the diet on the intestinal microbiota and the manner in which the nutrient-microbiota relationship modulates the animal's metabolism, particularly to reduce the presence of post-weaning diarrhea in the case of piglets, has also become important. Likewise, there has been increased research on the use of nutrients by the organism that impact pig production, such as the functional use of some amino acids. Another approach that has gained importance is to promote animal welfare by reducing stress and stereotyped behaviors, especially in the breeding herd and in weaned piglets.

Biotechnology products: Biotechnology has been defined as "any technological application that uses biological systems, living organisms or derivatives thereof, to make or modify products or processes for a specific use". More and more biotechnological products are becoming available for animal feeding, such as: pro- and prebiotics, crystalline amino acids, exogenous enzymes, growth hormone, vitamins, chelated trace minerals, etc. The use of which has allowed to increase production efficiency, as well as to reduce the environmental impact of swine farming.

Regarding the breeding herd

With respect to the challenges and perspectives in the short, medium and long term, in a survey conducted in 2015 in Canada, USA, Mexico, Brazil, Ecuador and Chile, to determine the main factors affecting pig production, the predominant factors up to 2015 were found to be "Nutrition and Feeding Strategies, Biosecurity, Health, as well as increasing the Volume of Production", the main factors in pig production being feed efficiency and piglets weaned per female per year [(138)]. Feeding strategies employed during the growth of replacement sows can influence their short- and long-term reproductive performance. For example, in the short term it is possible to manipulate the ovulatory rate and, in the long term, the amount and type of body reserves, which can have a major impact on subsequent reproductive efficiency and sow longevity. In particular, the feeding strategies used during gestation and lactation are important factors that influence the productive performance of the sow and can interact, to a greater or lesser extent, with the feed received by the sows during their growth.

Conclusions

Due to the great diversity of topics to be researched and the breadth and diversity of knowledge areas involved (nutrition, reproduction, immunology, microbiology, proteomics, metabolomics, etc.), as well as the costs associated with the development of research, it is imperative to establish bonds with different institutions and research groups both nationally (UNAM, State Universities, College of Postgraduates, etc.) and internationally, working on topics of common interest. Strengthening should be two-fold: firstly, by strengthening joint research through the formation of interdisciplinary and interinstitutional groups, including the incorporation of new researchers to the program. And secondly, by strengthening the physical infrastructure of INIFAP, which is concentrated in the CENID Fisiología y Mejoramiento Animal (experimental farm and metabolic unit), as well as the institutional laboratories of Nutrition, Meat Quality, Molecular Biology, Proteomics, and through the creation of the Metabolomics laboratory, which would favor frontier research in swine farming.

Obituary: The authors wish to express our posthumous recognition to Dr. José Antonio Rentería Flores, DVSc, who passed away on December 17, 2020; and who was well known for his lifelong dedication to his work and for his interest in research, as well as for his active participation in the development of this publication. May he rest in peace!

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