Open Access
Check for updates
International Journal of Medical Science and Dental Health (ISSN: 2454-4191)
Volume 11, Issue 07, July 2025,
Doi https://doi.org/10.55640/ijmsdh-11-07-14

The Role of Nrf2 (Nfe2l2) In the Physiological and Biochemical Pathways Underlying Oxidative Stress-Induced Male Infertility

Rasha Hamzah Abdulhussein
Department of Physiology, Hammurabi College of Medicine, University of Babylon, Iraq

Zahraa Hamid Mohan Al-Gawwam
Department of anatomy, Hammurabi College of Medicine, University of Babylon, Iraq

Rafid A. Taj-Aldeen
Department of Science, College of Basic Education, University of Babylon, Iraq

Hameda Abd Almahdi Ghazi
Department of Anatomy, Hammurabi College of Medicine, University of Babylon, Iraq

Received: 22 June 2025, **accepted:** 08 July 2025, **Published Date:** 28 July 2025

Abstract

Male infertility related to oxidative stress begins with a severe imbalance between the overwhelming generation of reactive oxygen species and restricted capacity of endogenous antioxidant defenses. A chain reaction is initiated by this oxidative imbalance in structural and functional damages to the sperm, such as peroxidation of lipids in the plasma membrane, oxidative modifications to proteins, mitochondrial dysfunction, and fragmentation to both nuclear and mitochondrial DNA. Such molecular damages motility of sperm reduce fluidity in membranes and general fertility thus leads ultimately reduces reproductive success. NRF2 (nuclear factor erythroid 2-related factor 2) has been described as a master regulator in controlling cellular antioxidant responses and hence playing central protective roles against oxidative stresses. In conditions of oxidation NRF2 separates from its cytoplasmic repressor Keap1 moves to nucleus binds on ARE then induces transcription detoxification as well as antioxidant genes including HO-1 heme oxygenase-1 NAD(P)H quinone oxidoreductase -1 superoxide dismutase glutathione peroxidase. It is this signaling pathway that maintains redox homeostasis and protection against cellular damage induced by ROS. On the other hand, impaired NRF2 activation or polymorphisms in the NFE2L2 gene have been associated with increased oxidative stress as well as increased sperm DNA damage and decreased sperm quality. Therefore, elucidating the NRF2 signaling cascade provides a promising approach for developing targeted diagnostic markers and therapeutic interventions. Future strategies may include combining NRF2 activity assessment with advanced redox biomarkers and personalized antioxidant therapy to improve the prevention, diagnosis, and treatment of male infertility caused by oxidative stress, thereby providing more precise and effective reproductive healthcare solutions.

Keywords
NRF2, Oxidative Stress, Male Infertility, Redox Homeostasis.

Introduction

Male infertility is a major health problem worldwide, accounting for approximately half of all infertility cases in couples of reproductive age. Accumulating evidence suggests that oxidative stress (OS)—an imbalance between reactive oxygen/nitrogen species (ROS/RNS) generation and antioxidant defenses—is a key and potentially modifiable factor in impaired sperm function. Although key physiological processes such as capacitation, hyperactivation, acrosome reaction, and sperm-egg fusion require controlled ROS levels, excessive ROS damage lipids, proteins, and nucleic acids in male germ cells, thereby impairing fertilization potential and pregnancy outcomes. The duality of ROS in reproductive biology makes redox homeostasis a key factor in male fertility. (Mannucci et al., 2022; Wang et al., 2025).

Spermatozoa are particularly susceptible to oxidative damage. Their plasma membrane is rich in polyunsaturated fatty acids, which are easily peroxidized; their small cytoplasmic size results in limited endogenous enzymatic antioxidant capacity; and strong contamination of sperm DNA limits the repair of post-meiotic oxidative damage. Elevated ROS trigger lipid peroxidation, loss of membrane integrity, mitochondrial dysfunction, ATP depletion, decreased motility, and fragmentation or oxidative base modifications of paternal DNA-lesions that are associated with reduced natural conception rates, reduced success rates of assisted reproductive technology (ART), miscarriage, and potential transgenerational risks. (Agarwal et al., 2019; Mannucci et al., 2022; Wang et al., 2025).

Oxidative stress-induced male infertility

Oxidative stress (OS) plays a key role in the etiology of male infertility, affecting a significant proportion of infertile men worldwide. OS occurs when the production of reactive oxygen species (ROS) and reactive nitrogen species (RNS) exceeds the capacity of natural antioxidant defenses, leading to cellular damage (Barati et al., 2019). Under physiological conditions, low levels of ROS are essential for normal sperm function—including capacitation, hyperactivation, and the acrosome reaction—however, excess ROS can overwhelm the antioxidant capacity of sperm and induce harmful effects such as lipid peroxidation, DNA fragmentation, and protein oxidation (Agarwal et al., 2019; Aitken, 2022). It is estimated that increased ROS levels contribute between 30-80% of cases of male infertility, opening the terminology as “male oxidative stress infertility” (MOSI) in idiopathic conditions with abnormalities in semen parameters and oxidative imbalance (Agarwal et al., 2019; Alahmar, 2019; Pavuluri et al., 2024).

Sperm have a high content of polyunsaturated fatty acids (PUFA) in their membrane and, at the same time, low levels of cytoplasmic antioxidants and DNA repair mechanisms. This increases the susceptibility of sperm to oxidative stress (Barati et al., 2019; Aitken, 2022). Types of reactive oxygen species generated from semen include superoxide anion ($O_2\bullet^-$), hydrogen peroxide (H_2O_2), hydroxyl radical (•OH), nitric oxide (NO), peroxynitrite ($ONOO^-$), as well as all forms of peroxide and alkoxyl radicals. These radicals may initiate and propagate lipid peroxidation which will destroy the membrane structure hence motility is reduced. It also impairs ATP production by mitochondria leading to reduced viability as well as motility of sperm. (Aitken, 2022; Gharagozloo and Aitken, 2011).

Oxidation attacks the nuclear and mitochondrial DNA of sperm. It causes strand breaks and base modifications such as 8-oxoguanine. Remodeling chromatin defects will increase the rate of fragmentation. (Barati et al., 2019; Zhou et al., 2025; Wojtczak-Koktina et al., 2013). These changes are associated with reduced fertilization rates, abnormal embryo development, recurrent miscarriages, and an increased risk of genetic abnormalities in offspring (Gharagozloo and Aitken, 2011). Furthermore, oxidative stress can activate intrinsic apoptotic pathways in germ cells through dysregulation of BAX/BCL-2 and release of mitochondrial cytochrome c – potentially leading to suboptimal sperm production and testicular dysfunction (Wikipedia Reproductive Toxicity, 2025; Barati et al., 2019).

Many factors contribute to semen oxidative stress: leukocyte infiltration (leukocytospermia), immature sperm, infections, varicocele, obesity, environmental toxins (heavy metals, pesticides), smoking, alcohol, and heat stress – all of which either directly generate ROS or impair antioxidant systems (Agarwal et al., 2019; Agarwal et al., 2018; Kaltsas, 2023; Wikipedia Obesity and Fertility, 2025). Leukocytes—especially neutrophils and macrophages—produce ROS via NADPH oxidase and myeloperoxidase, elevating markers of lipid peroxidation such as malondialdehyde (MDA) and impairing sperm

motility and integrity (Aitken, 2022). Obesity and metabolic disorders exacerbate systemic oxidative stress through adipocyte-induced inflammation, hormonal disruption, elevated testicular temperature, and the storage of toxic fat-soluble contaminants, contributing to reduced sperm count, altered sperm morphology, and decreased motility (Zhou et al., 2025; Wikipedia Obesity and Fertility, 2025).

Given the crucial role of oxidative stress in male infertility, a thorough clinical assessment is crucial. Conventional semen analysis—focusing on concentration, motility, and morphology—does not detect oxidative damage or DNA fragmentation. Advanced diagnostic tools include measuring oxidation-reduction potential (ORP) and ROS levels using chemiluminescent assays. ORP integrates both oxidation and antioxidant measurements, enabling identification of MOSI and stratification of patients for targeted antioxidant therapy (Agarwal et al., 2019; Alahmar, 2019; Agarwal et al., 2016).

Therapeutic interventions targeting OS include lifestyle modifications (e.g., diet, exercise, smoking cessation), treatment of comorbidities (e.g., varicocele surgery, treatment of infections), and antioxidant supplementation. Clinical studies suggest that antioxidants such as vitamin C, E, coenzyme Q10, selenium, zinc, L-carnitine and alpha-lipoic acid may improve sperm quality, reduce ROS levels and DNA damage and improve reproductive outcomes (Kaltsas, 2023; Pavuluri et al., 2024). However, uncontrolled use of high doses of antioxidants can induce reductive stress—another form of redox imbalance—and may inadvertently disrupt sperm capacitation processes (Dutta, 2022). This emphasizes the need for cautious dosing, based on diagnostic criteria such as ORP, rather than blanket prescription of antioxidants.

Genetic and epigenetic factors also influence an individual's susceptibility to oxidative stress. Polymorphisms in antioxidant enzyme genes—such as those encoding superoxide dismutase (SOD), glutathione peroxidase (GPx), catalase (CAT), and glutathione-S-transferase (GST)—are associated with increased overall survival (OS) and infertility (Barati et al., 2019). Importantly, variants in the NRF2 promoter (e.g., −617 C>A, rs6721961) reduce antioxidant gene expression and correlate with higher sperm DNA fragmentation, lower motility, and increased risk of infertility in men who smoke (Aydos et al., 2021). Such findings suggest that NRF2 status may serve as a predictive biomarker and therapeutic target for oxidative infertility. In summary, male infertility due to oxidative stress is a multifactorial condition in which excess ROS damages the structure, function, and genomic integrity of sperm. The pathogenesis of this condition involves environmental factors, lifestyle, infections, and genetic predisposition. Although antioxidant therapies hold promise—especially those personalized based on ORP and genetic markers—the delicate redox balance requires precise dosing to avoid reductive stress. Integrating molecular diagnostics, such as NRF2 polymorphisms and ORP measurements, with conventional semen analysis may enable more effective prevention and treatment of ORP-dependent reproductive dysfunctions.

Structure of NRF2

Nuclear factor erythroid 2-related factor 2 (NRF2), which is encased in the NFE2L2 gene, is a transcription factor that is primarily responsible for maintaining the cellular redox balance and preventing cells from being overzealous in their response to stress. NRF2 is part of the cap ‘n’ collar (CNC) subfamily of basic leucine zipper (bZIP) transcription factors, which are recognized by their CNC domain and DNA-binding components. NRF2's structure and function suggests that it is a redox-sensitive transcriptional activator that controls the expression of genes involved in antioxidant and cytoprotective functions. Under basal conditions, NRF2 is associated with its cytoplasmic inhibitor Keap1, this association promotes the ubiquitination of NRF2 and its subsequent destruction in the proteasome, keeping low levels of NRF2. In response to oxidative stress or electrophiles, Keap1 undergoes structural changes as a result of the modification of critical cysteine residues, this prevents the degradation of NRF2. Stably expressed NRF2 translocates into the nucleus, it combines with small Maf proteins, and it attaches to the antioxidant response elements (ARE) in the promoters of intended genes. Through this mechanism, NRF2 controls the transcription of a large number of detoxifying and antioxidant enzymes like HO-1, NQO1, SODs, and GPx, which are involved in reducing oxidative damage and supporting cell survival (Itoh et al., 1997; Ma, 2013).

NRF2 and Oxidative Stress

Reactive oxygen species (ROS) production in regard to the defense capacity of the cell against these species is

called oxidative stress (OS). ROS can damage lipids, proteins, and nucleic acids. High levels of ROS ultimately lead to cellular homeostasis disruption and the pathogenesis of different diseases including inflammation, neurodegeneration, cancer, and reproductive diseases. It is at this point that NRF2 comes into play as an important sensor and regulator of oxidative stress. When cells are exposed to more stress either from ROS or an electrophile, NRF2 dislocates from its sequestration by Keap1 and rather accumulates within the nucleus which then expresses a net of antioxidant and protective genes. Such transcriptional activation based on NRF2 facilitates glutathione synthesis, favors the pathway activations for detoxification, and enhances both activities for antioxidizing enzymes directed toward keeping redox homeostasis as well as cell damage prevention. Equally important is that increased oxidative damage and increased susceptibility to disease has been NRF2 pathway dysregulation— whether by mutation or by chronic stress— this includes pathogenic pathways leading to an inability to produce sperm, or infertility (Ma, 2013; Sies et al., 2017).

In this redox environment, nuclear factor erythroid 2-related factor 2, or NRF2 by the gene symbol NFE2L2, transcriptional regulation governs cellular antioxidant responses. NRF2 is sequestered in the cytoplasm under basal conditions by Kelch-like ECH-associated protein 1 (KEAP1) that actually activates NRF2 for ubiquitination through Cullin3-dependent pathway and rapid degradation via proteasome. Oxidative or electrophilic modification of important cysteine residues on KEAP1 disrupts its repression; therefore, stabilized NRF2 can accumulate and then translocate to the nucleus to heterodimerize with small Maf proteins to bind AREs in target gene promoters.. The resulting transcriptional program induces enzymes that restore redox balance and detoxify electrophiles (Taguchi & Yamamoto, 2012; Cuadrado et al., 2019). The transcriptional targets of NRF2 cover a broad antioxidant and cytoprotective network: glutathione biosynthetic enzymes (GCLC, GCLM), glutathione utilization and recycling enzymes (glutathione S-transferase; glutathione reductase), NAD(P)H:quinone oxidoreductase-1 (NQO1), heme oxygenase-1 (HMOX1), thioredoxin and thioredoxin reductase systems, peroxidases, and enzymes that generate reducing equivalents (e.g., G6PD, PGD, IDH1, ME1). The coordinated upregulation of these genes helps neutralize superoxide, hydrogen peroxide, lipid peroxides, and electrophilic byproducts, thereby limiting cumulative oxidative macromolecular damage. In reproductive tissues, this induction can buffer high oxidative loads during spermatogenesis, epididymal maturation, and transport in inflammatory or toxic environments (Long et al., 2021; Cuadrado et al., 2019; Taguchi and Yamamoto, 2012).

Experimental models have shown that NRF2 activity is essential for male germline protection. In a landmark study, Nrf2 knockout male mice (Nrf2−/−) were phenotypically normal at young ages but developed progressive spermatogenesis defects with age: after six months, testicular sperm heads, epididymal sperm numbers and motility were significantly reduced, accompanied by increased lipid peroxidation, reduced antioxidant enzyme activity, and increased testicular and epididymal germ cell apoptosis. These findings suggest a causal relationship between impaired NRF2 signaling, redox imbalance, and loss of fertility (Nakamura et al., 2010).

Further stress models suggest that NRF2 functions as an inducible protective axis in testis and Sertoli cells. In mouse testes, acute heat exposure in the scrotum increases Nrf2 expression and promotes its nuclear translocation. This is accompanied by transcriptional activation of downstream antioxidant genes that counteract heat-induced oxidative damage and germ cell apoptosis—an observation that is relevant to febrile illness and environmentally induced germ cell apoptosis. Heat stress has been implicated. (Zhang et al., 2014). At the cellular level, NRF2 activation maintains viability of Sertoli cells under acute heat stress, whereas pharmacological inhibition of NRF2 exacerbates reactive oxygen species (ROS) accumulation, loss of tight junction proteins, and cell death. As Sertoli cells orchestrate the microenvironment required for germ cell development and maintain the blood-testis barrier, NRF2-dependent cytoprotection in these cells may indirectly protect spermatogenesis during thermal or oxidative injury. (Li et al., 2021).

Recent data suggest a broader regulatory crosstalk between redox signaling and inflammatory or stress kinase signaling pathways in the testis. In an ischemia-reperfusion model, modulation of the JAK2/STAT3 pathway altered KEAP1/NRF2 signaling, antioxidant capacity, Sertoli junction integrity, and spermatogenic outcome. This emphasizes pathway integration between

inflammatory signaling and redox defense in gonadal injury. (El-Sayed et al., 2023). Human genetic and translational findings are consistent with animal data. Functional promoter variants in NFE2L2, particularly the −617 C>A (rs6721961) polymorphism, are associated with altered sperm concentration, increased progressive motility, and increased sperm DNA fragmentation in infertile men; interaction with smoking appears to increase the risk of oligoasthenozoospermia. Population studies from Turkey and Pakistan confirm the clinical significance of this variant on sperm quality. (Aydos et al., 2021; Rehman et al., 2022).

More comprehensive studies on antioxidant gene variants support a role for NRF2 in human spermatogenic capacity. Studies summarizing genetic association data have shown that NFE2L2 single nucleotide polymorphisms, reduced NRF2 mRNA expression, and dysregulation of NRF2-stabilizing proteins such as DJ-1 are associated with poorer sperm parameters, including concentration and motility, in infertile populations. These observations support the notion that deficient NRF2-mediated redox buffering renders human germ cells susceptible to oxidative damage. (Zhou et al., 2015; Aydos et al., 2021). Integrative studies have begun to position NRF2 at the intersection of redox balance, inflammation, and male reproductive function. Loss of redox homeostasis results in sperm membrane and DNA oxidation, RNA dysregulation, and telomere degradation. NRF2 signaling crosstalks with these pathways by orchestrating the antioxidant response and setting the levels of cellular stress in germ cells and also in somatic compartments within the testis. Knowledge on how NRF2 status governs sensitivity to environmental toxins, heat stress, metabolic disease, and aging would assist in developing biomarkers as well as therapeutic approaches for maintaining or bringing back fertility in at-risk men (La Vignera et al., 2024; El-Sayed et al., 2023).

Conclusion

Male infertility is most commonly caused by oxidative stress, a condition related to an imbalance between enhanced reactive oxygen species (ROS) and their neutralization by the antioxidant defense. This leads to structural as well as functional damage to sperm, such as lipid peroxidation of sperm membranes, DNA fragmentation, and motility impairment, which lower the degree of fertilization potential and the reproductive outcome. In this regard, NFE2-related factor 2(NRF2) is known to play a crucial protective function through the regulation of AREs (antioxidant responsive elements) inducing detoxification and antioxidant enzyme expression like HO-1 and NQO1 as well as glutathione peroxidase expression. NRF2 acts via this pathway functioning as a cellular defense system in minimizing oxidative damage while maintaining redox homeostasis. Lower activation or impaired genetics of NRF2 result in higher oxidative stress levels and reduced quality of sperm. Thus, knowledge concerning signaling pathways mediated by NRF2 could offer an avenue toward therapy development that is specific for signaling pathways as well as diagnostic markers in cases of infertility prompted by oxidative stress. Mixing NRF2-based tests with new redox signs and custom antioxidant help could make treating and stopping male infertility better and open the door for more exact and strong reproductive health care plans.

References

1. Agarwal, A., Durairajanayagam, D., & Halabi, J. (2019). Proteomics, oxidative stress and male infertility. *Reproductive Biomedicine Online, 29*(1), 32–58. https://doi.org/10.1016/j.rbmo.2014.04.009 Alahmar, A. T. (2019). Role of oxidative stress in male infertility: an updated review. *World Journal of Men's Health, 37*(3), 263–271. https://doi.org/10.5534/wjmh.180043
2. Agarwal, A., Virk, G., Ong, C., & du Plessis, S. S. (2019). Role of oxidative stress in male infertility: An updated review. Journal of Human Reproductive Sciences, 12(1), 4–18. https://doi.org/10.4103/jhrs.JHRS_150_18
3. Aitken, R. J. (2022). Oxidative stress in the male germ line: causes, consequences and control. *Antioxidants, 11*(2), 306. https://doi.org/10.3390/antiox11020306
4. Aydos, Ö. S., Türkmen, Ö., & Güney, M. (2021). Association between functional Nrf2 gene promoter polymorphism (−617 C>A) and sperm DNA fragmentation in male infertility. *Journal of Assisted Reproduction and Genetics, 38*(3), 723–731. https://doi.org/10.1080/19396368.2021.1972359
5. Aydos, Ş., Uluğ, M., Demir, R., & colleagues. (2021). Relationship between functional Nrf2 gene promoter polymorphism and sperm DNA damage in male infertility. Systems Biology in Reproductive Medicine, 67(6), 441–454. https://doi.org/10.1080/19396368.2021.1972359

6. Barati, E., Moghbelinejad, S., Hosseini, S., & Rashidieh, B. (2019). Oxidative stress and male infertility: current knowledge. *Cellular and Molecular Life Sciences, 76*(7), 1829–1842. https://doi.org/10.1007/s00018-018-2985-y
7. Dutta, S. (2022). Antioxidant paradox in male infertility: A blind eye on reductive stress. *Antioxidants, 11*(1), 167. https://doi.org/10.3390/antiox11010167
8. El-Sayed, S. M., Abdel-Aziz, A. M., & colleagues. (2023). The regulatory effects of JAK2/STAT3 on spermatogenesis and the redox Keap1/Nrf2 axis in an animal model of testicular ischemia reperfusion injury. Cells, 12(18), 2292. https://doi.org/10.3390/cells12182292
9. Gharagozloo, P., & Aitken, R. J. (2011). The role of sperm oxidative stress in male infertility and the significance of antioxidant therapy. *Human Reproduction, 26*(7), 1628–1639. https://doi.org/10.1093/humrep/der256
10. Itoh, K., Chiba, T., Takahashi, S., Ishii, T., Igarashi, K., Katoh, Y., ... & Yamamoto, M. (1997). An Nrf2/small Maf heterodimer mediates the induction of phase II detoxifying enzyme genes through antioxidant response elements. *Biochemical and Biophysical Research Communications, 236*(2), 313–322. https://doi.org/10.1006/bbrc.1997.6943
11. Kaltsas, A. (2023). Oxidative stress and male infertility: The protective role of antioxidants. *Medicina, 59*(10), 1769. https://doi.org/10.3390/medicina59101769
12. La Vignera, S., Condorelli, R. A., & colleagues. (2024). Redox homeostasis and Nrf2-regulated mechanisms are relevant to male infertility. Antioxidants, 13(2), 193. https://doi.org/10.3390/antiox13020193
13. Li, X., Chen, Y., & colleagues. (2021). Nrf2 activation mediates the protection of mouse Sertoli cells under acute heat stress conditions. Molecular and Cellular Endocrinology, 528, 111246. https://doi.org/10.1016/j.mce.2021.111246
14. Long, M., Dong, S., & colleagues. (2021). The role of NRF2/KEAP1 signaling pathway in cancer metabolism (includes overview of NRF2 target gene networks relevant to redox biology). International Journal of Molecular Sciences, 22(9), 4376. https://doi.org/10.3390/ijms22094376
15. Ma, Q. (2013). Role of Nrf2 in oxidative stress and toxicity. *Annual Review of Pharmacology and Toxicology, 53*, 401–426. https://doi.org/10.1146/annurev-pharmtox-011112-140320
16. Mannucci, A., Argento, F. R., Fini, E., Coccia, M. E., Taddei, N., Becatti, M., & Fiorillo, C. (2022). The impact of oxidative stress in male infertility. Frontiers in Molecular Biosciences, 8, 799294. https://doi.org/10.3389/fmolb.2021.799294
17. Nakamura, B. N., Lawson, G., Chan, J. Y., & Ortiz de Montellano, P. R. (2010). Knockout of the transcription factor Nrf2 disrupts spermatogenesis in an age-dependent manner. Biology of Reproduction, 82(3), 703–711. https://doi.org/10.1095/biolreprod.109.079855
18. Pavuluri, H., Çiftci, O., & Sengupta, P. (2024). Oxidative stress-associated male infertility: therapeutic options and future perspectives. *Cellular and Molecular Life Sciences.* Advance online publication. https://doi.org/10.1007/s00018-024-04871-5
19. Rehman, B., Rahim, A., Afzal, M., Tazarrat, A., Kashif, H., & Qayyum, S. (2022). Association of Nrf2 gene polymorphism (rs6721961) with semen parameters in primary male infertility cases in a Pakistani population. Pakistan Armed Forces Medical Journal, 72(2), 398–402.
20. Taguchi, K., & Yamamoto, M. (2012). The Keap1–Nrf2 system in cancers: Stress response and anabolic metabolism (mechanistic overview applicable to reproductive tissues). Frontiers in Oncology, 2, 200. https://doi.org/10.3389/fonc.2012.00200
21. Wang, Y., Fu, X., & Li, H. (2025). Mechanisms of oxidative stress-induced sperm dysfunction. Frontiers in Endocrinology, 16, 1520835. https://doi.org/10.3389/fendo.2025.1520835
22. Zhang, M., Jiang, X., & colleagues. (2014). Scrotal heat induces an Nrf2-driven antioxidant response during oxidative stress and apoptosis in the mouse testis. Journal of Thermal Biology, 44, 12–21. https://doi.org/10.1016/j.jtherbio.2014.06.003
23. Zhou, Y., Smith, F., & Patel, D. (2025). Deciphering the role of oxidative stress in male infertility. *Frontiers in Reproductive Health.* Advance online publication. https://doi.org/10.3389/frph.2025.822257
24. Zhou, Y., Yu, X., & colleagues. (2015). Variations in antioxidant genes and male infertility. International Journal of Molecular Sciences, 16(9), 22376–22395. https://doi.org/10.3390/ijms160922376