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Facultad de Ciencias Agropecuarias

Universidad Nacional de Trujillo

REVIEW

Porcine reproductive physiology

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Abstract

The objective of this review is to synthesize current scientific knowledge on the physiological processes that govern porcine reproduction and their interactions with key metabolic and hormonal factors. It addresses gametogenesis (oogenesis and spermatogenesis), the estrous cycle, folliculogenesis, and the hypothalamic-pituitary-gonadal (HPG) axis, as well as critical fertilization events such as sperm capacitation, the acrosomal reaction, and fertilization itself. Embryogenesis and gestation are also examined, with emphasis on underlying biochemical and hormonal mechanisms. Special attention is given to metabolic analytes—glucose, triglycerides, and cholesterol—and their influence on the synthesis and regulation of reproductive hormones including estradiol (E_2), progesterone (P_4), and testosterone. The review focuses on physiological and biochemical aspects specific to domestic pigs (Sus scrofa domesticus), offering a targeted analysis relevant to both livestock production and biomedical research. The integration of metabolic and endocrine perspectives enhances our understanding of how nutrient availability, energy balance, and environmental stress affect reproductive efficiency. Key findings highlight the central role of the HPG axis in coordinating gonadotropin release and steroidogenesis, the impact of metabolic homeostasis on gamete quality and embryo viability, and the importance of hormonal feedback in regulating the reproductive cycle. Practical applications such as estrus synchronization and artificial insemination are discussed in light of these physiological insights. In conclusion, porcine reproductive physiology is shaped by a complex interplay of hormonal and metabolic factors that determine fertility and gestational success. Despite recent advances, further research is needed to better understand metabolic–hormonal crosstalk, particularly during gestation, and to enhance outcomes in both agricultural and biomedical contexts.

Keywords: swine; reproduction; performance; efficiency; and development.

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1. Introduction

Porcine reproductive physiology is fundamental in animal production and biomedical research. It enables the optimization of fertility and the advancement of reproductive technologies (Bortolozzo et al., 2023). Understanding the biological mechanisms underlying reproduction enhances not only reproductive efficiency in swine but also offers comparative insights applicable across mammalian species (Hunter, 2012). Key processes such as oogenesis, spermatogenesis, follicular dynamics, the estrous cycle, and the functioning of the hypothalamic-pituitary-gonadal (HPG) axis are central to reproductive success (Kraeling & Webel, 2015). These physiological events are intricately regulated by sex steroids—estradiol (E_2), progesterone (P_4), and testosterone—in conjunction with metabolic indicators including glucose, triglycerides, and cholesterol. These factors significantly impact gametogenesis, fertilization, embryo development, and gestational outcomes (Das et al., 2023b). Oogenesis involves the coordinated action of follicle-stimulating hormone (FSH) and luteinizing hormone (LH) to regulate follicular development and ovulation (Esbenshade et al., 1990). At the same time, spermatogenesis is hormonally driven and essential for the continuous production of functionally mature sperm (Rodriguez-Martinez et al., 2022). The HPG axis governs endocrine feedback mechanisms that ensure hormonal balance and reproductive readiness (Kaiser, 2011). Metabolic substrates serve dual roles in reproduction: as energy sources (e.g., glucose for ATP production) and as precursors for steroid hormone synthesis (e.g., triglycerides and cholesterol for steroidogenesis). Disruptions in metabolic homeostasis can compromise hormonal regulation and, consequently, fertility (Das et al., 2023b). In applied contexts, technologies such as estrus synchronization and artificial insemination capitalize on this physiological knowledge to improve reproductive efficiency and economic returns (Bortolozzo et al., 2024). In addition, due to anatomical and physiological similarities to humans, pigs serve as valuable models in reproductive biotechnology (Peltoniemi et al., 2023). Investigating the intricate relationship between reproductive hormones and metabolic factors is essential for improving fertility and reducing reproductive losses in both agricultural and biomedical fields (Meyerholz et al., 2024). This review compiles and integrates current knowledge on the major physiological events in porcine reproduction, emphasizing the relationship between hormonal control and metabolic regulation to support future advances in both veterinary and translational reproductive science.

2. Oogenesis

Oogenesis is the process by which oocytes develop and mature in the ovaries of female pigs (Figure 1). This process is strongly regulated by metabolism and sex hormones, then, meiotic division begins in fetal life but stops in prophase I until puberty at 110 d of age (Marchais et al., 2022). During the oestrus cycle, the process resumes, and at ovulation, the oocyte completes the first meiosis. The second meiosis is only completed if fertilization occurs (Wassarman & Litscher, 2022b). During the 7th week, the embryo takes on male or female sexual characteristics.

Ovogonia are oocyte precursor cells (Zhao et al., 2023a). At the beginning of gonadal development, the so-called gonadal folds or gonadal ridges appear. Following epithelial proliferation, the primitive sex cords that structure the ovarian medulla are formed (Wassarman and Litscher, 2022b). This is followed by a 2nd proliferation of germ cells called cortical cords (Krajnik et al., 2023). These cells fuse with the germ cells to produce ovogonia (Mao et al., 2022). They undergo mitotic division and differentiate into primary oocytes, which replicate their deoxyribonucleic acid (DNA) and initiate a process of cell apoptosis (Lema et al., 2022). Only ovogonia and oocytes (Table 1) in prophase I near the ovarian surface remain intact.

Moreover, it is in the oocyte that the zona pellucida is formed which is made of a layer of glycoproteins crucial for protection and for specific interaction with the sperm during fertilization (Wassarman and Litscher, 2022a).

Table 1
Number of oocytes at birth of different mammalian species

Species	Number of oocytes at birth	Source
Swine	80,000 thousand	(Jochems et al., 2022)
Humans	1 - 2 million	(Nikiforov et al., 2022)
Bovine	250,000 thousand	(Báez et al., 2022)
Equine	46,000 thousand	(Goszczynski et al., 2021)

During meiosis, the number of chromosomes is reduced by the formation of polar bodies, which are small cells that contain excess genetic material but do not participate in fertilization due to their infertility (Samura et al., 2023). In the case of sows, energy metabolism is essential for follicular growth. Mitochondrial ATP synthesis from glycolysis is utilized by granulosa cells for pyruvate production; it is then used by the oocyte to synthesize ATP and reach maturation (Strauss et al., 2014). Therefore, mitochondrial and cytoplasmic activity is decisive for the maturation and potential development of oocytes under competition in hyperprolific sows (Sun et al., 2026).

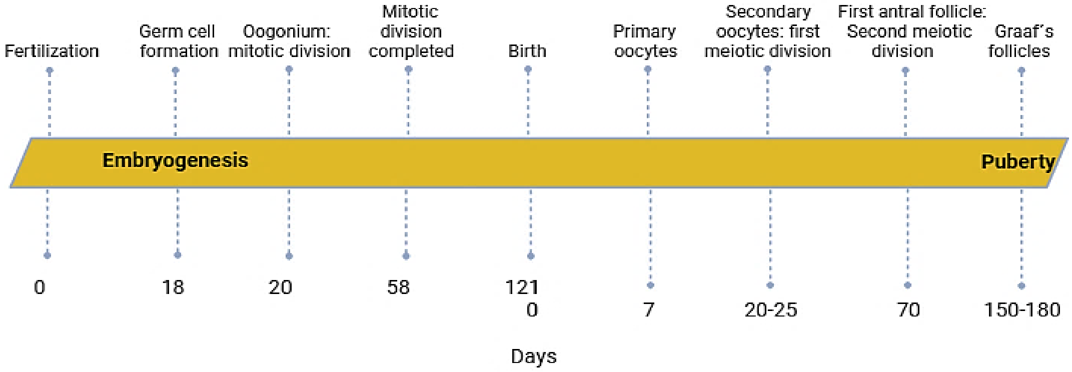

Figure 1. Oogenesis in sows. Source: own elaboration based on (Wassarman and Litscher, 2022b).

During follicular development, follicular cells store triglycerides that can be mobilized to produce fatty acids, which are used in the mitochondria for ATP generation in the oocyte. Next, cholesterol is a key precursor of steroid hormones such as E_2 and P_4; where cholesterol is converted to pregnenolone in the theca cells, which triggers the steroid cascade that regulates the oestrus cycle and oocyte maturation (Strauss et al., 2014). In tandem, folliculogenesis is stimulated by both FSH and LH which aid in the growth and maturation of ovarian follicles, and ovulation. LH induces the rupture of the follicle de Graaf, allowing the release of the oocyte. That is, the oocyte was developed within an ovarian follicle, which increases in size and produces follicular fluid over time (10 ± 2 d).

3. Spermatogenesis

Spermatogenesis is a physiological process in the male that gives rise to spermatozoa (Zheng et al., 2022). This process takes place in the seminiferous tubules of the testes at approximately 2°C below body temperature and begins with the onset of puberty (Lei et al., 2026). Puberty in pigs begins at 150-180 d after birth (Gałęska et al., 2022). Spermatogenesis occurs throughout their reproductive life continuously in cycles of 34-45 d (Shimazaki et al., 2022). Before reaching its final form, the spermatozoon undergoes several changes. First, there is the transformation from primordial germ cells (PGCs) to type A spermatogonia. Continuing with type B it divides and results in primary spermatocytes. The next phase is a meiotic division resulting in secondary spermatocytes (Mekata and Yamamoto, 2022). The cells undergo another meiotic division producing round haploid cells called spermatids that mature and take their final form as spermatocytes (Seneda et al., 2023) (Figure 2). Spermatogenesis is regulated by hormones such as testosterone, LH, and FSH (Faheem et al., 2021). Gonadotropins regulate the production of testosterone in Leydig cells and the maturation of germ cells in seminiferous tubules. On the other hand, testosterone, produced by Leydig cells, is essential for sperm development. Its effects include the maturation of spermatogonia and the maintenance of the proper environment for spermatogenesis. A deficit of testosterone or an alteration in gonadotropin signaling can disrupt sperm maturation, resulting in immature sperm or sperm with abnormal morphologies (Strauss et al., 2014).

Likewise, during spermatid differentiation, proteins such as protamine, which replaces histones, are synthesized and accumulated, allowing DNA compaction to be properly organized and distributed (Bao & Bedford, 2016). Damage or errors in this phase can result in sperm with fragmented DNA or structural malformations. Damage to sperm DNA can lead to fertilization failure, miscarriages, or genetic malformations in the offspring (Strauss et al., 2014). During spermiogenesis, vesicles of the Golgi apparatus also develop that will form the acrosome, a structure necessary for fertilization. Then, the development of the sperm tail is formed from the centriole, which allows motility (Miyata et al., 2024). Sperm abnormalities, which affect semen quality, may originate from alterations during spermatogenesis (Flowers, 2022). Spermatogenesis can be influenced by several physicochemical mechanisms that affect sperm integrity and function, such as oxidative stress where free radicals or reactive oxygen species (ROS) are produced in a controlled manner, but an excessive increase can generate oxidative damage to DNA, cell membranes and sperm proteins (Pintus & Ros-Santaella, 2021).

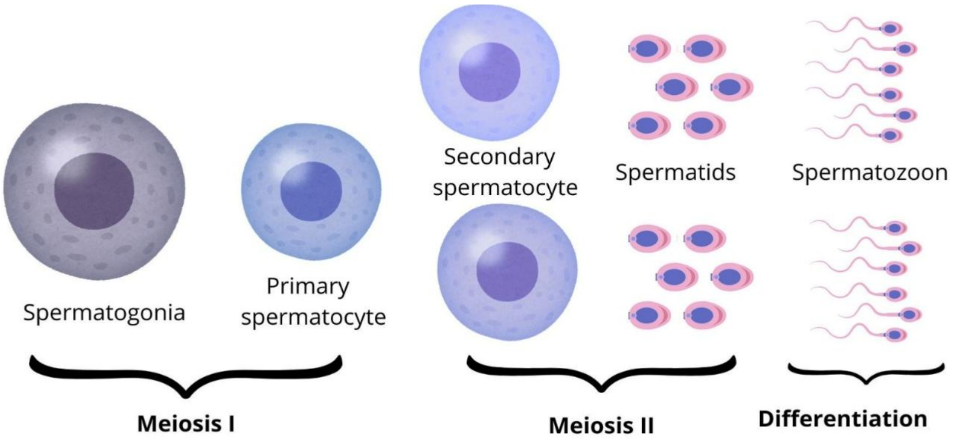

Figure 2. Spermatogenesis. Source: own elaboration based on (Gałęska et al., 2022).

Oxidative stress can cause abnormalities in sperm morphology (amorphous head, defective flagellum) and a decrease in sperm motility and viability (Sutovsky et al., 2024). Some triggers such as heat stress, infections, antioxidant deficiencies, and environmental toxins can increase ROS production, affecting the redox balance in the testes (Zhang et al., 2026). On the other hand, ions such as calcium (Ca^{++}), sodium (Na^{+}), and potassium (K^{+}) are crucial for maturation and the ability of sperm to move properly. Atypical changes in the central nervous system can affect the functioning of ion channels during spermatogenesis and affect their development (Akhavizadegan et al., 2025). Exposure to heavy metals, nutritional imbalances or pathologies such as varicocele can alter ionic homeostasis in the testes.

4. Oestrus cycle

The sow are continuously polyoestrus (Figure 3) (Jackson et al., 2022). With a cycle length between 20-21 d, it includes the follicular and luteal phases. The follicular phase is characterized by high estrogen levels and ovulation, while the luteal phase is characterized by high progesterone levels, regulating fertility (Figure 4). An endocrinological understanding of the oestrous cycle can lead to 1. The exact timing of ovulation, caused by secretion of oestradiol from the LH-Pulse dependent follicles, 2. successful insemination (mating or artificial insemination), 3. increased fertility rates (Glencorse et al., 2025).

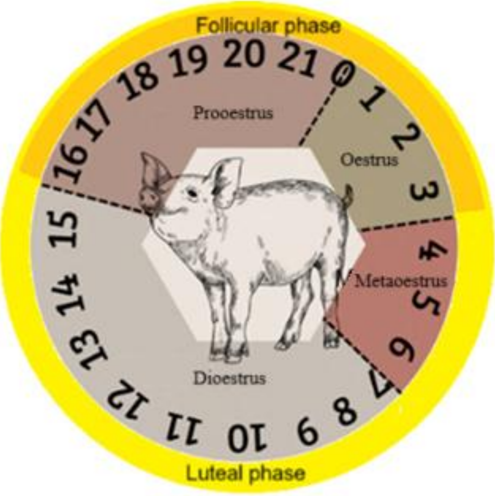

Figure 3. Oestrus cycle of the sow. Source: own elaboration based on Jackson et al. (2022).

The duration of the oestrus phase is 48-72 h (Kawashima et al., 2022). Ovulation occurs within 40-42 h within the duration of oestrus (Li et al., 2022b). Gardela et al. (2022) mentions pre-ovulatory times of 8-10 h, a peri-ovulatory period of 2 h and post-ovulatory times of 8-10 h. The oestrus cycle is divided into four phases: a) *Prooestrus*: lasts approximately two d (48 h) (López-Gatius et al., 2022). Signs can be seen as females mount each other, but do not accept the male and physically we can see edematous, reddened vulva and secretions in the vulva (Sato et al., 2022).

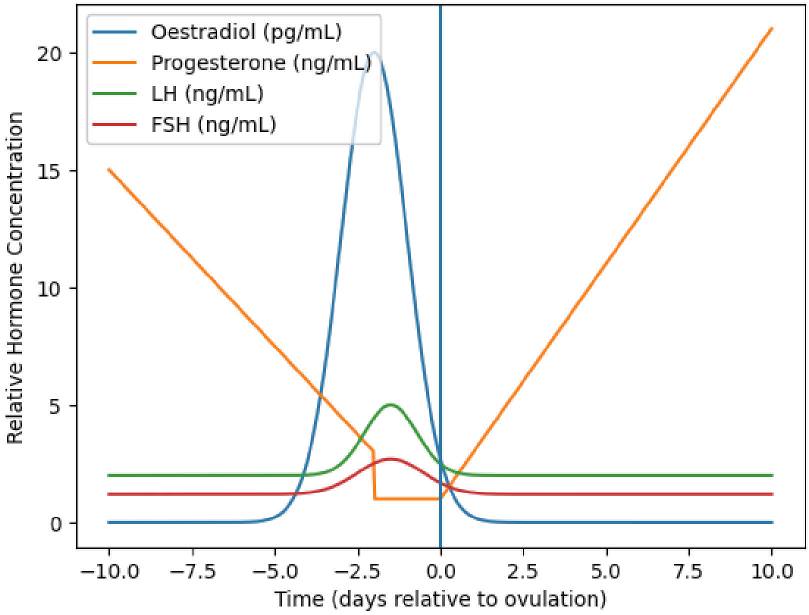

Figure 4. Serum hormone concentration during the estrous cycle in sows. LH = luteinizing hormone; FSH = follicle-stimulating hormone. Source: own elaboration based on (Soede et al. 2011).

Physiologically, the tertiary follicle develops. b). *Oestrus*: lasts 2-3 d (48 - 72 h) (Choudhary et al., 2022), during this period there may be secretions at the commissure of the vulva, they may emit noises (grunting), inappetence and quietness (riding sign), and mating can take place (Heringstad and Wethal, 2023). During this phase, gonadal hormones such as P_4 and E_2 act on the brain to produce ovulation. c). *Metaoestrus* (Mao et al., 2022): lasts 7 d (168 h), signs of estrus disappear and physiologically the corpus luteum is organized. d). *Dioestrus* (Zhi et al., 2022): estimated duration is 9 d (216 h), in this phase if no gestation occurs there is a regression of the corpus luteum, and if gestation occurs which P production will start$_4$ and embryo formation will begin (Park et al., 2022).

5. Folliculogenesis

Folliculogenesis begins during the embryonic stage (Cañón-Beltrán et al., 2023). In the same way as in oogenesis until reaching sexual maturity or puberty. This process gives rise to the formation of the follicular antrum for the release of the oocyte or follicular atresia. The stages of folliculogenesis include: the activation of the primary or primordial follicles, which will contain an oocyte surrounded by a layer of granulosa cells with 2 to 4 layers (Ford et al., 2021). The tertiary follicles which increase their number of granulosa layers from 4 to 6 and finally antral follicles where the oocyte enters metaphase II (Ghezelayagh et al., 2022). It will enter quiescence until the time of fertilization which allows meiosis II to resume and end (Seneda et al., 2023). In sows, recruitment of primordial follicles occurs between days 14 and 16 of the cycle. During this phase, the FSH surge induces the initial growth of follicles, which progress from the primary to the antral stage (Faheem et al., 2021). As the follicles grow, FSH regulates their development until they reach the preovulatory stage. Only a subset of antral follicles, usually the larger ones, are selected to ovulate, while smaller follicles experience atresia (Soede et al., 2011). At this stage, estradiol secreted by the theca cells of the dominant follicles contributes to the inhibition of the less developed follicles. The growth of antral follicles depends on the coordinated activity of pulsatile FSH and LH, which stimulate the production of androgens and their conversion to E_2 in the granulosa cells (Casarini & Crépieux, 2019). In this phase, the relationship between the number of granulosa cells and follicular volume plays a key role and is where hormonal fluctuations that determine the fate of the follicles are observed. Finally, tonic LH triggers ovulation of dominant follicles (Soede et al., 2011).

On the other hand, estradiol concentration peaks just before the LH peak, which initiates oocyte release. Membrane receptors for FSH and LH located on granulosa and theca cells activate cyclic AMP (cAMP) second messenger signaling pathways, which, through activation of protein kinase A (PKA), promote steroidogenesis and follicular growth (Casarini & Crépieux, 2019). Insulin-like growth factor I (IGF-I) and IGF-binding proteins (IGF-BP) significant regulator in folliculogenesis and modulate the response to gonadotropins, enhancing granulosa cells, steroidogenesis and oocyte maturation by activating the Phosphatidylinositol 3-kinase/AKT and Mitogen-activated protein kinase pathways through binding to the IGF-1R (Howard & Ford, 1994). In fact, significantly reduced levels of IGF-1 have been observed in follicular fluid and granulosa cells in mice from patients with low ovarian response compared to those with normal ovarian response (Hu et al., 2026). Enzymes involved in steroid synthesis include aromatase, which converts androgens to E_2, and 17β-hydroxysteroid dehydrogenase (17β-HSD), which regulates androgen and estrogenic activity. Folliculogenesis depends on adequate energy supply, regulated by the balance between gluconeogenesis and glycolysis, which ensures a constant supply of ATP for growing follicles (de Souza et al., 2022). Also, follicles use fatty acids as a source of energy. High-density lipoproteins (HDL) facilitate the transport of cholesterol to granulosa cells for E_2 synthesis. Sows with a diet adequate in essential amino acids show better follicular quality and higher fertility rates, as well as proteases that are essential during ovulation (Prunier & Quesnel, 2000).

6. Hypothalamus-pituitary gonadal axis

The nervous system directs most of the activities of all living things (Owumi et al., 2022). Gonadotropin-Releasing hormone (GnRH) is a decapeptide hormone produced by the hypothalamus that acts directly on specific cells in the anterior pituitary (adenohypophysis), known as gonadotropic cells. These cells are responsible for the synthesis and release of gonadotropins: LH and FSH (Fabová et al., 2023). Then, influences the gonads where they regulate ovarian function, gametogenesis, synthesis, and secretion of hormones, ovulation, etc. The process initiates within the hypothalamus by secreting GnRH in a pulsatile manner, but in frequent and irregular waves that are regulated by gonadotropin feedback (Wei et al., 2022). Acting on a selection of gonadotropic cells of the adenohypophysis that in turn release LH-pulse and FSH-pulse, the rapid release of GnRH stimulates LH-surge (Owumi et al., 2022). On the other hand, their slow release favors FSH secretion; both hormones act in the ovary by binding to granulosa and theca cells thus initiating folliculogenesis (de Souza et al., 2022). The production of different ovarian hormones (Table 2) such as E_2, P_4, and androgens, together can release gonadal peptides (activin, inhibin, and follistatin) and growth factors (Fabová et al., 2023). These ovarian-derived factors feed back to the hypothalamus and pituitary which increase or decrease the generation of GnRH and gonadotropins (Figure 5). The GnRH receptor in the gonadotropic cell activates several intracellular proteins, such as G protein, which in turn activates phospholipase C (PLC). This enzyme converts phosphatidylinositol bisphosphate (PIP2) to inositol triphosphate (IP3) and diacylglycerol (DAG), which trigger the release of intracellular Ca^+ and activate protein kinase C (PKC) (Wei et al., 2022). However, in some systems, especially other hormones, cAMP can act as a second messenger, which is activated through adenylate cyclase. When cAMP is elevated in the gonadotropic cell, it activates protein kinase A (PKA), which phosphorylates various proteins in the cytoplasm and nucleus (Li et al., 2024).

Table 2

Ovarian zones where hormones are produced and the concentration at which they are produced (Fabová et al., 2023)

Organ	Structure Hormones	Concentration
Follicle	Estradiol	High
	Progesterone	Media
Corpus luteum	Androgens	Download
	Progesterone	High
	Estrogens	Download

Some of these activated proteins are transcription factors, which move into the nucleus and bind to specific DNA sequences to regulate the transcription of genes coding for the α and β subunits of the gonadotropins (LH and FSH) (Pak & Chung, 2024).

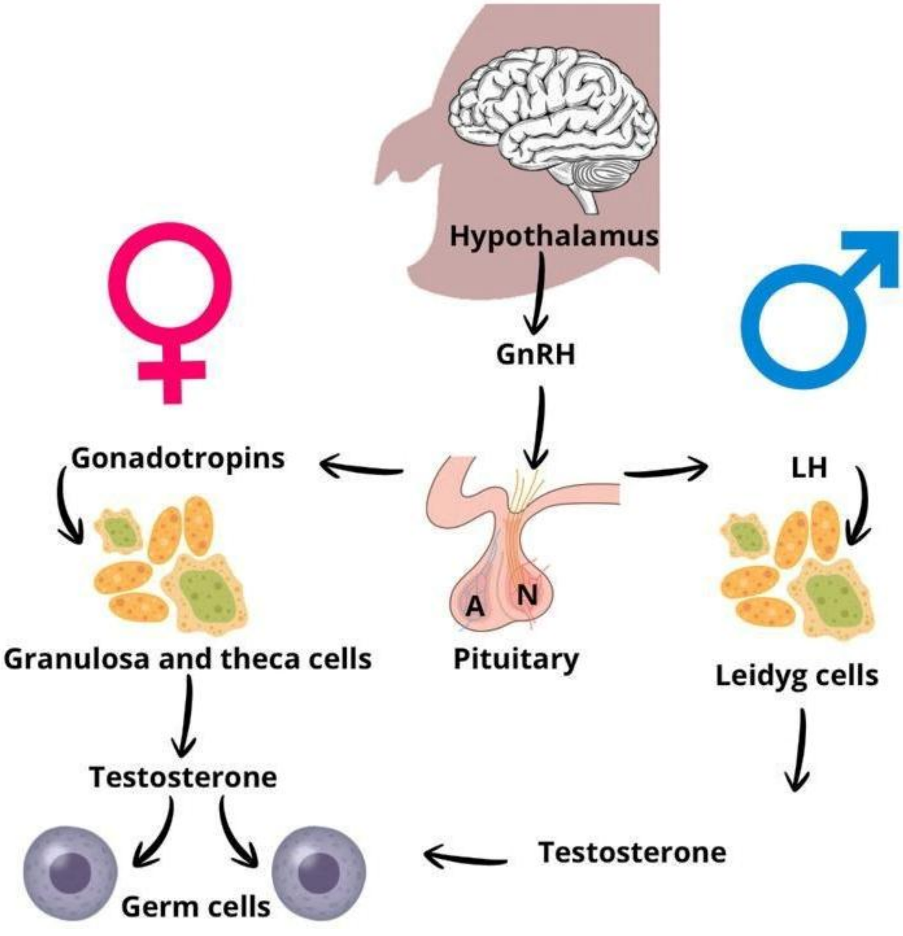

Figure 5. Hypothalamic-pituitary gonadal axis. GnRH = gonadotropin-releasing hormone; LH = luteinizing hormone; FSH = follicle-stimulating hormone; A = Adenohypophysis; B = Neurohypophysis. Source: own elaboration based on (Owumi et al., 2022).

These subunits are required for gonadotropins to assemble and are secreted by gonadotropic cells into the bloodstream, where they perform their function in target organs, such as the ovaries and testes. Once the transcription factors activate the corresponding genes, the DNA is transcribed into messenger RNA (mRNA). This mRNA is processed and transported out of the nucleus into the cytoplasm. In the cytoplasm, ribosomes translate the mRNA into proteins corresponding to the α and β subunits of LH and FSH (Kaiser, 2011).

7. Capacitation and acrosomal reaction

When the spermatozoa come into contact with the vaginal tract, they must complete a process called sperm capacitation (SC; Figure 6) (Wassarman & Litscher, 2022a). This is the process of physiological and biochemical changes that the sperm undergo during passage through the female reproductive tract where it acquires the ability to fertilize the oocyte (Albrizio et al., 2022). In this process, the seminal plasma is removed, which helps to protect the sperm from early SC. Other changes are in membrane properties, ion concentration, and enzyme activity; these changes affect the flagellum so that it can initiate hyperactivation (Balu et al., 2022). Cholesterol is the most important lipid because it forms lipid rafts that through activation of certain receptors allow SC (Baranizadeh et al., 2022). The acrosomal reaction refers to the moment of union between the zona pellucida (ZP) and the spermatozoon (Fujihara et al., 2023). This process can only occur if the sperm reaches maturity, which is the moment when it acquires its SC. Molecules found in the acrosome recognize the sperm and oocyte. This process triggers a series of molecular events, one of which is the entry of Ca^{++} leading to an increase in intracellular Na^{+} and outflow of hydrogen (H^{+}) (Gao et al., 2022). This whole process causes the action potential (pH) within the acrosome to rise, which activates enzymes to break through the ZP of the oocyte (Kurata et al., 2022).

8. Hyperactivation and fertilization

Hyperactivation is the process that facilitates sperm movement. Because as they pass through the reproductive tract of the female, they encounter natural fluids that are viscous (Takei, 2022). Without this process, they would not be able to pass through the reproductive tract to reach the oocyte (Sharif et al., 2022). On the other hand, it will help in the moment of ascent towards the oviduct to the fertilization site. It will prevent transient adhesion exerted between the gamete and the oviductal epithelium (Sharif et al., 2022). The movement during hyperactivation is characterized as vigorous flagellar, with low amplitude, but long wavelength and relatively symmetrical allowing it to advance rapidly and in a linear fashion (Figure 7) (Kurata et al., 2022). These movements change when they have advanced and become flagellar movements, with higher amplitude, but low wavelength, asymmetric, and with circular or irregular trajectory. Fertilization is the union of the haploid gametes of the female and the male (Cañón-Beltrán et al., 2023). It results in a diploid zygote that will develop into a new individual. In pigs, the male deposits semen in the uterus unlike other species, but fertilization occurs in the oviducts specifically in the oviductal ampulla (Figure 8) (Lange-Consiglio et al., 2022). Before to fertilization, previous events occur such as sperm migration between the cells of the ZP, adhesion, and migration through the corona radiata, and fusion of the sperm and oocyte membranes (Li et al., 2022a). When sperm is in the ampulla of the oviduct, the possibility of joining with an oocyte increase. The sperm makes its way into the ZP where it will join with the oocyte by means of glycoproteins (ZP1, ZP2, ZP3, and sperm galactosyltransferase) (Popli et al., 2022).

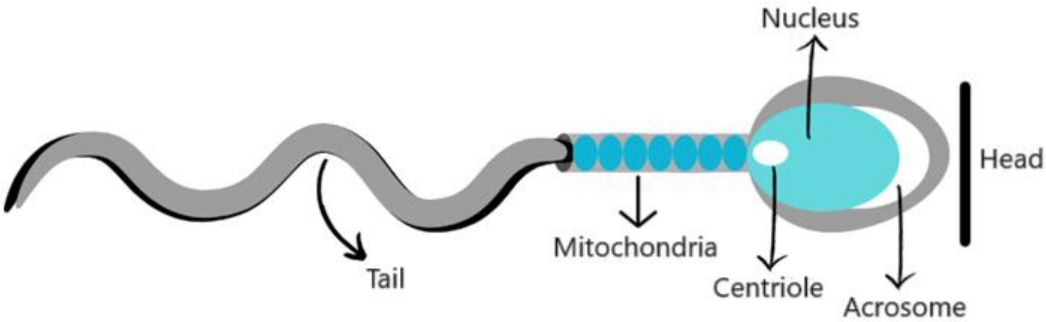

Figure 6. Spermatozoon. Source: own elaboration based on (Wassarman and Litscher, 2022a).

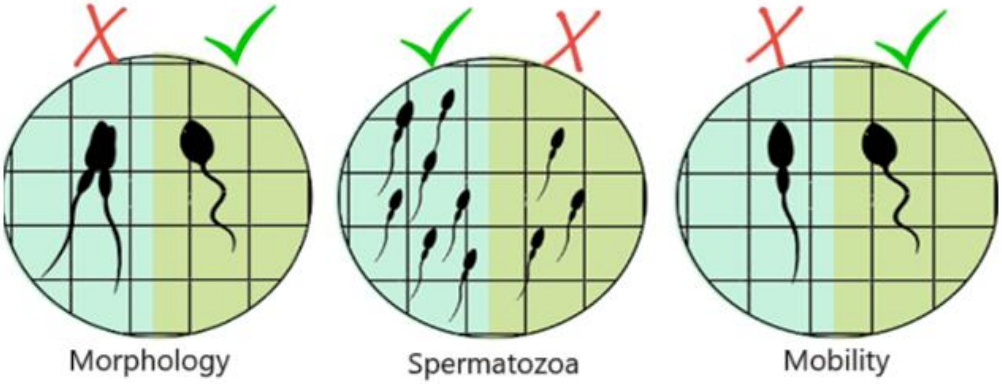

Figure 7. Characteristics to evaluate sperm quality. Source: own elaboration based on (Kurata et al., 2022).

Also, to corona radiata by hyperactivation and enzymatic action. Galactosyltransferase will also prevent other sperm from penetrating the oocyte. After 5-15 minutes of fixation, the acrosomal reaction occurs, and the release of enzymes housed in the acrosome such as hyaluronidase, acrosin, proteinase, neuraminidase, phosphatase, collagenase, phospholipase helps it to make its way between the cells of the ZP of the oocyte (Kern et al., 2023). In pigs, this multivalent model of sperm–zona pellucida interaction is strongly supported by functional inhibition studies demonstrating that several seminal plasma proteins modulate sperm binding capacity in a dose-dependent manner. Spermadhesins such as AQN-1, AWN-1, and AWN-2 have been shown to significantly reduce sperm attachment to ZP-intact oocytes when oocytes are preincubated with isolated proteins prior to insemination, suggesting competitive occupation of ZP ligands or masking of sperm-binding domains (Zelenkova et al., 2025). Similarly, the seminal plasma protein pB1/DQH markedly decreases the proportion of zona-bound spermatozoa when present during gamete co-incubation, reinforcing the concept that native protein conformation is critical for effective receptor–ligand interaction (Maňásková et al., 2007). The inhibitory effect of SLIP1 (AS-A) further illustrates this principle, as its denaturation abolishes the blocking capacity, indicating that tertiary structure integrity is essential for biological function. Moreover, experimental preincubation of porcine oocytes with a 55 kDa sperm protein resulted in complete suppression of sperm binding at higher concentrations (50–100 µg), confirming a clear dose-dependent mechanism (Zelenkova et al., 2025). Collectively, these findings support the hypothesis that porcine fertilization relies on coordinated, reversible, and quantitatively regulated interactions between multiple sperm surface proteins and ZP glycoproteins rather than a single high-affinity receptor system.

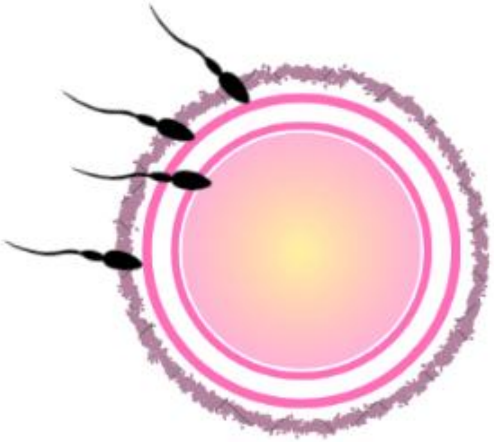

Figure 8. Representation of the moment of fertilization of an oocyte by a spermatozoon. Source: own elaboration based on (Lange-Consiglio et al., 2022).

9. Embryogenesis and gestation

Embryonic development or embryogenesis is the process that gives rise to the embryo (Kozieradzka-Kiszkurno, 2021). It starts with the formation of the zygote. Subsequently, it will divide into several cells and this process takes place in the oviduct (Kolomeitseva et al., 2021). The first simultaneous cell divisions are called cleavage or segmentation (Figure 9) (Kang et al., 2021b). They occur in utero approximately after d4 post fertilization. Each of the cells is called a blastomere (Kang et al., 2021b).

After cleavage, an embryo is formed from two blastomeres, a process that will continue and repeat until a structure of more than 16 blastomeres is formed and renamed morulae (Kang et al., 2021a). It then continues with a process called cell compaction. Around d 7 the morula will become a blastocyst where a central cell mass will differentiate, which is the part of the embryo that gives rise to the fetus and trophoblast which will be responsible for forming the placenta (Jia et al., 2021).

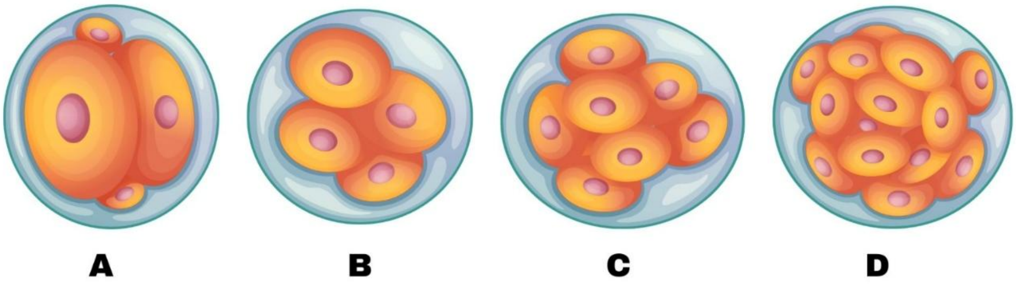

Figure 9. Early embryonic development A. Zygote B. Embryo of 2 blastomeres C. 4 blastomeres embryo and D. 8-cell embryo. Source: own elaboration based on (Kang et al., 2021b).

Gestation is the period of embryo-fetal development (Zhang et al., 2022a). This process takes place in the uterus where it is nourished, grows, and adapts for birth by forming an epitheliochorial placenta. The ideal temperature for the sow during gestation is 13 – 18 °C and avoid direct exposure to sunlight (Zhang et al., 2022b). The gestation time in this species is approximately 114 d (Table 3). On average, this species has a litter of 8 - 10 piglets in first-birth females and 10 - 16 in multiparous females. The cellular and molecular mechanism that occurs from the beginning of gestation depends on biochemical and cellular interactions (Yang et al., 2022). Such a process known as maternal recognition of pregnancy occurs in the female reproductive tract. It is induced by hormones, immune system cells, and cytokines allowing the fetus to survive until birth (Laporta et al., 2022). The embryo and subsequently the fetus undergoes the following events: attachment to the uterus, maintenance of gestation, preparation for lactation, and the moment of birth.

Table 3
The gestation time of different mammal species

Species	Gestation time (days)	Source
Sow	113-115	(Zhang et al., 2022a)
Cow	283-285	(Arboccó et al., 2023)
Bitch	58-68	(Spruijt et al., 2022)
Mare	330-345	(Sielhorst et al., 2022)

10. Biochemical analytes and reproductive hormones

10.1 Glucose

Glucose is the main source of energy in animals and serves as the main source of energy for cellular processes during the reproductive cycle. The main source of glucose for pigs is starch. Glucose is found and transported in the blood; in pigs, the normal concentration is 70-100 milligrams (mg) per 100 ml of blood (Fang et al., 2020). Adequate glucose levels can improve the rate of oestrus expression by optimizing ovarian function, as well as promoting ovarian metabolic health, which can translate into a higher fertility rate because it is essential for proper ovarian function and subsequent ovulation (van den Brand et al., 2000). In males, glucose can influence testosterone synthesis, which affects libido and reproductive behavior. The Krebs cycle and oxidative phosphorylation provide energy from glucose and fatty acids. Signaling mechanisms such as second messengers (cAMP, calcium) regulate the use of substrates within the cell for hormone synthesis (Lounsbury, 2009). Thus, ATP elicitation through glycolysis has effects on the synthesis of LH, FSH, E_2, P_4, and testosterone so that various biochemical reactions can be driven that depend on the integrity of mitochondrial function and lipid and cholesterol metabolism. Key enzymes in steroidogenesis (such as cholesterol desmolase, 3β-hydroxysteroid dehydrogenase, and aromatase, among others) are proteins whose synthesis and maintenance require energy (Zaidi et al., 2012). Glycolysis, as an important pathway for rapid ATP production, provides energy for the translation and synthesis of these proteins in steroidogenic cells. Active transport of lipids and cholesterol across cell membranes for steroidogenic processing is also an ATP-dependent process. Transporter proteins, such as low-density lipoproteins (LDL), use energy to facilitate cholesterol uptake into steroidogenic cells, a key step in hormone synthesis (Dalen & Li, 2024). In situations of metabolic stress, where glucose availability is limited, steroid hormone synthesis can be impaired. Indeed, AMP-activated protein kinase (AMPK), is activated under low ATP conditions and has an important regulatory role in energy metabolism (Ballester et al., 2018). AMPK can inhibit lipid and cholesterol synthesis under conditions of energy insufficiency, which directly affects reproductive hormone synthesis by reducing the availability of cholesterol for steroidogenesis. Interestingly, in animals subjected to heat stress (HS), it can be observed that the elimination of glucose from their body is more rapid. Insulin sensitivity has been shown to be higher in pigs in the growth phase because the animals require more glucose to maintain their thermal equilibrium. Under such scenarios, glucose levels drop because the immune system requires large amounts of glucose, and the immune system is stimulated in the presence of HS (Yang et al., 2020). In fact, when pigs are subjected to HS, feed intake decreases, since there is a chain of reactions where the production of insulin, which controls glucose levels, is altered (Serviento et al., 2020). Finally, the efficiency of glycolysis and the ability of steroidogenic cells to produce sufficient ATP influences oestrus expression, ovulation, follicular maturation, and fertility.

10.2 Triglycerides

Triglycerides are the major form of fat storage in the body. They can affect reproductive hormone synthesis in pigs due to their role in lipid metabolism, which is closely related to sex steroid production. When blood glucose levels are altered, they impact triglyceride levels, this is because when glucose deficiency exists triglycerides are used as a non-glucose energy source causing a negative energy balance (Sarandol et al., 2020). Therefore, altered triglyceride levels can influence the amount of cholesterol available for the synthesis of E_2, P_4, and testosterone. Triglycerides are released from hepatocytes and are used as energy, so long-term liver problems can occur if the animal is stressed. Their metabolism is mediated by lipoprotein lipase enzyme, which converts triglycerides into free fatty acids (Karzan Jalal, 2021). Triglycerides, through lipolysis, release free fatty acids and glycerol, which can be used for cholesterol synthesis (Karzan Jalal, 2021). Cholesterol is the direct precursor of steroid hormones in the gonads (ovaries in sows and testes in boars) via the steroidogenesis pathway. Triglycerides can also indirectly influence hormonal regulation through their impact on overall energy metabolism, which affects the secretion of hormones such as insulin and leptin (Harris, 2014). These hormones, in turn, can modulate the activity of LH and FSH, which control reproductive function in pigs.

10.3 Cholesterol

Cholesterol in pigs acts in organs such as adrenal glands, gonads, and liver, as a precursor of steroid hormones (glucocorticoids, mineralocorticoids, and reproductive hormones such as E_2, P_4 and testosterone), bile acids (alcoholic and taurocholic) and vitamin D and is used by connective, muscular, nervous and epithelial tissue to form cell membranes (Romoser et al., 2022). Steroidogenesis is the conversion of cholesterol to pregnenolone through the action of the enzyme cholesterol demolase (CYP11A1), also known as P450scc and occurs primarily in the mitochondria and endoplasmic reticulum of specialized cells, such as theca and granulosa cells in the ovaries and Leydig cells in the testes (Bremer & Miller, 2014). Both cholesterol and glucose are strongly related to energy metabolism in sows. Cholesterol levels can vary by age, breed, sex, environmental conditions, physiological state, and diet of the animals (Faheem et al., 2021). Levels are to be related to environmental adaptive capacity through altered metabolic activity. Proper management of cholesterol levels is important when applying oestrus synchronization protocols and artificial insemination programs. Proper production and regulation of steroid hormones are essential for protocols to be effective; if there is a deficiency of available cholesterol in the gonads, reproductive steroid hormone synthesis can be compromised, affecting ovarian and testicular function. This can lead to impaired oestrus expression, fertility, and prolificacy in sows, as well as decreased sperm quality in boars.

10.4 Estradiol

Estradiol is synthesized mainly in the granulosa cells of the ovaries in females and is essential in egg maturation and maintenance of reproductive cycles (Chen et al., 2025). They are also produced in smaller amounts in the placenta, adipose tissue, and brain. The typical structure includes three six-carbon rings (rings A, B, and C) and one five-carbon ring (ring D) (Fidarov et al., 2015). In addition, they possess a hydroxyl (-OH) group at position 3 of the A-ring and a double bond in the A-ring. E_2 are cholesterol-derived steroids, which are converted to pregnenolone by the enzyme cholesterol demolase (CYP11A1) in the mitochondria (Miller, 2017). From pregnenolone, a series of reactions mediated by enzymes such as 17α-hydroxylase and aromatase transform androgens (testosterone and androstenedione) into E_2 which in mammals include E_2, estriol (E_3), and estrone (E_1) (Fuentes & Silveyra, 2019). E_2 plays a key role in the reproductive physiology of sows, impacting oestrus expression, fertility, and prolificacy. At the molecular level, E_2 cross the cell membrane by facilitated transport and binds to E_2 receptors (ERα and ERβ), which act as transcription factors to regulate gene expression (Fuentes & Silveyra, 2019). This is essential for sex organ development and preparation for fertilization. There are also non-genomic mechanisms, such as activation of the G protein-coupled receptor (GPER1), which allows for more rapid effects on the cardiovascular system and metabolism through secondary messengers such as adenylyl cyclase and PKA (Tran, 2020). E_2 affects lipids, energy, and protein metabolism, this influences body fat distribution and energy expenditure in production animals. It has been observed that a reduction in E_2 can decrease energy expenditure, favoring greater fat accumulation, which can affect fertility via ovarian steroidogenesis and other reproductive parameters. In endocrine terms, E_2 levels fluctuate throughout the oestrus cycle, with peaks coinciding with ovulation, a critical time for oestrus expression (Williams & Cardoso, 2021). These hormonal peaks are crucial for oestrus synchronization protocols used in swine farming to improve reproductive efficiency through artificial insemination. The use of these protocols allows for more accurate prediction of the optimal time for insemination, thus improving fertility rate and prolificacy (Knox, 2019). It is therefore essential for pig farmers to properly monitor and manage E_2 levels in their animals. This not only improves reproductive efficiency but also optimizes resource use and increases farm productivity. With the use of tools such as oestrus synchronization and a detailed understanding of hormonal mechanisms, it is possible to maximize conception rate and litter size in sows.

10.5 Progesterone

P_4 has 21 carbon atoms, arranged in a cyclopentanoperhydrophenanthrene skeleton, which is the basic nucleus of all steroid hormones (Strauss & FitzGerald, 2019). It possesses a keto (=O) group at position 3 of the A-ring and a methyl (-CH3) group at carbon 21 of the D-ring (Kang et al., 2024). P_4 is synthesized mainly in the corpus luteum after ovulation, but also in the placenta during gestation, as well as in the adrenal cortex and in small amounts in the testes. Its main function is to prepare the endometrium for embryo implantation and to maintain gestation (Deryabin & Borodkina, 2024). In sows, P_4 levels increase after ovulation and remain elevated during gestation, inhibiting uterine contraction and preventing oestrus. However, when a pregnant sow is subjected to stress her levels of this hormone are reduced (Ake et al., 2023). During the luteal phase of the cycle, the production of P_4 is altered. This may prevent corpus luteum formation and cause early luteolysis by induction of prostaglandin $F_{2\alpha}$ (Giersch et al., 2022). Overall, there is an increase in lipopolysaccharide (LPS) which alters the receptivity of P_4 in the uterus which can also be reflected in the development and survival of the embryo. P_4 levels are modulated by the hypothalamus-pituitary-ovary axis. Once ovulation occurs, the luteal phase begins with the formation of the hemorrhagic corpus luteum (red), then the functional corpus luteum (yellow) that activates the synthesis of P_4 and finally the corpus luteum albicans (white) (Das et al., 2023a). P_4 is synthesized from cholesterol in the mitochondria of granulosa cells. The first reaction is catalyzed by cholesterol desmolase (CYP11A1), which converts cholesterol to pregnenolone. Then, 3β-hydroxysteroid dehydrogenase converts pregnenolone to P_4 and this synthesis is influenced by factors such as energy, lipid and protein metabolism, which impact reproductive efficiency (Payne & Hales, 2004). At the molecular level, P_4 exerts its action through specific receptors on target cells (Katzenellenbogen, 2000). In the uterus, it binds to P_4 receptors that modulate gene expression to prepare the endometrial tissue for implantation. These receptors act through intracellular second messengers, such as cAMP, which regulate the expression of genes necessary for gestation. In addition, enzymatic activity is key to the synthesis and degradation of P_4.

10.6 Prostaglandins F2α

Prostaglandins F2α (PGF2α) is a key hormone in the regulation of the oestrus cycle in sows, particularly in luteolysis, i.e. it ensures the interruption of P_4 secretion, which helps the restart of the oestrus cycle with the consequent follicular phase resulting in the return to oestrus so that they can be inseminated at the optimal time (De Rensis et al., 2012). Proper luteolysis allows maximizing the number of fertile cycles per year, which improves prolificacy. PGF2α is a carboxylic acid with a central cyclopentane ring with two hydrocarbon side chains. It has a hydroxyl group (-OH) on carbons 9 and 11 of the molecules (Ruan & Dogne, 2006). PGF2α is synthesized in the endometrium of sows, mainly towards the end of the oestrus cycle, when no embryo is present. Their synthesis by both the corpus luteum and the uterus is induced by the release of oxytocin which has contractile effects on smooth muscle (De Rensis et al., 2012). At the molecular level, cyclooxygenase enzymes (COX-1 and COX-2) are primarily responsible for converting arachidonic acid to prostaglandins, including PGF2α. Signaling pathways include the activation of membrane receptors such as the prostaglandin F receptor (FP) in the corpus luteum, which is a receptor belonging to the prostaglandin (PG) group of receptors. FP binds to PGF2α and modulates intracellular activity through second messengers such as cAMP (Smith et al., 2011). Also, PGF2α promotes luteal cell apoptosis. This process is mediated by signaling pathways that include second messengers such as inositol triphosphate

(IP3) involved in the increase of intracellular Ca^+ and the activation of proteases such as caspases, which induce programmed cell death of the corpus luteum. PGF2α synthesis depends on the availability of lipid precursors such as arachidonic acid (Hu et al., 2024). Phospholipase A2 (PLA2) is a key enzyme that releases arachidonic acid from membrane phospholipids, allowing PGF2α synthesis. Finally, knowing and managing PGF2α levels allows pig farmers to optimize on-farm reproductive efficiency by improving key parameters such as oestrus synchronization and artificial insemination.

10.7 Testosterone

Testosterone in boars plays a crucial role in regulating their reproductive functions, especially spermatogenesis, sexual behavior, and fertility (Guo et al., 2024). It consists of several carbon atoms, organized into four hydrocarbon rings (Kumar et al., 2016). It presents a hydroxyl group (-OH) at the 17th position of the D-ring, which classifies it as a 17β-hydroxyandrogen. In addition, it has a keto (=O) group at carbon 3 of ring A. Physiologically, testosterone is mainly produced by Leydig cells in response to LH stimulation, this involves a series of enzymatic steps where key enzymes such as 17β-hydroxysteroid dehydrogenase, which converts androstenedione to testosterone, are involved (Naamneh Elzenaty et al., 2022). From a biochemical and molecular point of view, testosterone is a cholesterol-derived steroid, and the regulation of its production depends on the transport of cholesterol into the mitochondria, a step mediated by the steroidogenic acute regulatory protein (StAR) (Galano et al., 2022). Androgen receptors, where testosterone binds, are critical for the hormone's action at the cellular level (Heinlein & Chang, 2002). These receptors are found in many tissues, and receptor activation triggers signaling pathways that regulate gene expression necessary for testicular development and reproductive function. The energy, lipid, and protein metabolism of the boar also has implications for testosterone levels (Bee et al., 2020). For example, an energy-rich diet can increase levels of this hormone, which improves libido and reproductive ability. In contrast, nutritional deficiencies, especially in lipids or essential amino acids, can negatively affect hormone synthesis and fertility. For pig farmers, it is critical to know testosterone levels in boars, as the hormone influences fertility rate, prolificacy, and the effectiveness of oestrus synchronization and artificial insemination protocols. Monitoring these levels can help optimize breeding programs and improve herd performance.

11. Current challenges and future trends

Porcine reproductive physiology confronts a dynamic and complex landscape shaped by multiple interrelated challenges that continue to limit optimal fertility, sow longevity, and overall productivity. These challenges range from infectious diseases and environmental stressors to the physiological limits imposed by hyperprolific genetics and evolving animal welfare standards. Each of these factors exerts its influence through distinct biochemical, enzymatic, and molecular mechanisms that compromise reproductive outcomes and efficiency. At the same time, the sector is witnessing the emergence of promising trends and biotechnological innovations designed to address these hurdles and support sustainable intensification in line with global food security targets, such as those articulated under the United Nations Sustainable Development Goal 2 (Zero Hunger) (Peltoniemi et al., 2023).

This section presents a comprehensive analysis of these current challenges and future trends, progressing from broad systemic issues to targeted reproductive solutions. Key aspects—including pathogen-mediated reproductive failure, the biochemical impact of climate-induced heat stress, and the consequences of genetic selection for litter size—are summarized in Table 4 to provide a clear and structured reference for readers. The table illustrates the intricate interplay between causal mechanisms (such as immune evasion by PRRS virus, enzymatic inhibition by endocrine-disrupting chemicals, and placental insufficiency in hyperprolific sows) and their direct impact on reproductive performance metrics, including conception rates, litter size uniformity, and piglet viability (Romoser et al., 2022; Bortolozzo et al., 2023).

Furthermore, this section emphasizes the crucial need to integrate biotechnological, genetic, and precision management innovations to mitigate these challenges. These include advanced assisted reproductive technologies (ART), genomic selection strategies, gene editing applications, and precision livestock farming tools that collectively aim to enhance reproductive resilience, improve sow welfare, and reduce environmental footprint, thereby supporting a more sustainable and productive swine industry for the future.

11.1 Current challenges

Porcine reproduction continues to face a broad range of challenges that jeopardize fertility, litter viability, and overall herd productivity. Figure 10 illustrates the anatomical and physiological stresses observed in hyperprolific sows, providing context to many of the issues discussed below.

Table 4
Current challenges and future trends in porcine reproductive physiology

Current Challenges	References
• Infectious diseases compromising fertility, including PRRSV and emerging pathogens that impair embryonic survival and cause reproductive failure.	(Lunney et al., 2016)
• Seasonal infertility and heat stress reducing oocyte and embryo quality, mediated by oxidative stress and hormonal disruption.	(Peltoniemi et al., 2023)
• Endocrine disruptors altering steroidogenic enzymes and hormone receptor signaling, affecting sow fertility.	(Peltoniemi et al., 2023)
• Hyperprolific sows with large litters leading to low birth weights, higher piglet mortality, and excessive maternal catabolism.	(Bortolozzo et al., 2023)
• Balancing prolificacy and sustainability to meet Sustainable Development Goals (SDG2; Zero Hunger) without compromising sow welfare and longevity.	(Koketsu et al., 2017)
Future Trends	
• Adoption of nonsurgical embryo transfer techniques with vitrified embryos to improve genetic dissemination and biosecurity.	(Gil et al., 2025)
• Integration of post-cervical and low-dose AI techniques to increase efficiency and reduce semen use.	(Bortolozzo et al., 2024)
• Application of genomic selection to enhance reproductive traits, resilience, and longevity.	(Zak et al., 2017)
• Development of PRRS-resistant pigs through gene editing (CD163 modification) to eliminate key disease bottlenecks.	(Nesbitt et al., 2024)
• Advancements in IVF and microfluidic embryo culture to improve in vitro embryo viability and scalability.	(Chen et al., 2021)

11.1.1 Infectious diseases and reproductive health

Infectious diseases remain one of the most significant barriers to optimal porcine reproductive performance. Porcine reproductive and respiratory syndrome virus (PRRSV) is particularly notorious, often regarded as the most economically damaging swine pathogen worldwide (Lunney et al., 2016). PRRSV, an arterivirus, targets macrophages and subverts host immunity via interference with interferon signaling pathways, enabling persistent infection. The result is reproductive failure manifesting as late-term abortion, stillbirth, and weak piglets. Additionally, PRRSV induces cytokine dysregulation and oxidative stress, impairing placental integrity and fetal development. Other pathogens, such as porcine parvovirus and Leptospira spp., contribute to embryonic mortality and abortion. Meanwhile, transboundary diseases like African swine fever (ASF) pose catastrophic risks, forcing culling and disrupting production (Ackerman, 2022). Despite vaccine efforts, high mutation rates and immune evasion limit PRRSV vaccine effectiveness, underscoring the need for improved antiviral and immunomodulatory strategies (Nesbitt et al., 2024).

11.1.2 Environmental stressors and endocrine disruptors

Environmental stress, particularly from heat, is a growing threat under climate change scenarios. Heat stress elevates cortisol and suppresses gonadotropin release, extending the weaning-to-estrus interval and reducing conception rates (Romo-Valdez et al., 2022). At the cellular level, it increases reactive oxygen species that damage ovarian follicles and disrupt steroidogenic enzyme activity (Lucy & Safranski, 2017). Chronic heat exposure thus promotes seasonal infertility and jeopardizes reproductive efficiency.

Endocrine-disrupting chemicals (EDCs) like phthalates, bisphenol A, and cadmium interfere with hormone receptor function and inhibit steroidogenic enzymes, compromising estrous cyclicity, ovulation, and embryo development (Guarnotta et al., 2022). Such molecular disruptions necessitate both improved management strategies (e.g. cooling systems, diet adjustments) and regulatory measures to mitigate environmental contamination (Peltoniemi et al., 2023).

11.1.3 Hyperprolific sows and management challenges

Genetic selection for prolificacy has increased litter sizes, often at the cost of individual piglet vitality. Hyperprolific sows frequently birth more piglets than they have functional teats, with declining average birth weights (Bortolozzo et al., 2023). Intrauterine crowding reduces placental efficiency, contributing to intrauterine growth restriction, elevated fetal cortisol, and increased stillbirth rates (van den Bosch et al., 2023). Postpartum, these sows experience extreme metabolic strain to meet milk demands, leading to catabolism that impairs subsequent ovarian function. Cross-fostering, while necessary, introduces stressors that affect piglet growth uniformity. Addressing these issues requires integrated nutritional, genetic, and housing solutions that enhance both sow resilience and piglet survival (Bortolozzo et al., 2023).

11.1.4 Housing, welfare, and management

Transitioning from gestation stalls to group housing aligns with welfare standards but introduces reproductive risks, as aggression during group mixing can cause embryonic loss via stress-mediated disruption of uterine receptivity (Chou & Parsons, 2022).

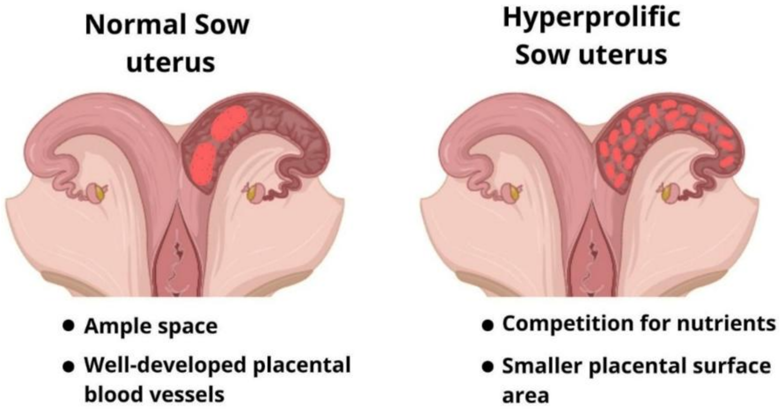

Figure 10. Comparison of normal vs. hyperprolific sow uterus.

Electronic sow feeders and optimized group strategies mitigate these effects but demand precise implementation. Artificial insemination (AI) remains widespread, but extended semen storage increases bacterial contamination risks, often requiring antibiotics in extenders—a practice under scrutiny given antimicrobial resistance (Waberski et al., 2019; Contreras et al., 2022). Innovation in non-antibiotic preservation is urgently needed.

11.1.5 Sustainable reproduction and SDG2

All these challenges connect directly to sustainability. Reduced fertility and piglet survival increase resource use per weaned piglet, undermining efficiency and food security (Tucker et al., 2021). Aligning with SDG2 (Zero Hunger) requires not just maximizing litter size but ensuring piglet viability, optimizing maternal longevity, and enhancing climate resilience to produce more pork with fewer resources.

11.2 Future trends

In response to the multifaceted challenges outlined above, porcine reproductive physiology is entering an era of transformative innovation. Future trends point toward the integration of advanced reproductive biotechnologies, precision management, and genetic engineering, all aimed at enhancing fertility, resilience, and sustainability in swine production. Figure 11 visually summarizes these advances and their expected synergies.

11.2.1 Advances in assisted reproductive technologies (ART)

Several improvements in ART are on the horizon for swine, aiming to enhance reproductive efficiency beyond traditional artificial insemination. One major breakthrough is in embryo transfer (ET) technology. Historically, ET in pigs was limited by the need for surgical procedures and the difficulty of non-surgical embryo deposition due to the complex cervical anatomy. Recent innovations have led to nonsurgical deep-uterine embryo transfer techniques that allow practitioners to deposit embryos directly into the uterine horns of sows or gilts without surgery (Das et al., 2023c). Gil et al. (2025) demonstrated that using a specialized transcervical catheter, high pregnancy rates and litter sizes can be achieved with deep-uterine ET, even with vitrified (frozen) embryos. This is a significant trend because it enables rapid dissemination of elite genetics or genetically engineered lines across farms and countries with minimal disease transmission risk (embryos can be washed and are less likely to carry pathogens than live animals or even semen). The underlying biological advancements include improved cryopreservation methods – notably, ultra-rapid vitrification that prevents ice crystal formation in embryos, thus maintaining viability upon thaw (Amini & Benson, 2023). Vitrification has overcome prior enzymatic and structural damage associated with slow-freezing methods in pig embryos. Moreover, refinements in embryo culture media (supplemented with antioxidants, energy substrates, and reproductive tract fluids) have improved in vitro embryo quality, addressing issues like polyspermy and developmental blocks. Despite these improvements, current in vitro-produced pig embryos still result in somewhat lower farrowing rates and smaller litters than in vivo embryos. Future research should focus on studying oviductal epithelium co-culture, microfluidic culture systems, and better synchronization of embryonic development with recipient physiology (Chen et al., 2021). Parallel to ET, the cornerstone of pig reproduction –artificial insemination – is also evolving. The trend is toward optimization of semen usage and fertility.

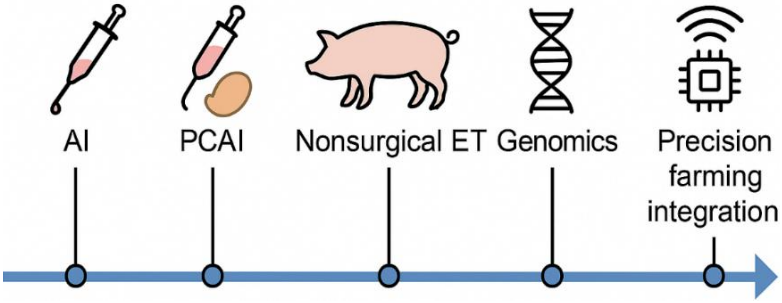

Figure 11. Schematic representation of integrated future technologies in porcine reproduction. AI, artificial insemination; PCAI, post-cervical AI; ET, Embryo Transfer.

Researchers are developing low-dose insemination protocols, such as post-cervical AI (PCAI), where semen is deposited closer to the uterine body or horns, reducing backflow and requiring fewer sperm per service. This is enabled by improved AI catheters and better understanding of uterine immune responses. By using only, a fraction of the traditional 2–3 billion sperm dose, boar stud resources can be stretched further, allowing one boar's ejaculate to inseminate many more sows without compromising conception rates (Bortolozzo et al., 2024). The molecular rationale here involves ensuring enough sperm reach the oviduct to undergo capacitation – advances in semen extenders (with appropriate buffers, energy sources, and decapacitation agents) keep sperm viable and fertilization-competent even at lower concentrations. Additionally, boar semen cryopreservation – long a challenge due to boar sperm's sensitivity to cooling (cholesterol-poor membranes suffer cold shock) – has seen progress. New cryoprotectants (e.g. specific penetrating and non-penetrating agents like glycerol combined with egg yolk plasma components) and cooling curves have improved post-thaw sperm motility and fertilizing ability (Zhang et al., 2024). Though not yet routine, cryopreserved boar semen may become more viable for on-demand global use of genetics, especially as transgenic or gene-edited boars of high value are produced. Furthermore, emerging techniques like sperm sex-sorting are under development for pigs. While flow cytometry-based sorting is slow and stressful to sperm, novel approaches such as immunological sexing (using antibodies against male-bearing or female-bearing sperm surface markers) are being investigated (Bai et al., 2025). If cracked, sexed semen would allow producers to choose the sex of offspring (for example, more females for breeding programs or more males for faster growth in finishing), which could improve efficiency and animal welfare (by reducing the need for practices like male pig castration). Underlying this is an intense focus on sperm physiology: understanding membrane differences between X and Y sperm or exploiting slight molecular weight differences in DNA content. In summary, the future of AI in pigs will be more precise and efficient – more pigs per drop of semen – achieved through better technology and deeper knowledge of gamete biology.

11.2.2 Emerging reproductive biotechnologies

Beyond AI and ET, other assisted reproduction techniques are advancing. In vitro fertilization (IVF) and in vitro embryo production in pigs have traditionally lagged behind cattle due to unique challenges (e.g. porcine oocytes are high in lipid, making them sensitive to in vitro manipulation, and pig sperm are prone to causing polyspermy) (Chen et al., 2021). However, future trends indicate significant improvements in IVF outcomes. Researchers have identified that mimicking the oviduct environment is key – for instance, adding oviductal fluid factors or using follicular fluid-conditioned media during oocyte maturation improves oocyte quality and reduces polyspermy at fertilization (Medeiros, 1999). Additionally, optimizing the timing of IVF (co-incubation intervals and sperm-to-oocyte ratios) and employing pre-IVF sperm selection (such as swim-up or microfluidic sorting to enrich the most motile, acrosome-intact sperm) have increased the yield of viable blastocysts. One exciting future avenue is the use of microfluidics and lab-on-a-chip systems to handle gametes and embryos under more physiological conditions – for example, devices that gradually expose fertilized zygotes to an "oviduct-on-chip" nutrient flow (Ma et al., 2024). On the molecular side, supplementing embryo culture with antioxidants (like melatonin or resveratrol) has been shown to reduce oxidative stress in vitro and improve blastocyst development, reflecting an understanding of the biochemical stressors of culture (Zarbakhsh, 2021). Moreover, gene expression studies on in vitro vs. in vivo embryos are guiding adjustments in culture media (amino acid composition, growth factors) to more closely match the uterine environment. Together, these innovations could eventually allow large-scale production of pig embryos in vitro with high viability. The implications are vast: farms might one day receive batches of elite embryos to implant, much as dairy farms purchase bull semen today.

Another biotechnology on the horizon is the refinement of gamete preservation and manipulation (Aponte et al., 2024). For example, the development of ovarian tissue cryopreservation and transplantation could preserve genetics from valuable sows or rare breeds. Also, progress in oocyte vitrification (rapid freezing of eggs) may enable female gamete banking similar to semen banks (Mukherjee et al., 2023). If successful, farms could store surplus oocytes from high-genetic-merit gilts and fertilize them on demand. Additionally, scientists are exploring interspecies surrogacy techniques (Choe et al., 2022) – such as using pigs as gestational carriers for embryos of other pig breeds or even other species (e.g. for conserving wild suid species) – though immunological barriers are a challenge. On the more experimental end, research into in vitro gametogenesis (IVG) – creating sperm or oocytes from stem cells – is a future possibility. While IVG in pigs is not yet reality, stem cell studies in rodents hint that in the long term, stem cell–derived gametes could circumvent some limitations of animal reproduction (Rosner et al., 2023). Such technology could allow propagation of genetics from, say, a tissue sample of a castrated male or a deceased boar, by inducing pluripotent stem cells to form functional sperm.

11.2.3 Advances in porcine genetics and genomic selection

Genetic improvement remains a cornerstone of future trends in reproductive performance. Traditional selection for litter size and related traits has already yielded more prolific sows, but with the trade-offs noted earlier. The future will leverage genomic tools to achieve balanced genetic gains – improving fertility and prolificacy while also enhancing piglet survival, disease resistance, and tolerance to stress. One major trend is the use of genomic selection, which incorporates dense SNP (single nucleotide polymorphism) genotyping and whole-genome data to more accurately predict breeding values for complex traits like sow lifetime productivity or litter size variability (Zhao et al., 2023b). By identifying genomic markers linked to reproductive success (for example, alleles of the estrogen receptor (ESR) gene or prolactin receptor that influence litter size, or markers for ovulation rate and uterine capacity), breeding companies can select replacements with greater precision (Zak et al., 2017). This genomics-driven approach uses statistical models to handle the polygenic nature of reproductive traits (Zhao et al., 2020; Yu et al., 2024). Importantly, it also enables selection for previously hard-to-improve traits, such as sow longevity or resilience. For instance, genetic analysis can reveal pigs that maintain reproductive performance under high temperatures (Romo-Valdez et al., 2022) – those with inherent heat tolerance – allowing breeders to propagate these genotypes in anticipation of climate change. We can expect breeding goals to increasingly include fitness and robustness traits (e.g. the ability to return to estrus quickly after lactation, or immunocompetence indicators) alongside classic production metrics. This aligns with One Health calls for more resilient pigs that can thrive without intensive interventions (Pinto Jimenez et al., 2023). The molecular basis of these traits is being unraveled through transcriptomics and epigenomics; for example, researchers are studying differential gene expression in the ovaries or endometrium of high-fertility vs. subfertile sows to find key regulatory genes or epigenetic marks that could serve as selection targets (Deryabin & Borodkina, 2024; Hosseinzadeh & Masoudi, 2024). In the coming years, it's plausible that specific gene variants (detected via genome-wide association studies) will be incorporated into selection indices to accelerate genetic progress in reproductive efficiency.

Perhaps the most revolutionary trend in genetics is the advent of gene editing in pigs. The CRISPR-Cas9 system has given scientists the ability to alter the pig genome with unparalleled precision, which can be used to address reproductive challenges and enhance traits. A landmark example is the creation of PRRS-resistant pigs by editing the gene CD163. CD163 encodes a receptor on macrophages that PRRS virus requires for entry; by deleting a small portion of this gene (specifically the SRCR5 domain), researchers produced pigs completely immune to PRRSV infection. Notably, these gene-edited pigs show normal development, growth, and reproductive performance, with no apparent side effects from the deletion. This breakthrough, confirmed by Nesbitt et al. (2024), illustrates how gene editing can directly solve a reproductive and health challenge that conventional breeding could not fix quickly. The biochemical reasoning is clear: removing the virus's entry receptor prevents the pathogen's life cycle from proceeding, thereby protecting the animal from disease and the associated reproductive losses. In the coming years, we may see regulatory approval for such disease-resistant pigs, which would be a game-changer for the swine industry's sustainability (fewer losses, less need for medications, etc.). Beyond disease resistance, gene editing is being explored for traits like eliminating boar taint (by knocking out genes in the androstenone/skatole pathway to obviate castration) (Squires et al., 2020) and enhancing skeletal development in large litters (e.g. overexpression of certain growth factors in utero to improve low birth weight outcomes – though this is in early stages) (Page et al., 2023). Molecular genome engineering might also enable more subtle improvements in reproduction: for instance, editing genes that regulate ovulation rate or embryo survival (Page et al., 2023). Caution is warranted, however, as reproduction traits are usually polygenic; editing single genes might have limited effect unless they are true rate-limiting factors. Another fascinating frontier is using gene editing to create universal embryo recipients (Kubikova et al., 2023)– for example, modifying pigs so they lack certain cell-surface antigens, allowing cross-breed or even cross-species embryo implantation without rejection (this concept is analogous to making pigs for xenotransplantation that lack human-incompatible antigens). While still speculative, it underscores the transformative potential of gene editing tools.

11.2.4 Integration of biotechnology with sustainable practices

Future trends will also see an integration of these biotechnologies with precision farming and sustainability efforts. Precision livestock farming (PLF) technologies, like real-time sensors and machine learning, will complement reproductive management – from automated estrus detection (e.g. activity monitors that identify standing heat with high accuracy) to smart climate control systems that mitigate heat stress effects on sow barns (Tzanidakis et al., 2023a; Tzanidakis et al., 2023b). Nutritional biotechnology is contributing as well: diets supplemented with specific additives (like omega-3 fatty acids, which can modulate inflammatory pathways, or antioxidants like vitamin E and selenium) are being optimized to improve sow ovarian function and piglet viability (Smołucha et al., 2024). Even the sow's microbiome is being studied for its role in reproduction – future probiotics might help prevent postpartum dysgalactia or improve energy harvest during lactation, thereby aiding reproductive recovery. In breeding, gene editing and genomic selection are not mutually exclusive but complementary: for instance, genomic selection will continue to improve polygenic traits, while gene editing tackles monogenic bottlenecks or disease susceptibilities.

Crucially, these future trends align with the goal of sustainable intensification in line with SDG2. By implementing advanced ARTs, producers can get more viable piglets from each sow while using fewer natural resources (since improvements like disease resistance and climate resilience reduce losses). Assisted reproduction also enables dissemination of best genetics globally without transporting animals, lowering the carbon footprint and biosecurity risks. In the future scenario, a high-health nucleus farm could send frozen embryos or semen around the world, helping improve local pig productivity without shipping live pigs. Likewise, gene edits like PRRS resistance directly reduce the need for feed and energy that would otherwise be "wasted" on sick or culled animals. However, it will be important to navigate ethical and regulatory dimensions – societal acceptance of gene-edited livestock, for example, is still evolving. International cooperation will be needed to ensure these technologies benefit food security broadly and do not widen gaps between high-tech producers and others.

12. Conclusions

Porcine reproductive physiology is a complex field that encompasses essential processes such as oogenesis, spermatogenesis, the oestrus cycle, follicular dynamics, fertilization, and gestation. These events are regulated by the interaction between the hypothalamic-pituitary-gonadal axis and various metabolic factors, such as glucose, triglycerides, and cholesterol. The proper synchronization of these processes is crucial for reproductive efficiency and productivity in the swine industry.

In females, hormonal regulation determines oocyte maturation, ovulation, and uterine preparation for embryo implantation, while in males, testosterone production is essential for spermatogenesis and fertility. Additionally, energy and lipid metabolism play a key role in providing essential substrates for hormone synthesis, directly affecting estrus expression, fertility, and prolificacy.

A detailed understanding of these mechanisms allows for the optimization of reproductive strategies such as artificial insemination and estrus synchronization, thereby improving production efficiency and reducing reproductive losses. However, knowledge gaps remain regarding the interaction between hormonal and metabolic factors during gestation, highlighting the need for further research.

Studying porcine reproductive physiology not only contributes to improving animal production but also has applications in reproductive biotechnology and comparative medicine. A deeper understanding of these processes will enable the development of new strategies to maximize reproductive efficiency and gestational success in pigs, benefiting both the livestock industry and biomedical research. Porcine reproductive physiology is also increasingly challenged by multifactorial stressors that threaten sow fertility, piglet survival, and overall herd productivity. Key challenges include infectious diseases such as Porcine Reproductive and Respiratory Syndrome Virus (PRRSV), environmental stressors like heat stress and endocrine-disrupting chemicals, and the physiological demands associated with hyperprolific sows. These factors contribute to reproductive inefficiencies, higher pre-weaning mortality, and compromised animal welfare, complicating efforts toward sustainable pig production.

Looking ahead, future trends in swine reproduction are driven by advances in assisted reproductive technologies, genomic selection, and gene editing. Innovations such as nonsurgical embryo transfer, low-dose artificial insemination, and CRISPR-mediated disease resistance offer promising tools to enhance reproductive performance while addressing biosecurity and animal welfare concerns. The integration of precision livestock farming technologies and nutritional biotechnologies further aligns with global objectives for sustainable intensification under frameworks such as the UN Sustainable Development Goal 2 (Zero Hunger). Nonetheless, ethical, regulatory, and societal acceptance challenges must be navigated to ensure these technologies contribute equitably and responsibly to global food security and animal health.

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Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this study.

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References

Ackerman, D. (2022). *2022 African swine fever virus research review* (L. Robinson, Ed.). STAR-IDAZ International Research Consortium.

Ake, A. S., Ayo, J. O., Aluwong, T., Mohammed, A., & Minka, N. S. (2023). Melatonin modulates rectal and body surface temperatures and their circadian rhythmicity in donkeys (Equus asinus) subjected to packing during the hot-dry season. *International Journal of Biometeorology*, *67*(2), 389-404. https://doi.org/10.1007/s00484-022-02418-8

Akhavizadegan, H., Farsani, R. M., Golmohammadi, P., & Van Der Walt, S. (2025). Chapter 11 - Infertility and the chromosomal abnormalities. In S. M. Kazem Aghamir (Ed.), Genetics and Epigenetics of Genitourinary Diseases (pp. 151-180). Academic Press. https://doi.org/10.1016/B978-0-443-27302-5.00004-8

Albrizio, M., Lacalandra, G. M., & Cinone, M. (2022). The role of bicarbonate in the modulation of capacitation, spontaneous acrosome reaction and motility of equine fresh and frozen spermatozoa. *Theriogenology*, *187*, 112-118. https://doi.org/10.1016/j.theriogenology.2022.04.032

Amini, M., & Benson, J. D. (2023). Technologies for vitrification based cryopreservation. *Bioengineering*, *10*(5), 508. https://doi.org/10.3390/bioengineering10050508

Aponte, P. M., Gutierrez-Reinoso, M. A., & Garcia-Herreros, M. (2024). Bridging the Gap: Animal Models in Next-Generation Reproductive Technologies for Male Fertility Preservation. *Life*, *14*(1), 17. https://doi.org/10.3390/life14010017

Arboccó, F. C. V., Persia, F. A., Zyla, L., Bernal, N., Sasso, V. C., Santiano, F., Gomez, S., Bruna, F., Pistone-Creydt, V., Lopez-Fontana, C., Jahn, G. A., Hapon, M. B., & Carón, R. W. (2023). Long-term impact of hypothyroidism during gestation and lactation on the mammary gland. *Journal of Developmental Origins of Health and Disease*, *14*(1), 122-131. https://doi.org/10.1017/S2040174422000320

Báez, F., López Darriulat, R., Rodríguez-Osorio, N., & Viñoles, C. (2022). Effect of season on germinal vesicle stage, quality, and subsequent in vitro developmental competence in bovine cumulus-oocyte complexes. *Journal of Thermal Biology*, *103*, 103171. https://doi.org/10.1016/j.jtherbio.2021.103171

Bai, L., Zhao, Y., Zhou, Y., Song, Y., Xiao, H., Zhao, G., Wang, Z., & Li, X. (2025). Advances in immunological sorting of X and Y chromosome-bearing sperm: from proteome to sex-specific proteins. *Frontiers in Veterinary Science*, *12*. https://doi.org/10.3389/fvets.2025.1523491

Ballester, M., Amills, M., González-Rodríguez, O., Cardoso, T. F., Pascual, M., González-Prendes, R., Panella-Riera, N., Díaz, I., Tibau, J., & Quintanilla, R. (2018). Role of AMPK signalling pathway during compensatory growth in pigs. *BMC Genomics*, *19*(1), 682. https://doi.org/10.1186/s12864-018-5071-5

Balu, R., Ramachandran, S. S., Mathimaran, A., Jeyaraman, J., & Paramasivam, S. G. (2022). Functional significance of mouse seminal vesicle sulfhydryl oxidase on sperm capacitation in vitro. *Molecular Human Reproduction*, *28*(9). https://doi.org/10.1093/molehr/gaac025

Bao, J., & Bedford, M. T. (2016). Epigenetic regulation of the histone-to-protamine transition during spermiogenesis. *Reproduction*, *151*(5), R55-R70. https://doi.org/10.1530/REP-15-0562

Baranizadeh, K., Mahboobian, M. M., Amiri, I., Tavilani, H., & Shafiee, G. (2022). Effects of progesterone nanoparticles on the sperm capacitation and acrosome reaction in asthenozoospermia men. *Andrologia*, *54*(1), e14258. https://doi.org/10.1111/and.14258

Bee, G., Quiniou, N., Maribo, H., Zamaratskaia, G., & Lawlor, P. G. (2020). Strategies to meet nutritional requirements and reduce boar taint in meat from entire male pigs and immunocastrates. *Animals*, *10*(11), 1950. https://doi.org/10.3390/ani10111950

Bortolozzo, F. P., Zanin, G. P., Christ, T. S., Rech, R. D., da Rosa Ulguim, R., & Mellagi, A. P. G. (2024). Artificial insemination and optimization of the use of seminal doses in swine. *Animal Reproduction Science*, *269*, 107501. https://doi.org/10.1016/j.anireprosci.2024.107501

Bortolozzo, F. P., Zanin, G. P., Ulguim, R. d. R., & Mellagi, A. P. G. (2023). Managing reproduction in hyperprolific sow herds. *Animals*, *13*(11), 1842. https://doi.org/10.3390/ani13111842

Bremer, A. A., & Miller, W. L. (2014). Chapter 13 - Regulation of Steroidogenesis. In A. Ulloa-Aguirre and P. M. Conn (Eds.), Cellular Endocrinology in Health and Disease (pp. 207-227). Academic Press. https://doi.org/10.1016/B978-0-12-408134-5.00013-5

Cañón-Beltrán, K., Cajas, Y. N., González, E., Fernández-González, R., Fierro, N., Lorenzo, P. L., Arias-Álvarez, M., García-García, R. M., Gutiérrez-Adán, A., & Rizos, D. (2023). Acquisition of fertilization competence in guinea pig spermatozoa under different capacitation protocols. *Theriogenology*, *198*, 231-240. https://doi.org/10.1016/j.theriogenology.2022.12.042

Casarini, L., & Crépieux, P. (2019). Molecular mechanisms of action of FSH. *Frontiers in Endocrinology*, *10*, 305. https://doi.org/10.3389/fendo.2019.00305

Chen, P. R., Redel, B. K., Kerns, K. C., Spate, L. D., & Prather, R. S. (2021). Challenges and considerations during in vitro production of porcine embryos. *Cells*, *10*(10), 2770. https://doi.org/10.3390/cells10102770

Chen, Y., Wang, S., & Zhang, C. (2025). The differentiation fate of granulosa cells and the regulatory mechanism in ovary. *Reproductive Sciences*, *32*(5), 1414-1426. https://doi.org/10.1007/s43032-024-01682-w

Choe, Y.-h., Sorensen, J., Garry, D. J., & Garry, M. G. (2022). Blastocyst complementation and interspecies chimeras in gene edited pigs. *Frontiers in Cell and Developmental Biology*, *10*. https://doi.org/10.3389/fcell.2022.1065536

Chou, J.-Y., & Parsons, T. D. (2022). A systematic review of the impact of housing on sow welfare during post-weaning and early pregnancy periods. *Frontiers in Veterinary Science*, *9*, 903822. https://doi.org/10.3389/fvets.2022.903822

Choudhary, S., Kamboj, M. L., Ungerfeld, R., & Singh, P. (2022). Calf-cow and bull-cow management in buffaloes: Effects on growth, productive and reproductive performance of mothers and their calves. *Reproduction in Domestic Animals*, *57*(11), 1428-1439. https://doi.org/10.1111/rda.14219

Contreras, M. J., Núñez-Montero, K., Bruna, P., García, M., Leal, K., Barrientos, L., & Weber, H. (2022). Bacteria and boar semen storage: Progress and challenges. *Antibiotics*, *11*(12), 1796. https://doi.org/10.3390/antibiotics11121796

Dalen, K. T., & Li, Y. (2024). Chapter 3 - Regulation of lipid droplets and cholesterol metabolism in adrenal cortical cells. In G. Litwack (Ed.), Vitamins and Hormones (Vol. 124, pp. 79-136). Academic Press. https://doi.org/10.1016/bs.vh.2023.06.007

Das, P. K., Mukherjee, J., & Banerjee, D. (2023a). Female Reproductive Physiology. In P. K. Das, V. Sejian, J. Mukherjee, and D. Banerjee (Eds.), Textbook of Veterinary Physiology (pp. 513-568). Springer Nature Singapore. https://doi.org/10.1007/978-981-19-9410-4_22

Das, P. K., Mukherjee, J., & Banerjee, D. (2023b). Fertilisation, gestation and parturition. In P. K. Das, V. Sejian, J. Mukherjee, and D. Banerjee (Eds.), Textbook of Veterinary Physiology (pp. 569-613). Springer Nature Singapore. https://doi.org/10.1007/978-981-19-9410-4_23

Das, P. K., Mukherjee, J., & Banerjee, D. (2023c). Functional Morphology of the Male Reproductive System. In P. K. Das, V. Sejian, J. Mukherjee, and D. Banerjee (Eds.), Textbook of Veterinary Physiology (pp. 441-476). Springer Nature Singapore. https://doi.org/10.1007/978-981-19-9410-4_19

De Rensis, F., Saleri, R., Tummaruk, P., Techakumphu, M., & Kirkwood, R. N. (2012). Prostaglandin F2α and control of reproduction in female swine: a review. *Theriogenology*, *77*(1), 1-11. https://doi.org/10.1016/j.theriogenology.2011.07.035

de Souza, V. G., Bandeira, L. B., Souza, N. C. S. e., Taboga, S. R., Martins, T. M. M., & Silva Perez, A. P. (2022). Prenatal and pubertal exposure to 17α-ethinylestradiol disrupts folliculogenesis and promotes morphophysiological changes in ovaries of old gerbils (*Meriones unguiculatus*). *Journal of Developmental Origins of Health and Disease*, *13*(1), 49-60. https://doi.org/10.1017/S2040174421000040

Deryabin, P. I., & Borodkina, A. V. (2024). The role of the endometrium in implantation: a modern view. International *Journal of Molecular Sciences*, *25*(17), 9746. https://doi.org/10.3390/ijms25179746

Esbenshade, K. L., Ziecik, A. J., & Britt, J. H. (1990). Regulation and action of gonadotrophins in pigs. *Journal of Reproduction and Fertility Supplement*, *40*, 19-32.

Fabová, Z., Loncová, B., & Sirotkin, A. V. (2023). MicroRNA miR-125b can suppress ovarian granulosa cell functions: Interrelationships with FSH. *Cell Biochemistry & Function*, *41*(2), 177-188. https://doi.org/10.1002/cbf.3771

Faheem, M. S., Dessouki, S. M., Abdel- Rahman, F. E. S., & Ghanem, N. (2021). Physiological and molecular aspects of heat-treated cultured granulosa cells of Egyptian buffalo (*Bubalus bubalis*). *Animal Reproduction Science*, *224*, 106665. https://doi.org/10.1016/j.anireprosci.2020.106665

Fang, W., Wen, X., Meng, Q., Liu, L., Xie, J., Zhang, H., & Everaert, N. (2020). Running head: heat affects cholesterol and bile acid alterations in cholesterol and bile acids metabolism in large white pigs during short-term heat exposure. *Animals*, *10*(2), 359. https://doi.org/10.3390/ani10020359

Fidarov, A. F., Vihma, V., Bogautdinov, R. P., Morozkina, S. N., Shavva, A. G., & Tikkanen, M. J. (2015). Novel structural features increase the antioxidant effect of estrogen analogues on low density lipoprotein. *The Journal of Steroid Biochemistry and Molecular Biology*, *154*, 142-149. https://doi.org/10.1016/j.jsbmb.2015.08.001

Flowers, W. L. (2022). Factors affecting the production of quality ejaculates from boars. *Animal Reproduction Science*, *246*, 106840. https://doi.org/10.1016/j.anireprosci.2021.106840

Ford, E. A., Frost, E. R., Beckett, E. L., Roman, S. D., McLaughlin, E. A., & Sutherland, J. M. (2021). Transcriptomic profiling of neonatal mouse granulosa cells reveals new insights into primordial follicle activation. *Biology of Reproduction*, *106*(3), 503-514. https://doi.org/10.1093/biolre/ioab193

Fuentes, N., & Silveyra, P. (2019). Chapter 3 - Estrogen receptor signaling mechanisms. In R. Donev (Ed.), Advances in Protein Chemistry & Structural Biology (Vol. 116, pp. 135-170). Academic Press. https://doi.org/10.1016/bs.apcsb.2019.01.001

Fujihara, Y., Kobayashi, K., Abbasi, F., Endo, T., Yu, Z., Ikawa, M., & Matzuk, M. M. (2023). PDCL2 is essential for sperm acrosome formation and male fertility in mice. *Andrology*, *11*(5), 789-798. https://doi.org/10.1111/andr.13329

Galano, M., Venugopal, S., & Papadopoulos, V. (2022). Role of star and SCP2/SCPx in the transport of cholesterol and other lipids. *International Journal of Molecular Sciences*, *23*(20), 12115. https://doi.org/10.3390/ijms232012115

Gałęska, E., Wrzecińska, M., Kowalczyk, A., & Araujo, J. P. (2022). Reproductive consequences of electrolyte disturbances in domestic animals. *Biology*, *11*(7), 1006. https://doi.org/10.3390/biology11071006

Gao, D.-D., Lan, C.-F., Cao, X.-N., Chen, L., Lei, T.-L., Peng, L., Xu, J.-W., Qiu, Z.-E., Wang, L.-L., Sun, Q., Huang, Z.-Y., Zhu, Y.-X., Zhou, W.-L., & Zhang, Y.-L. (2022). G protein-coupled estrogen receptor promotes acrosome reaction via regulation of Ca2+ signaling in mouse sperm. *Biology of Reproduction*, *107*(4), 1026-1034. https://doi.org/10.1093/biolre/ioac136

Gardela, J., Ruiz-Conca, M., Wright, D., López-Béjar, M., Martínez, C. A., Rodríguez-Martínez, H., & Álvarez-Rodríguez, M. (2022). Semen modulates cell proliferation and differentiation-related transcripts in the pig peri-ovulatory endometrium. *Biology*, *11*(4), 616. https://doi.org/10.3390/biology11040616

Ghezelayagh, Z., Khoshdel-Rad, N., & Ebrahimi, B. (2022). Human ovarian tissue in-vitro culture: primordial follicle activation as a new strategy for female fertility preservation. *Cytotechnology*, *74*(1), 1-15. https://doi.org/10.1007/s10616-021-00510-2

Giersch, G. E. W., Charkoudian, N., Morrissey, M. C., Butler, C. R., Colburn, A. T., Caldwell, A. R., Kavouras, S. A., & Casa, D. J. (2022). Corrigendum: estrogen to progesterone ratio and fluid regulatory responses to varying degrees and methods of dehydration. *Frontiers in Sports and Active Living*, *4*. https://doi.org/10.3389/fspor.2022.848595

Gil, M. A., Parrilla, I., Cuello, C., & Martinez, E. A. (2025). Current status of nonsurgical embryo transfer in swine. *Reproduction, Fertility and Development*, *37*(1), RD24137. https://doi.org/10.1071/RD24137

Glencorse, D., Grupen, C. G., & Bathgate, R. (2025). A Review of the Monitoring Techniques Used to Detect Oestrus in Sows. *Animals*, *15*(3), 331. https://doi.org/10.3390/ani15030331

Goszczynski, D. E., Tinetti, P. S., Choi, Y. H., Hinrichs, K., & Ross, P. J. (2021). Genome activation in equine in vitro–produced embryos. *Biology of Reproduction*, *106*(1), 66-82. https://doi.org/10.1093/biolre/ioab173

Guarnotta, V., Amodei, R., Frasca, F., Aversa, A., & Giordano, C. (2022). Impact of chemical endocrine disruptors and hormone modulators on the endocrine system. International *Journal of Molecular Sciences*, *23*(10), 5710. https://doi.org/10.3390/ijms23105710

Guo, S., Liu, C., Wang, Y., Chen, F., Zhu, J., Li, S., & Li, E. (2024). Effect of resveratrol on spermatogenesis in breeding boars and the proteomic analysis for testes. *Reproductive Biology*, *24*(4), 100930. https://doi.org/10.1016/j.repbio.2024.100930

Harris, R. B. S. (2014). Direct and indirect effects of leptin on adipocyte metabolism. *Biochimica et Biophysica Acta (BBA) - Molecular Basis of Disease*, *1842*(3), 414-423. https://doi.org/10.1016/j.bbadis.2013.05.009

Heinlein, C. A., & Chang, C. (2002). Theroles of androgen receptors and androgen-binding proteins in nongenomic androgen actions. *Molecular Endocrinology*, *16*(10), 2181-2187. https://doi.org/10.1210/me.2002-0070

Heringstad, B., & Wethal, K. B. (2023). Cow activity measurements can be used to define new fertility traits for use in genetic evaluation. *JDS Communications*, *4*(2), 99-100. https://doi.org/10.3168/jdsc.2022-0251

Hosseinzadeh, S., & Masoudi, A. A. (2024). Investigating the expression of fertility-regulating LncRNAs in multiparous and uniparous Shal ewe's ovaries. *Genome*, *67*(3), 78-89. https://doi.org/10.1139/gen-2023-0055

Howard, H. J., & Ford, J. J. (1994). Differential steroidogenic response of subpopulations of porcine granulosa cells to insulin-like growth factor-1 (IGF-1) or IGF-1 analogs. *Biology of Reproduction*, *51*(1), 108-115. https://doi.org/10.1095/biolreprod51.1.108

Hu, Y., Li, W., Cheng, X., Yang, H., She, Z.-G., Cai, J., Li, H., & Zhang, X.-J. (2024). Emerging roles and therapeutic applications of arachidonic acid pathways in cardiometabolic diseases. *Circulation Research*, *135*(1), 222-260. https://doi.org/10.1161/CIRCRESAHA.124.324383

Hu, Z., Yu, Y., Huang, G., Li, J., Yang, C., Long, A., Tang, J., Che, T., Zhao, S., & Zhang, T. (2026). IGF-1 deficiency serves as an integrated biomarker pathogenic driver and predictor in poor ovarian response. *Advanced Science*, e14483. https://doi.org/10.1002/advs.202514483

Hunter, R. H. F. (2012). Components of oviduct physiology in eutherian mammals. *Biological Reviews*, *87*(1), 244-255. https://doi.org/10.1111/j.1469-185X.2011.00196.x

Jackson, L. A., Shi, H., Acevedo, J., Lee, S., Annabi, N., Word, R. A., & Florian-Rodriguez, M. (2022). Effect of gelatin methacryloyl hydrogel on healing of the guinea pig vaginal wall with or without mesh augmentation. *International Urogynecology Journal*, *33*(8), 2223-2232. https://doi.org/10.1007/s00192-021-05031-2

Jia, H.-H., Xu, Y.-T., Yin, Z.-P., Wu, X.-M., Qing, M., Fan, Y.-J., Song, X., Xie, K.-D., Xie, Z.-Z., Xu, Q., Deng, X.-X., & Guo, W.-W. (2021). Transcriptomes and DNA methylomes in apomictic cells delineate nucellar embryogenesis initiation in citrus. *DNA Research*, *28*(5), dsab014. https://doi.org/10.1093/dnares/dsab014

Jochems, R., Gaustad, A. H., Styrishave, B., Zak, L. J., Oskam, I. C., Grindflek, E., Myromslien, F. D., Kommisrud, E., & Krogenæs, A. K. (2022). Follicular fluid steroid hormones and in vitro embryo development in Duroc and Landrace pigs. *Theriogenology*, *190*, 15-21. https://doi.org/10.1016/j.theriogenology.2022.07.004

Kaiser, U. B. (2011). Chapter 7 - Gonadotropin hormones. In S. Melmed (Ed.), The Pituitary (Third Edition) (pp. 205-260). Academic Press. https://doi.org/10.1016/B978-0-12-380926-1.10007-0

Kang, H.-I., Lee, C.-B., Kwon, S.-H., Park, J.-M., Kang, K.-S., and Shim, D. (2021a). Comparative transcriptome analysis during developmental stages of direct somatic embryogenesis in Tilia amurensis Rupr. *Scientific Reports*, *11*(1), 6359. https://doi.org/10.1038/s41598-021-85886-z

Kang, Y., Li, W., Zhang, L., & Qi, L. (2021b). Over-expression of the Cell-Cycle gene LaCDKB1;2 promotes cell proliferation and the formation of normal cotyledonary embryos during Larix kaempferi somatic embryogenesis. *Genes*, *12*(9), 1435. https://doi.org/10.3390/genes12091435

Kang, Y. C., Wetterer, R. T., Karimov, R. R., Kojima, M., Surke, M., Martín-Torres, I., Nicolai, J., Elkin, M., & Hartwig, J. F. (2024). Substitution, elimination, and integration of methyl groups in terpenes initiated by C–H bond functionalization. *ACS Central Science*, *10*(11), 2016-2027. https://doi.org/10.1021/acscentsci.4c01108

Karzan Jalal, S. (2021). The major pathways of lipids (triglyceride and cholesterol) and lipoprotein metabolism. *Zanco Journal of Pure and Applied Sciences*, *33*(4), 61-72. https://doi.org/10.21271/ZJPAS.33.4.6

Katzenellenbogen, B. S. (2000). Mechanisms of action and cross-talk between estrogen receptor and progesterone receptor pathways. *Journal of the Society for Gynecologic Investigation*, *7*(1_suppl), S33-S37. https://doi.org/10.1177/1071557600007001s10

Kawashima, N., Tokuda, J., Yagi, T., & Takahashi, K. (2022). Isolation of a Nocardiopsis chromatogenes strain that degrades PLA (polylactic acid) in pig waste-based compost. *Archives of Microbiology*, *204*(10), 599. https://doi.org/10.1007/s00203-022-03144-w

Kern, C., Wu, W., Lu, C., Zhang, J., Zhao, Y., Ocon-Grove, O. M., Sutovsky, P., Diaz, F., & Liu, W.-S. (2023). Role of the bovine PRAMEY protein in sperm function during in vitro fertilization (IVF). *Cell and Tissue Research*, *391*(3), 577-594. https://doi.org/10.1007/s00441-022-03717-7

Knox, R. V. (2019). Physiology and endocrinology symposium: factors influencing follicle development in gilts and sows and management strategies used to regulate growth for control of estrus and ovulation. *Journal of Animal Science*, *97*(4), 1433-1445. https://doi.org/10.1093/jas/skz036

Koketsu, Y., Tani, S., & Iida, R. (2017). Factors for improving reproductive performance of sows and herd productivity in commercial breeding herds. *Porcine Health Management*, *3*(1), 1. https://doi.org/10.1186/s40813-016-0049-7

Kolomeitseva, G. L., Babosha, A. V., Ryabchenko, A. S., & Tsavkelova, E. A. (2021). Megasporogenesis, megagametogenesis, and embryogenesis in Dendrobium nobile (Orchidaceae). *Protoplasma*, *258*(2), 301-317. https://doi.org/10.1007/s00709-020-01573-2

Kozieradzka-Kiszkurno, M. (2021). Embryogenesis in Crassulaceae: structural aspect of suspensor development. *Postepy Biochemii*, *68*(1), 38-45. https://doi.org/10.18388/pb.2021_406

Kraeling, R. R., & Webel, S. K. (2015). Current strategies for reproductive management of gilts and sows in North America. *Journal of Animal Science and Biotechnology*, *6*(1), 3. https://doi.org/10.1186/2049-1891-6-3

Krajnik, K., Mietkiewska, K., Skowronska, A., Kordowitzki, P., & Skowronski, M. T. (2023). Oogenesis in women: from molecular regulatory pathways and maternal age to stem cells. *International Journal of Molecular Sciences*, *24*(7), 6837. https://doi.org/10.3390/ijms24076837

Kubikova, N., Keefe, D. L., Wells, D., Oktay, K. H., & Feinberg, E. C. (2023). Should we use CRISPR gene editing in human embryos? *Fertility and Sterility*, *120*(4), 737-744. https://doi.org/10.1016/j.fertnstert.2023.08.009

Kumar, D., Kumar, V., & Jalwal, P. (2016). Systemic nomenclature of steroids [cyclopentaphenanthrene ring] their derivatives-an overview. *International Journal of Chemical Studies*, *4*(3), 124-132.

Kurata, S., Umezu, K., Takamori, H., Hiradate, Y., Hara, K., & Tanemura, K. (2022). Exogenous gamma-aminobutyric acid addition enhances porcine sperm acrosome reaction. *Animal Science Journal*, *93*(1), e13744. https://doi.org/10.1111/asj.13744

Lange-Consiglio, A., Capra, E., Giuliani, D., Canesi, S., Funghi, F., Bosi, G., Cretich, M., Frigerio, R., Galbiati, V., & Cremonesi, F. (2022). Endometrial and oviduct extra-cellular vescicles for in vitro equine sperm hyperactivation and oocyte fertilization. *Theriogenology*, *194*, 35-45. https://doi.org/10.1016/j.theriogenology.2022.09.023

Laporta, J., Dado-Senn, B., & Skibiel, A. L. (2022). Late gestation hyperthermia: epigenetic programming of daughter's mammary development and function. *Domestic Animal Endocrinology*, *78*, 106681. https://doi.org/10.1016/j.domaniend.2021.106681

Lema, S. C., Chow, M. I., Dittman, A. H., May, D., & Housh, M. J. (2022). Accustomed to the heat: Temperature and thyroid hormone influences on oogenesis and gonadal steroidogenesis pathways vary among populations of Amargosa pupfish (*Cyprinodon nevadensis* amargosae). *Comparative Biochemistry and Physiology Part A: Molecular & Integrative Physiology*, *272*, 111280. https://doi.org/10.1016/j.cbpa.2022.111280

Lei, Y., Liu, H., Xiang, Q., Liu, Y., Wu, D., Zhang, J., & Lin, Y. (2026). Dietary lycopene mitigates reproductive impairment in heat-stressed Rongchang boars: roles of antioxidant, anti-inflammatory and Nrf2 pathway. *Antioxidants*, *15*(2), 245. https://doi.org/10.3390/antiox15020245

Li, J., Yang, H., Qin, K., Wei, L., Xia, X., Zhu, F., Tan, X., Xue, C., & Zhao, Q. (2022a). Effect of pig manure-derived sulfadiazine on species distribution and bioactivities of soil ammonia-oxidizing microorganisms after fertilization. *Journal of Hazardous Materials*, *423*, 126994. https://doi.org/10.1016/j.jhazmat.2021.126994

Li, S., Wang, J., Li, J., Yue, M., Liu, C., Ma, L., & Liu, Y. (2022b). Integrative analysis of transcriptome complexity in pig granulosa cells by long-read isoform sequencing. *PeerJ*, *10*, e13446. https://doi.org/10.7717/peerj.13446

Li, W., Ye, C., He, M., Ko, W. K. W., Cheng, C. H. K., Chan, Y. W., & Wong, A. O. L. (2024). Differential involvement of cAMP/PKA-, PLC/PKC- and Ca2+/calmodulin-dependent pathways in GnRH-induced prolactin secretion and gene expression in grass carp pituitary cells. *Frontiers in Endocrinology*, *15*. https://doi.org/10.3389/fendo.2024.1399274

López-Gatius, F., Saleri, R., De Rensis, F., Llobera-Balcells, M., & Garcia-Ispierto, I. (2022). Transfer of a single fresh in vitro-produced embryo may prevent twin pregnancy without compromising the fertility of the cow. *Reproduction in Domestic Animals*, *57*(4), 450-455. https://doi.org/10.1111/rda.14079

Lounsbury, K. (2009). Chapter 6 - Signal Transduction and Second Messengers. In M. Hacker, W. Messer, and K. Bachmann (Eds.), Pharmacology (pp. 103-112). Academic Press. https://doi.org/10.1016/B978-0-12-369521-5.00006-3

Lucy, M. C., & Safranski, T. (2017). Heat stress in pregnant sows: thermal responses and subsequent performance of sows and their offspring. *Molecular Reproduction Development*, *84*(9), 946-956. https://doi.org/10.1002/mrd.22844

Lunney, J. K., Fang, Y., Ladinig, A., Chen, N., Li, Y., Rowland, B., & Renukaradhya, G. J. (2016). Porcine reproductive and respiratory syndrome virus (PRRSV): pathogenesis and interaction with the immune system. *Annual Review of Animal Biosciences*, *4*(4), 129-154. https://doi.org/10.1146/annurev-animal-022114-111025

Ma, J., Xie, Q., Zhang, Y., Xiao, Q., Liu, X., Qiao, C., and Tian, Y. (2024). Advances in microfluidic technology for sperm screening and in vitro fertilization. *Analytical and Bioanalytical Chemistry*, *416*(16), 3717-3735. https://doi.org/10.1007/s00216-023-05120-9

Maňásková, P., Pěknicová, J., Elzeinova, F., Ticha, M., & Jonakova, V. (2007). Origin, localization and binding abilities of boar DQH sperm surface protein tested by specific monoclonal antibodies. *Journal of Reproductive Immunology*, *74*(1-2), 103-113. https://doi.org/10.1016/j.jri.2006.11.003

Mao, H., Chen, L., Bao, R., Weng, S., Wang, M., Xu, N., Qi, L., & Wang, J. (2022). Mechanisms of oogenesis-related long non-coding rnas in porcine ovaries treated with recombinant pig follicle-stimulating hormone. *Frontiers in Veterinary Science*, *8*. https://doi.org/10.3389/fvets.2021.838703

Marchais, M., Gilbert, I., Bastien, A., Macaulay, A., & Robert, C. (2022). Mammalian cumulus-oocyte complex communication: a dialog through long and short distance messaging. *Journal of Assisted Reproduction and Genetics*, *39*(5), 1011-1025. https://doi.org/10.1007/s10815-022-02438-8

Medeiros, C. O. (1999). *Bovine sperm interaction with oviductal epithelial cells*. The University of Wisconsin-Madison.

Mekata, H., & Yamamoto, M. (2022). Single-nucleotide polymorphism on spermatogenesis associated 16 gene-coding region affecting bovine leukemia virus proviral load. *Veterinary Sciences*, *9*(6), 275. https://doi.org/10.3390/vetsci9060275

Meyerholz, D. K., Burrough, E. R., Kirchhof, N., Anderson, D. J., & Helke, K. L. (2024). Swine models in translational research and medicine. *Veterinary Pathology*, *61*(4), 512-523. https://doi.org/10.1177/03009858231222235

Miller, W. L. (2017). Disorders in the initial steps of steroid hormone synthesis. *The Journal of Steroid Biochemistry and Molecular Biology*, *165*, 18-37. https://doi.org/10.1016/j.jsbmb.2016.03.009

Miyata, H., Shimada, K., Kaneda, Y., & Ikawa, M. (2024). Development of functional spermatozoa in mammalian spermiogenesis. *Development*, *151*(14). https://doi.org/10.1242/dev.202838

Mukherjee, A., Das, P. K., Banerjee, D., & Mukherjee, J. (2023). Assisted reproductive technologies in farm animals. In P. K. Das, V. Sejian, J. Mukherjee, and D. Banerjee (Eds.), *Textbook of Veterinary Physiology* (pp. 615-636). Springer Nature Singapore. https://doi.org/10.1007/978-981-19-9410-4_24

Naamneh Elzenaty, R., du Toit, T., & Flück, C. E. (2022). Basics of androgen synthesis and action. *Best Practice & Research Clinical Endocrinology & Metabolism*, *36*(4), 101665. https://doi.org/10.1016/j.beem.2022.101665

Nesbitt, C., Galina Pantoja, L., Beaton, B., Chen, C.-Y., Culbertson, M., Harms, P., Holl, J., Sosnicki, A., Reddy, S., Rotolo, M., & Rice, E. (2024b). Pigs lacking the SRCR5 domain of CD163 protein demonstrate heritable resistance to the PRRS virus and no changes in animal performance from birth to maturity. *Frontiers in Genome Editing*, *6*, 1322012. https://doi.org/10.3389/fgeed.2024.1322012

Nikiforov, D., Grøndahl, M. L., Hreinsson, J., & Andersen, C. Y. (2022). Human oocyte morphology and outcomes of infertility treatment: a systematic review. *Reproductive Sciences*, *29*(10), 2768-2785. https://doi.org/10.1007/s43032-021-00723-y

Owumi, S. E., Arunsi, U. O., Otunla, M. T., & Oluwasuji, I. O. (2022). Exposure to lead and dietary furan intake aggravates hypothalamus-pituitary-testicular axis toxicity in chronic experimental rats. *Journal of Biomedical Research*, *37*(2), 100. https://doi.org/10.7555/JBR.36.20220108

Page, L., Younge, N., & Freemark, M. (2023). Hormonal determinants of growth and weight gain in the human fetus and preterm infant. *Nutrients*, *15*(18), 4041. https://doi.org/10.3390/nu15184041

Pak, T. R., & Chung, W. C. J. (2024). Chapter 2 - Neuroendocrine control of gonadotropins in mammals. In D. O. Norris and K. H. Lopez (Eds.), Hormones and Reproduction of Vertebrates (Second Edition) (Vol. 5, pp. 23-42). Academic Press. https://doi.org/10.1016/B978-0-443-15986-2.00013-7

Park, Y., Park, Y.-B., Lim, S.-W., Lim, B., & Kim, J.-M. (2022). Time series ovarian transcriptome analyses of the porcine estrous cycle reveals gene expression changes during steroid metabolism and corpus luteum development. *Animals*, *12*(3), 376. https://doi.org/10.3390/ani12030376

Payne, A. H., & Hales, D. B. (2004). Overview of steroidogenic enzymes in the pathway from cholesterol to active steroid hormones. *Endocrine Reviews*, *25*(6), 947-970. https://doi.org/10.1210/er.2003-0030

Peltoniemi, O., Tanskanen, T., & Kareskoski, M. (2023). One Health challenges for pig reproduction. *Molecular Reproduction and Development*, *90*(7), 420-435. https://doi.org/10.1002/mrd.23666

Pinto Jimenez, C. E., Keestra, S., Tandon, P., Cumming, O., Pickering, A. J., Moodley, A., & Chandler, C. I. R. (2023). Biosecurity and water, sanitation, and hygiene (WASH) interventions in animal agricultural settings for reducing infection burden, antibiotic use, and antibiotic resistance: a One Health systematic review. *The Lancet Planetary Health*, *7*(5), e418-e434. https://doi.org/10.1016/S2542-5196(23)00049-9

Pintus, E., & Ros-Santaella, J. L. (2021). Impact of oxidative stress on male reproduction in domestic and wild animals. *Antioxidants*, *10*(7), 1154. https://doi.org/10.3390/antiox10071154

Popli, P., Shukla, V., Kaushal, J. B., Kumar, R., Gupta, K., & Dwivedi, A. (2022). Peroxiredoxin 6 plays essential role in mediating fertilization and early embryonic development in rabbit oviduct. *Reproductive Sciences*, *29*(5), 1560-1576. https://doi.org/10.1007/s43032-021-00689-x

Prunier, A., & Quesnel, H. (2000). Influence of the nutritional status on ovarian development in female pigs. *Animal Reproduction Science*, *60-61*, 185-197. https://doi.org/10.1016/S0378-4320(00)00093-2

Rodriguez-Martinez, H., Roca, J., Alvarez-Rodriguez, M., & Martinez-Serrano, C. A. (2022). How does the boar epididymis regulate the emission of fertile spermatozoa? *Animal Reproduction Science*, *246*, 106829. https://doi.org/10.1016/j.anireprosci.2021.106829

Romo-Valdez, J., Silva-Hidalgo, G., Güémez-Gaxiola, H., Romo-Valdez, A., & Romo-Rubio, J. (2022). Heat stress: influence on the physiology, productive and reproductive performance of the pig. *Abanico Veterinario*, *12*, 1-19. https://doi.org/10.21929/abavet2022.37

Romoser, M. R., Bidne, K. L., Baumgard, L. H., Keating, A. F., & Ross, J. W. (2022). Effects of increased ambient temperature and supplemental altrenogest before pregnancy establishment in gilts. *Journal of Animal Science*, *100*(2), skac007. https://doi.org/10.1093/jas/skac007

Rosner, M., Horer, S., Feichtinger, M., & Hengstschläger, M. (2023). Multipotent fetal stem cells in reproductive biology research. *Stem Cell Research & Therapy*, *14*(1), 157. https://doi.org/10.1186/s13287-023-03379-4

Ruan, K.-H., & Dogne, J.-M. (2006). Implications of the molecular basis of prostacyclin biosynthesis and signaling in pharmaceutical designs. *Current Pharmaceutical Design*, *12*(8), 925-941. https://doi.org/10.2174/138161206776055994

Samura, O., Nakaoka, Y., & Miharu, N. (2023). Sperm and oocyte chromosomal abnormalities. *Biomolecules*, *13*(6), 1010. https://doi.org/10.3390/biom13061010

Sarandol, E., Tas, S., Serdar, Z., & Dirican, M. (2020). Effects of thiamine treatment on oxidative stress in experimental diabetes. *Bratislavske Lekarske Listy*, *121*(3), 235-241. https://doi.org/10.4149/BLL_2020_036

Sato, R., Satoh, H., Okada, S., Goda, Y., Sueun, K., Kuroda, K., Inoue, Y., Kitahara, G., & Osawa, T. (2022). Intra-abdominal mass containing controlled internal drug release (CIDR) devices detected by CT in a Japanese Black cow. *Journal of Veterinary Medical Science*, *84*(8), 1088-1092. https://doi.org/10.1292/jvms.22-0180

Seneda, M. M., Zangirolamo, A. F., González, S. M., & Morotti, F. (2023). Oogenesis and folliculogenesis. In Sustainable Agriculture Reviews 59: Animal Biotechnology for Livestock Production 3 (pp. 59-88). Springer. https://doi.org/10.21451/1809-3000.Rbra2021.042

Serviento, A. M., Lebret, B., & Renaudeau, D. (2020). Chronic prenatal heat stress alters growth, carcass composition, and physiological response of growing pigs subjected to postnatal heat stress. *Journal of Animal Science*, *98*(5). https://doi.org/10.1093/jas/skaa161

Sharif, M., Hickl, V., Juarez, G., Di, X., Kerns, K., Sutovsky, P., Bovin, N., & Miller, D. J. (2022). Hyperactivation is sufficient to release porcine sperm from immobilized oviduct glycans. *Scientific Reports*, *12*(1), 6446. https://doi.org/10.1038/s41598-022-10390-x

Shimazaki, M., Wittayarat, M., Sambuu, R., Sugita, A., Kawaguchi, M., Hirata, M., Tanihara, F., Takagi, M., Taniguchi, M., Otoi, T., & Sato, Y. (2022). Disruption of cell proliferation and apoptosis balance in the testes of crossbred cattle-yaks affects spermatogenic cell fate and sterility. *Reproduction in Domestic Animals*, *57*(9), 999-1006. https://doi.org/10.1111/rda.14166

Sielhorst, J., Roggel-Buecker, U., Neudeck, K.-C., Kahler, A., Rohn, K., Luettgenau, J., Bollwein, H., Hollinshead, F., & Sieme, H. (2022). Effect of acetylsalicylic acid on uterine blood flow, gestation length, foal birth weight and placental weight in pregnant thoroughbred mares – a clinical pilot study. *Journal of Equine Veterinary Science*, *118*, 104107. https://doi.org/10.1016/j.jevs.2022.104107

Smith, W. L., Urade, Y., & Jakobsson, P.-J. (2011). Enzymes of the cyclooxygenase pathways of prostanoid biosynthesis. *Chemical Reviews*, *111*(10), 5821-5865. https://doi.org/10.1021/cr2002992

Smołucha, G., Steg, A., & Oczkowicz, M. (2024). The role of vitamins in mitigating the effects of various stress factors in pigs breeding. *Animals*, *14*(8), 1218. https://doi.org/10.3390/ani14081218

Soede, N. M., Langendijk, P., & Kemp, B. (2011). Reproductive cycles in pigs. *Animal Reproduction Science*, *124*(3), 251-258. https://doi.org/10.1016/j.anireprosci.2011.02.025

Spruijt, A., van Stee, L., Wolthers, K., & de Gier, J. (2022). Case report: medical management of prolonged gestation of a mummified fetus in a bitch. *Frontiers in Veterinary Science*, *9*. https://doi.org/10.3389/fvets.2022.888807

Squires, E. J., Bone, C., & Cameron, J. (2020). Pork production with entire males: directions for control of boar taint. *Animals*, *10*(9), 1665. https://doi.org/10.3390/ani10091665

Strauss, J. F., & FitzGerald, G. A. (2019). Chapter 4 - Steroid hormones and other lipid molecules involved in human reproduction. In J. F. Strauss and R. L. Barbieri (Eds.), Yen and Jaffe's Reproductive Endocrinology (pp. 75-114.e117). Elsevier. https://doi.org/10.1016/B978-0-323-47912-7.00004-4

Strauss, J. F., Modi, B., & McAllister, J. M. (2014). Chapter 18 - Defects in ovarian steroid hormone biosynthesis. In A. Ulloa-Aguirre and P. M. Conn (Eds.), Cellular Endocrinology in Health and Disease (pp. 285-309). Academic Press. https://doi.org/10.1016/B978-0-12-408134-5.00018-4

Sun, Y., Li, X., Jiang, C., Huang, G., Wang, J., Tian, Y., Jiang, L., Shi, X., Zhao, J., & Huang, J. (2026). Eicosapentaenoic acid improves porcine oocyte cytoplasmic maturation and developmental competence via antioxidant and mitochondrial regulatory mechanisms. *Antioxidants*, *15*(1), 137. https://doi.org/10.3390/antiox15010137

Sutovsky, P., Hamilton, L. E., Zigo, M., Ortiz D'Avila Assumpção, M. E., Jones, A., Tirpak, F., Agca, Y., Kerns, K., & Sutovsky, M. (2024). Biomarker-based human and animal sperm phenotyping: the good, the bad and the ugly. *Biology of Reproduction*, *110*(6), 1135-1156. https://doi.org/10.1093/biolre/ioae061

Takei, G. L. (2022). Regulation of sperm hyperactivation by transporters involved in Na+ homeostasis. *Folia Pharmacologica Japonica*, *157*(3), 176-180. https://doi.org/10.1254/fpj.21110

Tran, Q.-K. (2020). Reciprocality between estrogen biology and calcium signaling in the cardiovascular system. *Frontiers in Endocrinology*, *11*. https://doi.org/10.3389/fendo.2020.568203

Tucker, B. S., Craig, J. R., Morrison, R. S., Smits, R. J., & Kirkwood, R. N. (2021). Piglet viability: A review of identification and pre-weaning management strategies. *Animals*, *11*(10), 2902. https://doi.org/10.3390/ani11102902

Tzanidakis, C., Simitzis, P., & Panagakis, P. (2023a). Precision livestock farming (PLF) systems: improving sustainability and efficiency of animal production. In F. P. García Márquez and B. Lev (Eds.), Sustainability: Cases and Studies in Using Operations Research and Management Science Methods (Vol. 333, pp. 285-337). Springer International Publishing. https://doi.org/10.1007/978-3-031-16620-4_15

Tzanidakis, C., Tzamaloukas, O., Simitzis, P., & Panagakis, P. (2023b). Precision livestock farming applications (PLF) for grazing animals. *Agriculture*, *13*(2), 288. https://doi.org/10.3390/agriculture13020288

van den Bosch, M., Soede, N., Kemp, B., & van den Brand, H. (2023). Sow nutrition, uterine contractions, and placental blood flow during the peri-partum period and short-term effects on offspring: a review. *Animals*, *13*(5), 910. https://doi.org/10.3390/ani13050910

van den Brand, H., Dieleman, S. J., Soede, N. M., & Kemp, B. (2000). Dietary energy source at two feeding levels during lactation of primiparous sows: I. Effects on glucose, insulin, and luteinizing hormone and on follicle development, weaning-to-estrus interval, and ovulation rate1. *Journal of Animal Science*, *78*(2), 396-404. https://doi.org/10.2527/2000.782396x

Waberski, D., Riesenbeck, A., Schulze, M., Weitze, K. F., & Johnson, L. (2019). Application of preserved boar semen for artificial insemination: Past, present and future challenges. *Theriogenology*, *137*, 2-7.

Wassarman, P., and Litscher, E. (2022a). Mouse zona pellucida proteins as receptors for binding of sperm to eggs. *Trends in Developmental Biology*, *15*, 1-13.

Wassarman, P. M., & Litscher, E. S. (2022b). Female fertility and the zona pellucida. *eLife*, *11*, e76106. https://doi.org/10.7554/eLife.76106

Wei, J., Liang, Y., Jiang, N., & Hu, G. (2022). IFN-γ differential expression in the hypothalamus-pituitary-ovary axis of thyroidectomized rats. *BMC Endocrine Disorders*, *22*(1), 317. https://doi.org/10.1186/s12902-022-01223-z

Williams, G. L., & Cardoso, R. C. (2021). Chapter 24 - Neuroendocrine control of estrus and ovulation. In R. M. Hopper (Ed.), Bovine Reproduction (pp. 269-291). https://doi.org/10.1002/9781119602484.ch24

Yang, W.-R., Li, B.-B., Hu, Y., Zhang, L., & Wang, X.-Z. (2020). Oxidative stress mediates heat-induced changes of tight junction proteins in porcine sertoli cells via inhibiting CaMKKβ-AMPK pathway. *Theriogenology*, *142*, 104-113. https://doi.org/10.1016/j.theriogenology.2019.09.031

Yang, Y., Jin, H., Qiu, Y., Liu, Y., Wen, L., Fu, Y., Qi, H., Baker, P. N., & Tong, C. (2022). Reactive oxygen species are essential for placental angiogenesis during early gestation. *Oxidative Medicine and Cellular Longevity*, *2022*(1), 4290922. https://doi.org/10.1155/2022/4290922

Yu, W., Cheng, Q., & Biology, A. (2024). Accelerating yam breeding cycles with genomic selection. *Genomics and Applied Biology*, *15*(6), 319-331.

Zaidi, S. K., Shen, W.-J., & Azhar, S. (2012). Impact of aging on steroid hormone biosynthesis and secretion. *Open Longevity Science*, *6*, 1-30. https://doi.org/10.2174/1876326X01206010001

Zak, L. J., Gaustad, A. H., Bolarin, A., Broekhuijse, M. L. W. J., Walling, G. A., & Knol, E. F. (2017). Genetic control of complex traits, with a focus on reproduction in pigs. *Molecular Reproduction and Development*, *84*(9), 1004-1011. https://doi.org/10.1002/mrd.22875

Zarbakhsh, S. (2021). Effect of antioxidants on preimplantation embryo development in vitro: a review. *Zygote*, *29*(3), 179-193. https://doi.org/10.1017/S0967199420000660

Zelenkova, N., Kraus, V., Maresova, A., Pilsova, Z., Pilsova, A., Klusackova, B., Chmelikova, E., Komrskova, K., & Postlerova, P. (2025). Functional Methods for Studying Sperm-Zona Pellucida Interaction in Mammals. *Methods and protocols*, *8*(4), 95. https://doi.org/10.3390/mps8040095

Zhang, Y.-P., Tian, L., Xie, X.-Q., Wang, Y.-T., Lyu, P., & Xi, Z.-G. (2022a). Effects of nanopolystyrene nanoplastic exposure on the development and neurotoxicity of fetal rats during gestation. *Chinese Journal of Applied Physiology*, *38*(6), 760-765. https://doi.org/10.12047/j.cjap.6379.2022.138

Zhang, Y., Otomaru, K., Oshima, K., Goto, Y., Oshima, I., Muroya, S., Sano, M., Roh, S., & Gotoh, T. (2022b). Maternalnutrition during gestation alters histochemical properties, and mrna and microrna expression in adipose tissue of Wagyu fetuses. *Frontiers in Endocrinology*, *12*, 797680. https://doi.org/10.3389/fendo.2021.797680

Zhang, S., Wang, D., Qi, J., Li, J., Liu, S., Sun, H., Liang, S., & Sun, B. (2026). Multiomics analysis reveals that chlorogenic acid alleviates heat stress-induced oxidative damage in prepubertal boar testes via the BLVRA-GPX3 pathway: in vivo and in vitro evidence. *Journal of Animal Science and Biotechnology*, *17*(1), 7. https://doi.org/10.1186/s40104-025-01336-0

Zhang, L., Jiang, C., Wang, X., et al. (2024). Freezing Hu ram semen: influence of different penetrating cryoprotectants and egg yolk level on the post-thaw quality of sperm. *Anim Biosci*, *37*(9), 1548-1557. https://doi.org/10.5713/ab.24.0167

Zhao, H., Wang, Y., & Yang, Y. (2023a). Follicular development and ovary aging: single-cell studies. *Biology of Reproduction*, *109*(4), 390-407. https://doi.org/10.1093/biolre/ioad080

Zhao, W., Lai, X., Liu, D., Zhang, Z., Ma, P., Wang, Q., Zhang, Z., & Pan, Y. (2020). Applications of support vector machine in genomic prediction in pig and maize populations. *Frontiers in Genetics*, *11*. https://doi.org/10.3389/fgene.2020.598318

Zhao, W., Zhang, Z., Ma, P., Wang, Z., Wang, Q., Zhang, Z., & Pan, Y. (2023b). The effect of high-density genotypic data and different methods on joint genomic prediction: A case study in large white pigs. *Animal Genetics*, *54*(1), 45-54. https://doi.org/10.1111/age.13275

Zheng, Y., Gao, Q., Li, T., Liu, R., Cheng, Z., Guo, M., Xiao, J., Wu, D., & Zeng, W. (2022). Sertoli cell and spermatogonial development in pigs. *Journal of Animal Science and Biotechnology*, *13*(1), 45. https://doi.org/10.1186/s40104-022-00687-2

Zhi, M., Zhang, J., Tang, Q., Yu, D., Gao, S., et al. (2022). Generation and characterization of stable pig pregastrulation epiblast stem cell lines. *Cell Research*, *32*(4), 383-400. https://doi.org/10.1038/s41422-021-00592-9