Review

Optimizing Fertility and Hatchability in Poultry Production: An Integrative Review of Key Factors and Best Practices

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Abstract | Day-old chicks constitute a critical component of the poultry production chain, as their quality and availability directly determine overall productivity and economic efficiency. Fertility and hatchability, the primary indicators of reproductive efficiency, are affected by a range of factors including breed, flock age, nutrition, body weight, environmental temperature, and eggshell quality. Elevated temperatures can impair mating behaviour and reduce fertility rates; however, controlled-environment housing systems can help mitigate these effects. Proper egg storage maintaining consistent temperature and humidity, positioning eggs broad-end up, and limiting storage to within 10–14 days is crucial for preserving hatchability. Extended storage durations adversely affect egg quality, thereby lowering hatching success. Stable incubation conditions, particularly a consistent temperature of 37.8 °C, are essential for optimal embryonic development, as deviations may lead to increased embryonic mortality. Advances in incubation technology, including precise control of temperature, humidity, ventilation, and egg turning, have significantly improved hatchability rates and reduced embryo losses. Optimizing fertility and hatchability thus requires comprehensive breeder flock management, controlled environmental conditions, and meticulous egg handling. Key practices include maintaining optimal storage conditions, minimizing egg holding time, and ensuring accurate incubation parameters to support embryo viability and successful hatching.

Keywords | Chick quality, Poultry production, Fertility, Hatchability, Production efficiency

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INTRODUCTION

Poultry production has emerged as a vital component of food security and economic development in many developing countries, primarily due to its role in providing affordable, high-quality meat and eggs sourced from chickens, turkeys, ducks, geese, guinea fowl, and game birds such as quail and pheasants, serve as rich sources of protein and essential amino acids, contributing significantly to daily dietary requirements (Daghir *et al*., 2021).

Although Pakistan holds a modest position in the global poultry market, the sector plays a pivotal role in rural livelihoods, generating income and ensuring food security. A key driver of sustained growth in poultry production is the reliable availability of high-quality day-old chicks, which is contingent upon the efficient operation of hatcheries (Mottet and Tempio, 2017).

These hatcheries depend on the precise control of several incubation parameters, including temperature (typically 37.5–37.8 °C), humidity (40–70%), ventilation, stress management, and lighting systems. Among these, temperature regulation is particularly critical; even slight deviations can result in embryonic mortality. High temperatures may cause dehydration, metabolic dysfunction, and cellular damage, while low temperatures may delay development and impair organogenesis, leading to failed hatching (Okai *et al*., 2025). These risks underscore the importance of precise thermal control during incubation.

Another essential factor influencing hatchability is egg sanitation. Dirty or contaminated eggs are more susceptible to microbial invasion through pores or shell cracks, permitting pathogens such as *Salmonella* and *Escherichia coli* to infect the developing embryo (Oliveira *et al*., 2024). This not only reduces hatchability but can also pose post-hatch health risks. Traditionally, disinfectants like 70% ethyl alcohol have been used, but recent studies suggest that 14% propolis, a natural antimicrobial agent, is a safer and more effective alternative Propolis effectively reduces surface bacterial load without compromising embryo viability, thereby enhancing hatchability (Oliveira *et al*., 2022). This review aims to synthesise both empirical data and theoretical insights to provide a comprehensive understanding of the multifactorial influences on fertility and hatchability in poultry. Particular attention is given to underexplored domains such as the integration of artificial intelligence and modern technological innovations into hatchery practices. The review further identifies critical gaps in the literature and provides evidence-based recommendations for future research.

Problem statement

Traditional determinants of poultry fertility and hatchability such as incubation conditions, nutrition, and breeder management are well established. However, limited work has examined how emerging technologies like artificial intelligence (AI), the Internet of Things (IoT), and automation can be integrated with these foundations to enhance hatchery performance. This review therefore adopts a forward-looking focus on technology integration, outlining key conventional factors only as context and critically analysing the readiness, applications, and constraints of AI- and IoT-based tools for optimising fertility and hatchability in modern poultry production.

Methodological approach

Research strategy

A comprehensive research strategy was developed to gather relevant and contemporary evidence on the factors influencing fertility and hatchability in poultry. Although the search followed systematic principles, this work is designed as an integrative narrative review rather than a full systematic review. This approach was selected to accommodate the broad and interdisciplinary nature of the topic, encompassing biological, environmental, managerial, and technological dimensions that would be constrained by rigid systematic review protocols such as PRISMA. Searches were conducted in Web of Science, Scopus, PubMed, and Google Scholar, using combinations of the keywords fertility, hatchability, incubation, poultry, egg quality, and incubation technology joined by Boolean operators. The literature search covered studies published between 1991 and 2024, ensuring both historical context and inclusion of recent advances.

Inclusion criteria

This review included original research articles, systematic reviews, and selected policy documents that specifically addressed poultry fertility and hatchability. Eligible studies were required to be published in peer-reviewed journals, written in English, and focus exclusively on poultry species, including broilers, layers, and quail. Studies were considered if they examined topics such as egg characteristics, incubation procedures (natural or artificial), breeder flock management, or environmental influences including temperature, humidity, and storage conditions.

Exclusion criteria

Studies were excluded if they focused on non-poultry species, reported on mixed-animal populations without extractable poultry-specific data, or failed to assess fertility or hatchability as a primary outcome. Publications were also excluded if they lacked a clearly described methodology, were published in languages other than English, or originated from non-peer-reviewed sources, including conference abstracts, unpublished theses, and non-scientific reports.

Data extraction and synthesis results

Relevant data were systematically extracted and categorized using a thematic synthesis approach. The reviewed studies were grouped into key thematic areas, including:

- Egg characteristics: Size, weight, shell quality, porosity
- Environmental conditions: Incubation temperature, humidity, and ventilation
- Incubation practices: Turning frequency, single- vs. multi-stage incubation
- Breeder and genetic factors: Breeder age, mating ratios,

flock management, and genetic background

This categorization facilitated a comprehensive synthesis of the multifactorial influences on fertility and hatchability in poultry, enabling the identification of recurring trends, gaps, and best practices across the literature.

Factors affecting fertility and hatchability in poultry

Fertility and hatchability are fundamental indicators of reproductive efficiency in poultry production and are influenced by a complex interplay of genetic, environmental, and management-related factors. These include breeder age, egg storage conditions, mating systems, incubation temperature, lighting regimens, and the genetic background of the flock (Ajayi and Agaviezor, 2016). Between 1985 and 2005, hatchability-related losses in turkey and broiler production nearly doubled, increasing from $260 million to $500 million (Schaal and Cherian, 2007). More recently, the turkey industry experienced an 8.5% decline in hatchability, while broiler production grew only marginally by 0.6% (Tyl *et al*., 2020). These setbacks were compounded by the outbreaks of highly pathogenic avian influenza (HPAI) during 2022–2023, which significantly disrupted fertility and hatchability rates (Fujiwara *et al*., 2022). These trends underscore the urgent need for more resilient and efficient reproductive practices in commercial poultry systems. Historically, natural incubation by broody hens ensured temperature and humidity regulation (37.5–38.5°C and 75-85% humidity). Although this method was economical, it was labour-intensive, limited in scale, and highly influenced by seasonal variations (Adriaensen *et al*., 2022). In contrast, artificial incubation allows for the standardized control of environmental parameters and supports commercial-scale production. Breed-specific differences in fertility rates are also noteworthy (King'Ori, 2011). Lighter breeds such as the White Leghorn typically exhibit higher fertility compared to heavier breeds like the White Rock, Rhode Island Red, and Plymouth Rock. Factors affecting fertility and hatchability span several domains.

- Egg-related factors: Age, weight, shell thickness, porosity, and shape index
- Bird-related factors: Breeder flock age and reproductive health
- Incubation-related factors: Temperature, humidity, ventilation, and egg turning
- Management factors: Nutrition, housing system, and mating practices

A developing embryo relies entirely on the nutrients deposited by the hen. Therefore, any deficiency in the maternal diet can adversely affect embryogenesis, particularly in the late stages of incubation (Wang *et al*., 2024). Mortality occurring between days 8–14 often indicates maternal nutritional deficits. For instance, a deficiency in vitamin A has been linked to reduced hatchability and increased embryonic mortality, as affected embryos may be too weak to hatch or die shortly after hatching (Grochowska *et al*., 2019). Essential nutrients including lipids, proteins, fat-soluble vitamins (A, D, E, K), minerals, and calcium are provided by the yolk, albumen, and eggshells as shown in Table 1 (Ogbu *et al*., 2018).

Egg storage

The storage of hatching eggs is a critical component of incubation management in commercial hatcheries. Prolonged or improper storage can compromise embryo viability and reduce hatchability (Tainika *et al*., 2024). A key physiological change during storage is the rise in albumen pH (from the normal range of 7.6–8.0), which reduces viscosity, facilitates excessive gaseous diffusion, and weakens nutrient transfer to the blastoderm. These changes increase the risk of embryonic malformations and mortality (Senbeta and Science, 2016). The detrimental effects of storage are exacerbated in eggs from older breeder flocks. Hatchability typically declines when eggs are stored for more than 10 days, with some studies reporting a 1% reduction in hatchability for each additional day of storage (Ayeni *et al*., 2020). Furthermore, prolonged storage leads to water loss and deteriorates albumen quality, as evidenced by a decrease in the albumen index and Haugh unit scores in species such as pheasants and partridges (Alkan, 2015). These observations highlight the need for stringent control of storage conditions including temperature, humidity, and duration to preserve egg quality and maximize hatchability.

The role of diet in poultry fertility and hatchability

Nutrition plays a pivotal role in reproductive performance, affecting both male fertility and female egg production. Inadequate or imbalanced diets can impair spermatogenesis, reduce semen volume and motility, and decrease mating Vigour in males (Xue *et al*., 2022). In females, poor nutrition compromises energy balance and egg formation, ultimately reducing fertility and hatchability (Birnie-Gauvin *et al*., 2017). Eggshell quality is a particularly critical trait for both hatchery and table egg production. Poor eggshell quality not only leads to mechanical damage during handling but also reduces the likelihood of successful incubation. Nutritional deficiencies particularly in calcium and vitamin D_3 can compromise shell formation, while mycotoxin-contaminated feed (e.g., with ochratoxin A) disrupts vitamin D_3 metabolism and kidney function. These effects contribute to reduced shell strength, weak skeletal development, and diminished embryo survival (Ogbu *et al*., 2018). In addition to structural effects, diet composition influences the yolk's biochemical profile, especially its fatty acid content. This has downstream effects on embryonic growth and hatchability. For example, biotin deficiency is known to elevate embryonic mortality, particularly during the first and third weeks of incubation. Similarly, dietary protein levels in hens correlate positively with egg weight and the overall quality of hatched chicks (Uğurlu *et al*., 2017). Specific micronutrients and supplements have been shown to enhance reproductive parameters. Organic selenium, for instance, improves the condition of sperm storage tubules in the oviduct, prolongs sperm retention time, and increases the number of sperm penetration points on the yolk, thereby improving fertilization success (King'Ori, 2011). Moreover, while conjugated linoleic acid (CLA) has been linked to improved hatchability, its use may inadvertently reduce egg and yolk size, thus requiring careful dose management.

Vitamins such as E, B-complex, and folic acid also contribute significantly to embryonic development and hatchability, but organic selenium remains one of the most effective enhancers of fertile egg viability (Ogbu *et al*., 2018). Conversely, the presence of anti-nutritional factors such as gossypol a naturally occurring toxin in cottonseed meal can be detrimental (Mageshwaran, 2021). Gossypol impairs mitochondrial function in spermatozoa, reduces sperm output, and contributes to male infertility. Its inclusion in breeder diets should be carefully regulated; cottonseed meal should not exceed 50% of the soybean meal component (Adeyamo *et al*., 2007). In female birds, excessive cottonseed use can induce pink-white disease, characterized by rubbery or mottled albumen and compromised egg quality (see Table 1).

Impact of storage duration on egg quality and hatchability

Egg storage is a critical phase in the poultry production cycle and has a profound effect on both egg quality and hatchability. The key factors influencing this stage include storage duration, temperature, relative humidity, and egg orientation. Maintaining temperatures between 10–15 °C and relative humidity levels of 75–80 % helps minimise moisture loss through the shell and sustain embryo viability (Adame and Ameha, 2023).

Table 1: Essential feed ingredients and recommended dietary levels for poultry.

Feed ingredient	Recommended level in poultry diet	Function and significance	Ref
Vitamin D_3	200 IU/kg (broilers aged 0–8 weeks)	Essential for embryonic development, bone calcification, improved hatchability, chick quality, feed efficiency, and growth.	(Saunders-Blades and Korver, 2015)
Calcium	2–3 g/day (laying hens)	Cofactor in collagen synthesis, supports eggshell quality, promotes bone mineralisation, and enhances immune response.	(Adhikari *et al*., 2020)
Folic Acid	13 mg/kg	Promotes muscle protein deposition and enhances broiler growth performance.	(Liang *et al*., 2022)
Vitamin B Complex	B1: 1.8 mg/kg; B2: 3.6 mg/kg; B6: 3.0–3.5 mg/kg; B12: 10 µg/kg	Supports growth, metabolism, embryonic development, antioxidant defence, blood formation, and immunity.	(Alagawany *et al*., 2021)
Vitamin E	75–100 mg/kg	Protects sperm and egg lipids from oxidative damage, improves semen quality, enhances egg quality, and boosts hatchability.	(Rengaraj and Hong, 2015)
Conjugated Linoleic Acid (CLA)	1.0–1.5% of diet	Reduces lipid peroxidation and reactive oxygen species, decreases intramuscular fat, and optimises fatty acid composition.	(Liu *et al*., 2017)
Organic Selenium	0.1–0.15 mg/kg	Enhances fertility, improves semen quality, supports antioxidant mechanisms in embryos, and increases hatchability.	(Saeed *et al*., 2024; Surai *et al*., 2014)
Biotin	100 µg/kg	Regulates fat metabolism, gluconeogenesis, enzymatic activity, and carbon dioxide transport; enhances antioxidant capacity.	(Hasan Kadhim *et al*., 2022)
Cottonseed Meal	10–15% of diet	High-protein feed ingredient but limited by gossypol toxicity; must be used cautiously to avoid impaired fertility and egg quality	(Świątkiewicz *et al*., 2016)
Soybean Meal	~30% of diet	Rich source of lysine and high-quality vegetable protein; supports muscle development and immune function.	(Banaszkiewicz and Nutrition, 2011)
Corn	~60% of diet	Provides energy and protein, supplies vitamin A as an antioxidant, and contributes xanthophylls for yolk pigmentation.	(Ojeda, 2023)
Wheat	50–60% of diet	Enhances gizzard development, lowers pH, improves digestion, and protects against proventriculitis.	(Singh *et al*., 2014)

Note: Recommended levels may vary depending on breed, age, physiological status, and production system. Diet formulations should be adapted accordingly.

Table 2: Recent studies on egg storage duration and its effect on hatchability: A comprehensive analysis.

Storage time	Hatchability percentage	Finding	Ref
0 day 2 days 3 days 4 days 6 days 8 days	75.75% 71.31% 66.46% 49.79% 10.40% 9.09%	Extending the storage time lowers the hatchability percentage resulting in increased embryonic mortality.	(Khan *et al*., 2014)
2 days 3 days 5 days 7days	73.23% 70.70% 58.78% 26.56%	Storing eggs for more than three days decreases the hatchability percentage and results in a decrease in their internal quality.	(Khan *et al*., 2014)
3 days 7 days 11 days	87.33% 78.67% 71.00%	Studies show that Koekoek chicken eggs should not be stored for more than 3 days. Extended storage duration has a negative effect on embryonic development, chick quality, and post-hatch performance.	(Molapo *et al*., 2021)
4 days 7 days 10days 14days	83.4% 80.1% 77.3% 73.4%	The author reported that egg weight loss during storage affects hatchability and embryonic mortality. Both egg weight loss and storage period affect chick quality.	(Gharib, 2013)
4 days 12 days 16 days	87.5% 87.5% 80.0%	Studies show that storage length does not affect fertility and hatchability but ultimately decreases chick weight at hatch.	(Goliomytis *et al*., 2015)
5 days 12 days 19 days	74.2% 72.6% 69.2%	Egg storage negatively affects the quality of the egg and ultimately embryo development. The duration of egg storage is closely related to the age of the parent flock. Egg storage affects the internal organs (lower heart percentage, disturbed intestinal morphology) of the hatchling	(Nasri *et al*., 2020)
1 day 4 days 7 days 10 days 13 days	92.59% 92.96% 86.30% 85.56% 78.52%	The author reported that during storage, egg position and storage duration negatively affect chick quality and weight. Eggs should not be stored for more than 4 days.	(Ayeni *et al*., 2020)

Note: Variations in hatchability percentages across studies, even under similar storage durations, are likely due to differences in breed genetics, parent flock age, egg quality, storage orientation, and incubation conditions. These methodological and biological differences were considered when interpreting the findings and synthesising the evidence.

Hatchability generally remains stable for up to seven days of storage but declines sharply beyond 14 days, accompanied by elevated embryonic mortality (Pokhrel *et al*., 2018). his reduction results from cumulative physiological and biochemical changes, such as moisture loss, carbon-dioxide depletion, and protein denaturation (Kumari *et al*., 2020). Egg quality indicators including albumen height, Haugh unit, and yolk integrity deteriorate progressively, while albumen pH rises from about 7.6 to 9.5, reflecting the loss of dissolved carbon dioxide. Temperature fluctuations accelerate these changes by increasing evaporation and protein degradation (Nasri *et al*., 2020). Storage beyond 14 days further reduces egg weight, facilitates the migration of amino acids from the yolk to the albumen, lowers yolk solid concentration, and increases albumen pH. These shifts disrupt the nutritional equilibrium essential for embryo growth, leading to developmental abnormalities, higher mortality, and reduced hatchability (Saunders-Blades and Korver, 2015). In addition to biochemical effects, physical handling also matters: Storing eggs blunt-end-up or at a slight angle improves hatchability compared with narrow-end-down positioning (Çam *et al*., 2022). Periodic turning during storage, similar to incubation practice, can reduce membrane damage and improve gas exchange, partly mitigating the negative effects of prolonged storage (Shrestha and Khanal, 2024).

The influence of storage duration on hatchability varies considerably across studies, reflecting differences in experimental design, breeder stock, and environmental control. Table 2 summarises these contrasting findings, showing that hatchability outcomes range widely from minimal effects under optimal storage to steep declines when temperature, humidity, or handling are inconsistent. This variability underscores the need to interpret results contextually rather than as contradictory evidence.

Critical interpretation of conflicting findings

As indicated in Table 2, outcomes differ across studies: some report severe reductions after only a few days of storage (Khan *et al.*, 2014; Ayeni *et al.*, 2020), while others (Goliomytis *et al.*, 2015) note little impact up to twelve days. Such differences arise from genetic background, breeder age, and baseline egg quality, which affect shell porosity, albumen composition, and desiccation resistance. Environmental factors temperature stability, humidity control, and pre-warming before incubation also contribute, as do egg orientation and turning frequency during storage (Çam *et al.*, 2022; Shrestha and Khanal, 2024). Therefore, variation among studies reflects context-specific interactions rather than inconsistencies in principle. In summary, short-term storage (< 7 days) under controlled conditions causes minimal harm, whereas prolonged storage consistently compromises embryo viability through cumulative physical and biochemical disruption. The differing results highlight the importance of standardised storage protocols that account for genetics, flock age, and environmental stability when evaluating hatchability.

Impact of environmental temperature and photoperiod on fertility and hatchability

Heat stress and its impact on male fertility

Temperature and photoperiod are two critical environmental factors that directly influence reproductive performance and hatchability in poultry (Uğurlu *et al.*, 2017). Seasonal variations, particularly elevated ambient temperatures during summer, have been strongly associated with reduced fertility and hatchability due to heat stress. Optimal egg production and hatchability are typically achieved when environmental temperatures remain below 24 °C. In males, heat stress induces oxidative stress and lipid peroxidation, leading to testicular tissue damage and disrupted spermatogenesis (Durairajanayagam *et al.*, 2015). Chickens maintain a baseline body temperature of approximately 41 °C (Edgar *et al.*, 2013), and even small ambient temperature increases (e.g., 27 °C to 29 °C) can lower feed intake, egg production, and egg quality, while increasing water consumption. Heat stress elevates respiratory rates up to 10- to 20-fold, causing CO_2 loss, alkalosis, and disturbances in acid-base balance. It can be acute (sudden exposure to high temperatures) or chronic (prolonged exposure). Chronic heat stress further impairs immune function and intestinal integrity (Xie *et al.*, 2014; Saeed *et al.*, 2019) and may result in abnormal lipid deposition around thermoregulatory tissues, ultimately contributing to testicular degeneration in male quail and broilers (Kumar *et al.*, 2021).

Nutritional strategies to mitigate heat stress

Nutritional interventions play a pivotal role in counteracting heat-induced reproductive impairment. Supplementation with vitamin E (200 mg/kg) and selenium (0.3 mg/kg) has been shown to enhance sperm concentration, motility, and viability, while reducing abnormal spermatozoa (Table 3) (Fouad *et al.*, 2020; Ebeid, 2012). Heat stress also compromises eggshell quality, resulting in thinner, lighter shells due to disrupted calcium metabolism and reduced blood flow to the oviduct (Oguntunji and Alabi, 2010). Panting-induced respiratory alkalosis lowers circulating ionised calcium (Ca^{2+}), further impairing shell formation (Ebeid, 2012).

To mitigate these effects, strategies such as environmental cooling systems, continuous thermal monitoring, and nutritional optimisation are essential for maintaining fertility and hatchability under high-temperature conditions.

Photoperiod and light quality in reproduction

Photoperiod, the daily duration of light exposure, regulates reproductive hormones via the hypothalamic–pituitary–gonadal (HPG) axis (Figure 1) (Liu *et al.*, 2025). Light signals stimulate the hypothalamus to release luteinising hormone-releasing hormone (LHRH), which increases luteinising hormone (LH) secretion, triggering ovulation and enhancing reproductive performance (Patel *et al.*, 2016).

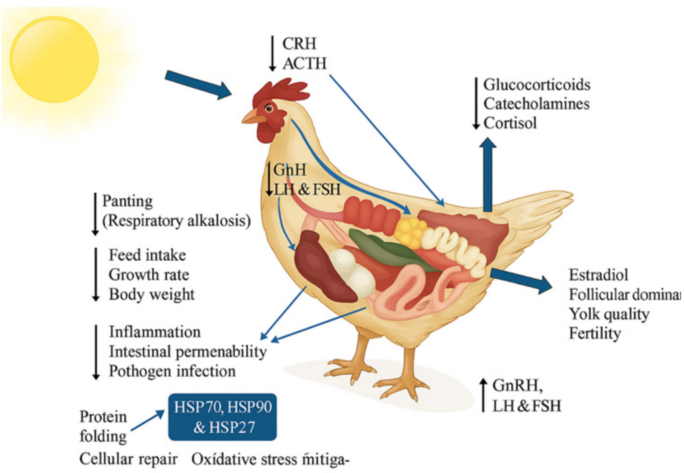

Figure 1: Schematic representation of the physiological and molecular responses of laying hens to heat stress (created by the authors based on literature synthesis). Elevated temperatures activate the HPA axis, increase glucocorticoid secretion, and impair the HPG axis, reducing fertility. Heat shock proteins (HSP70, HSP90, HSP27) mitigate oxidative stress, but chronic heat stress still causes alkalosis, reduced feed intake, inflammation, and compromised productivity.

In White Leghorns, a 14-hour photoperiod accelerates gonadal development and improves sperm count, motility, and morphology compared to shorter photoperiods (Cui *et al.*, 2019). Conversely, restricted photoperiods delay

Table 3: Physiological roles, dietary sources, and deficiency effects of key vitamins in poultry.

Vitamin	Primary dietary sources	Physiological role	Deficiency consequences	Symptoms of deficiency	Recommended intake	Treatment	Ref
Vitamin K	Alfalfa meal, green leafy vegetables	Blood clotting, bone mineralisation, egg formation	Haemorrhages, embryonic mortality, poor hatchability	Prolonged clotting, organ bleeding, anaemia	1 mg/lb feed	Menadione sodium bisulfite supplementation	(Rengaraj and Hong, 2015; Zhang *et al*., 2003)
Vitamin C	Ascorbic acid supplements, premixes	Antioxidant defence, immune enhancement, stress reduction	Poor immunity, oxidative stress, growth retardation	Muscle pain, joint swelling, bleeding, impaired collagen synthesis	~200 mg/kg feed	Ascorbic acid supplementation	(Egbuna and Dable-Tupas, 2020)
Vitamin D_3	Cholecalciferol, 25-OH-D_3, premixes	Calcium and phosphorus absorption, bone mineralisation, eggshell quality	Skeletal deformities, reduced egg production, poor hatchability	Soft/cracked shells, osteoporosis, cage layer fatigue	~1,400 IU/kg feed	Vitamin D_3 or 25-OH-D_3 supplementation	(Adhikari *et al*., 2020)
Vitamin A	Fish liver oil, synthetic retinol, premixes, corn, alfalfa	Immune function, antioxidant defence, reproduction, vision, epithelial integrity	Reduced egg production, embryonic mortality, abnormalities, decreased fertility and hatchability	Ocular deformities, embryonic death, neurological pathologies	8,000–14,000 IU/kg	Dietary supplementation, oral administration, feed fortification	(Shastak and Pelletier, 2023)
Vitamin E	Maize, soybean oil, vegetable oils	Antioxidant protection, fertility enhancement, hatchability improvement	Reduced semen quality, poor egg production, embryonic mortality	Nervous, muscular, immune, and reproductive system disorders	5 IU/lb (laying hens), 7.5 IU/lb (breeding hens)	5–10 mg d-α-tocopheryl acetate per lb feed	(Rengaraj and Hong, 2015; Bryant, 2013)
Vitamin B-Complex	Oilseeds, soybean meal, cornmeal, premixes	Coenzymes in metabolism, antibody production, growth	Reduced hatchability, poor growth, metabolic disorders	Anorexia, polyneuritis, leg paralysis, weakness, convulsions	Thiamine 1 mg/lb, Riboflavin 2–2.5 mg/lb, Niacin 25–30 mg/kg, Pantothenic acid 7 mg/lb, Folic acid 13 mg/kg, Cobalamin 0.005 mg/lb	Supplementation with vitamin-mineral premix	(Karageçili and Karadaş, 2024; Ameen *et al*., 2020)

sexual maturity and lower early semen quality (Shi *et al*., 2021). Extending photoperiods by two hours at 18 weeks has been reported to improve fertility in broiler breeders (Borille *et al*., 2013).

1. Light wavelength also influences reproductive outcomes.
2. Red LED light enhances semen quality and egg production.
3. Green and blue LEDs prolong peak laying periods compared to red or white light
4. Combining 14 hours of red with 2 hours of green light further boosts laying performance (Oso *et al*., 2022).

Thermal manipulation (TM) for improved thermotolerance

Thermal manipulation (TM) involves strategic alterations of incubation temperature during critical embryonic periods to improve thermotolerance, physiological adaptation, and post-hatch performance. TM is typically applied between embryonic days (ED) 7 and 18, increasing incubation temperatures to 38–39.5 °C for 6–24 hours/day while maintaining the standard 37.5 °C outside these intervals (Figure 2) (Han *et al*., 2022).

Research demonstrates that TM during ED 10–18 enhances thermotolerance in broilers, which helps counteract heat stress after hatching (Han *et al*., 2022). TM also improves skeletal development, bone mineral density, and immune competence in layer strains (Al-Amaz and Mishra, 2024). Conversely, short-term cold TM exposure (15 °C for 30–60 minutes) during late incubation has been shown to promote thyroid activity, support growth performance, and reduce cold-related stress and ascites risks (Han *et al*., 2022). While TM is predominantly studied in broilers, its application in layers and other poultry species remains underexplored, providing an opportunity for future research.

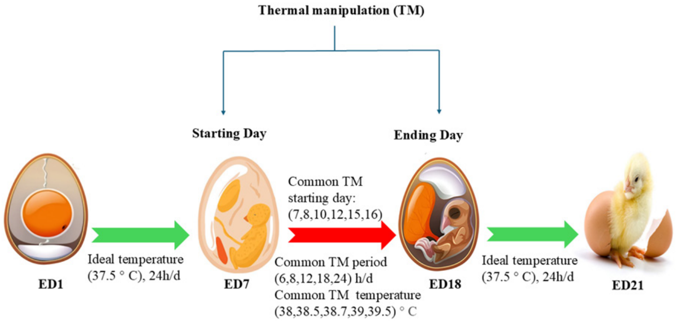

Figure 2: Thermal manipulation (TM) involves temporarily adjusting incubation temperatures between embryonic days (ED) 7 and 18 to influence embryonic development and hatching. TM periods (e.g., ED 7, 8, 10, 12, 15, or 16) involve raising temperatures to 38–39°C for 6–24 hours per day, while standard incubation is maintained at 37.5°C. "Ideal temperature" bars indicate recommended daily ranges, and "Common TM" highlights typical schedules used in experimental studies (Al Amaz and Mishra, 2024).

Influence of egg quality and breeding practices on hatchability outcomes

Effect of egg quality

Hatchability in poultry is influenced by an interplay of physical, chemical, and environmental factors. Among these, egg weight, shell thickness, porosity, and shape index are particularly critical, as they directly impact gas exchange, moisture retention, and mechanical strength (King'Ori, 2011). Eggshells typically contain around 8,000 pores that facilitate the exchange of oxygen and carbon dioxide. An optimal shell thickness ranging from 0.33 to 0.35 mm promotes effective gas exchange while minimizing the risk of dehydration or embryonic mortality, as illustrated in Table 4 (Yadav *et al*., 2021). However, thin or brittle eggshells often caused by inadequate nutrition, aging breeder flocks, or genetic predisposition are more vulnerable to breakage during handling and incubation, leading to decreased hatchability (Addo, 2016). In addition, poor sanitation, improper storage, and suboptimal environmental conditions can further compromise eggshell quality and embryo viability. Maintaining high hygiene standards, stable temperature and humidity, and gentle handling during collection and transfer are thus essential to preserving egg integrity. Hatchability also tends to decline in breeder flocks older than 45 weeks, due to increased embryonic mortality and reduced fertility (Ulmer-Franco *et al*., 2010). Even minor eggshell imperfections such as hairline cracks can significantly increase the risk of bacterial contamination and embryo death during incubation (Van den Brand *et al*., 2016). In severe cases, damaged eggs may explode during transfer, posing risks to nearby eggs and hatchery equipment (El-Safty, 2012). While genetic selection plays a vital role in improving eggshell strength and structure, environmental management and dietary optimization remain critical. Selective breeding programs have demonstrated success in enhancing traits linked to improved shell quality. However, external factors including mineral and vitamin supplementation, sanitation, and housing conditions, must be simultaneously addressed to realize maximum hatchability outcomes (Fathi *et al*., 2019).

On fertility and hatchability

Breed-specific reproductive characteristics significantly influence fertility and hatchability in poultry. Recent findings by Elsagheer *et al*. (2024) recommend mating ratios of 1:5 to 1:7 (male to female) in breeder flocks to optimize fertilization rates. Poor management of these ratios may lead to reduced mating success and diminished hatchability (Elsagheer *et al*., 2024). In commercial hatcheries, eggs from breeder flocks of varying ages are often incubated under standardized conditions. However, breeder age-specific incubation protocols can significantly improve outcomes (Narinc *et al*., 2013). For instance, eggs from 26- and 44-week-old breeders exhibit delayed hatching due to slower embryonic metabolism, often pipping and hatching later in the typical 504-hour incubation period (AbUCābOS, 2010). Tailoring incubation settings particularly temperature and humidity to the specific needs of different age groups is essential to ensure uniform development. In fertility management, sperm collection using the abdominal massage technique has proven effective. Semen can be safely collected up to three times per week without compromising sperm quality. Routine staining and microscopy allow for accurate assessment of sperm motility, viability, and morphology critical parameters influencing fertilization success (Fischer *et al*., 2025). While sperm motility is a reliable indicator of male fertility, comprehensive evaluation of sperm health is necessary for accurate reproductive diagnostics (Bongalhardo, 2024).

Impact of incubation methods on poultry fertility and hatchability

Incubation

Improving fertility and hatchability remains a central goal of poultry production systems. Advances in breeding, nutrition, and incubation technologies have collectively enhanced reproductive efficiency. Incubation methods, in particular, play a decisive role in determining the success of embryo development and chick viability (Ogbu *et al*., 2018). Two primary methods are used in poultry production: Natural incubation and artificial incubation (Kasielke, 2020).

Natural incubation

Traditional or natural incubation is still widely used in backyard or small-scale poultry farming. In this method, a broody hens incubates 10–15 eggs using her own body heat. The hen's body temperature rises to approximately 43.3 °C during brooding, which is essential for embryonic development (King'Ori, 2011). Humidity is naturally regulated as the hen wets her feathers or beak to soften the eggshell near hatching. Although this method is energy-efficient and requires minimal infrastructure, it yields relatively low output typically 10–12 chicks per cycle and is unsuitable for large-scale operations (King'Ori, 2011).

Artificial incubation

In contrast, artificial incubation enables controlled, large-scale hatching in commercial settings, as illustrated in Figure 3. This approach involves two key phases:

- Setter phase (first 18 days): Eggs are loaded into trays that automatically rotate every hour to prevent embryo adhesion to the shell. During this phase, temperature (37.5–38°C) and humidity (55–60%) are carefully maintained to support uniform embryonic growth (Adame and Ameha, 2023).
- Hatcher phase (final 3 days): Eggs are transferred to hatching trays where rotation stops. The temperature is slightly reduced, and humidity is increased (65–75%) to soften the eggshell, facilitating chick emergence. This stage also accounts for the metabolic heat generated by the embryos (Adame and Ameha, 2023).
- Artificial incubation employs thermostatically controlled heating rods, humidifiers or mist systems, and motorized egg turners to precisely manage environmental conditions. Multi-stage incubators where eggs at various stages are incubated simultaneously have demonstrated superior efficiency compared to single-stage systems, improving hatch rates and chick quality (see Table 4).

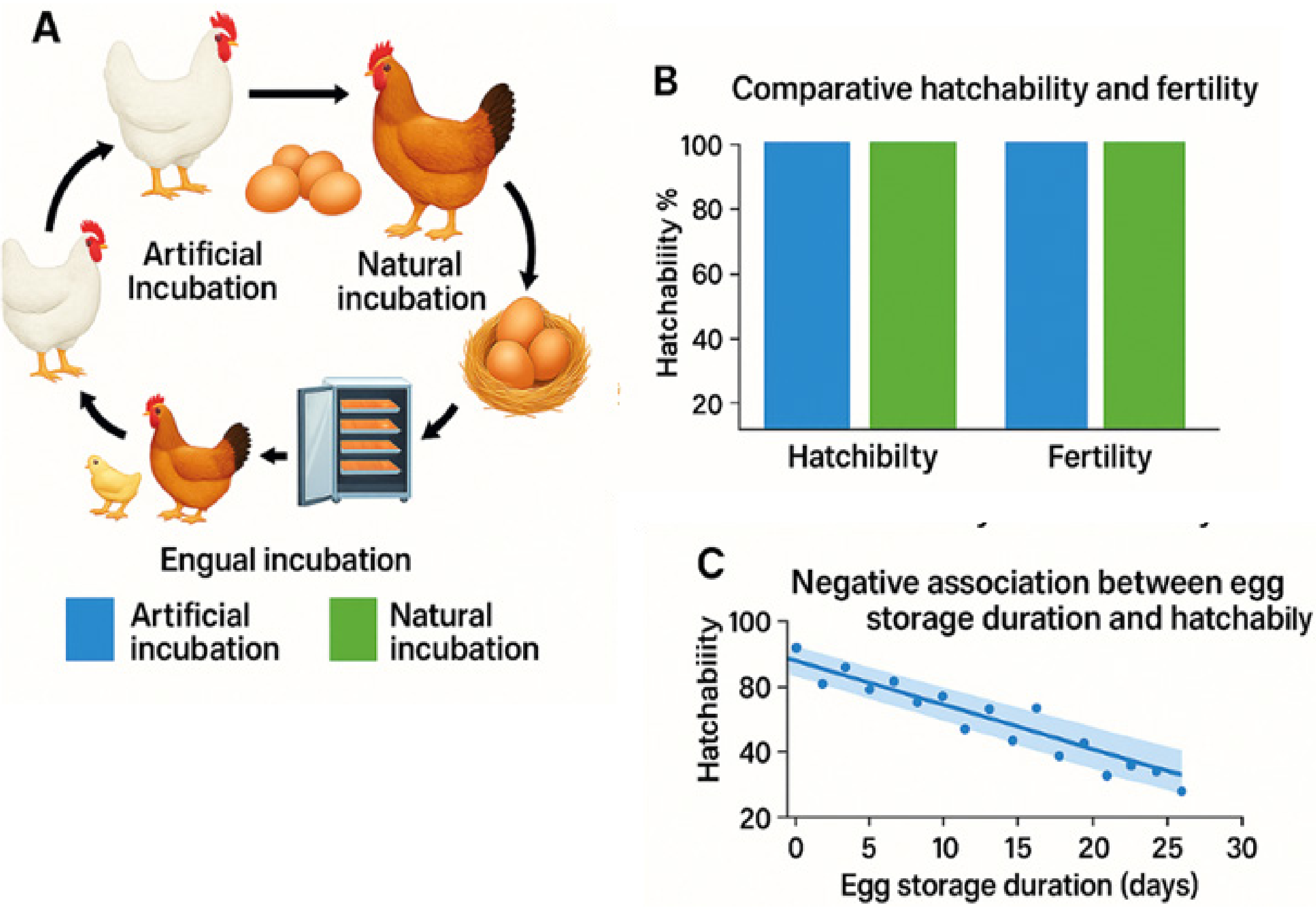

Figure 3: Comparative overview of artificial and natural incubation methods and their effects on hatchability and fertility (created by the authors based on literature synthesis). (A) Schematic representation of artificial and natural incubation cycles. (B) Comparative hatchability and fertility rates under artificial and natural incubation, based on representative values from peer-reviewed literature (Kasielke, 2020; King'Ori, 2011; Adriaensen *et al.*, 2022). Artificial incubation generally achieves higher and more consistent hatchability (~85–90%) and fertility (~88–92%) compared with natural incubation (~65–75% and ~70–78%, respectively). (C) Conceptual trend illustrating the negative relationship between egg storage duration and hatchability, synthesized from consistent patterns reported across multiple studies (Ayeni *et al.*, 2020; Khan *et al.*, 2014; Nasri *et al.*, 2020). No formal meta-analysis was performed; the curve represents a theoretical visualization of the general declining trend observed in the literature. Hatchability declines progressively with extended storage, highlighting the importance of minimizing pre-incubation delays to optimize hatching success.

Table 4: Critical factors influencing hatchability and recommended best practices.

Factor category	Sub-factor	Impact on hatchability	Best practice / recommendation	Reference
Egg factors	Egg shape and size	Medium-sized eggs (49–56 g) achieve higher hatchability compared to smaller or larger eggs. Large eggs are associated with increased embryonic mortality.	Use medium-weight eggs (55–60 g) for optimal hatchability outcomes.	Iqbal *et al.*, 2016
	Eggshell quality	Eggshell thickness has minimal effect on hatchability in guinea fowl and pheasants, but extreme thinness can increase contamination risks.	Maintain eggshell thickness between 0.33–0.35 mm for optimal gas exchange and reduced embryo mortality.	Rodríguez-Navarro *et al.*, 2024
	Storage duration and turning	Prolonged storage (>14 days) reduces hatchability and increases early and late embryonic mortality. Turning mitigates adverse effects.	Store eggs for ≤8 days when possible; if storage exceeds 8 days, turn eggs 2–24 times daily to improve hatchability.	Melo *et al.*, 2021; Gregrova *et al.*, 2024
	Storage temperature	Fluctuations of ±2–4 °C around 21.1 °C reduce hatchability by up to 3.5%.	Maintain storage temperatures near 21.1 °C; avoid dropping below 21 °C (physiological zero) to prevent arrested embryonic development.	Özlü *et al.*, 2018; Yalcin *et al.*, 2022
Breed Effects	Breeder age	Hatchability decreases by ~9% and fertility by ~11% in breeders aged 60 weeks compared to 35 weeks, largely due to poor mating success and embryo quality.	Use breeders within optimal age ranges (35–45 weeks) to maintain higher hatchability rates.	Ayeni *et al.*, 2020
Incubation conditions	Incubation temperature	High incubation temperatures (>38.9 °C) in later stages reduce chick quality, while mild early-stage heating accelerates embryo development and hatching.	Maintain 37.5–37.7 °C for optimal growth; short-term pre-heating at 38.1 °C in early incubation can improve chick quality.	Yalcin *et al.*, 2022; Molenaar *et al.*, 2011
	Incubation humidity	Low humidity increases water loss, causing higher embryonic mortality; excessively high humidity delays hatching and lowers chick quality.	Maintain relative humidity between 55–60% for optimal hatchability and chick health.	Van der Pol *et al.*, 2013; Bruzual *et al.*, 2000
	Turning frequency	Insufficient turning increases early and late embryo mortality and leads to developmental abnormalities.	Turn eggs at least 24 times/day at a 45° angle from day 1 to day 18 for maximum hatchability.	Rideout *et al.*, 2012; Elibol *et al.*, 2002
Environmental Factors	Heat stress	High ambient temperatures (>32 °C) reduce feed intake by ~20%, impair egg/sperm quality, and decrease male fertility by ~42%.	Maintain rearing environments within 12–26 °C to avoid heat-stress-induced fertility and hatchability losses.	Wasti *et al.*, 2020

Relative humidity for incubation

Relative humidity plays a critical role in embryonic development during incubation. Inadequate humidity can lead to embryonic dehydration, causing developmental delays, poor hatchability, or even embryonic death. For optimal embryonic growth, relative humidity should be maintained between 55% and 60% when the eggshell temperature is 37.8°C (Yalcin *et al.*, 2022). Low humidity increases moisture loss from the egg, leading to desiccation and elevated embryonic mortality. Conversely, excessively high humidity can delay hatching and result in poor chick quality, producing so-called "B-grade" chicks those that are wet, weak, or unviable at hatch (Boleli *et al.*, 2016).

Ventilation for incubation

Proper ventilation ensures adequate gas exchange specifically oxygen intake and carbon dioxide expulsion essential for embryonic metabolism and survival. Oxygen is required for cellular respiration, while carbon dioxide must be eliminated to avoid toxic accumulation (Okur *et al.*, 2022). The ambient oxygen level, typically 21%, is sufficient for most embryos; however, inadequate airflow within the incubator can lead to hypoxia or gas buildup inside the egg, resulting in embryonic death (Rodríguez-Navarro *et al.*, 2022; Melo *et al.*, 2021). During the final days of incubation, ventilation should be moderately reduced to maintain ideal humidity for hatching (Tona *et al.*, 2022). However, it must still allow enough airflow to support oxygen-demanding embryos approaching pipping and emergence (Haron *et al.*, 2021).

Turning

Turning eggs during incubation involves four major factors: egg position, turning angle, turning frequency, and timing of turning. Effective turning impacts embryonic physiology,incubation conditions, and post-hatch performance. Orientation enhances hatchability by up to 90%, as it positions the embryo's head near the air sac, facilitating easier hatching (Adame and Ameha, 2023).

Failure to turn eggs during the first and second weeks of incubation increases embryonic mortality. Research indicates that the third to seventh days are particularly critical; lack of turning during this period results in decreased hatchability and impaired embryonic development (Tona *et al.*, 2022). During the first week, inadequate turning increases all types of embryonic mortality, leading to lower hatchability of fertile eggs (Oliveira *et al.*, 2020). Optimal hatchability is achieved by turning the eggs 96 times a day, with turning 24 times a day being a lower frequency. The critical periods for turning are from 1 to 3 days, 4 to 7 days, and 7 to 14 days (Tona *et al.*, 2022). Commercial incubators typically use automatic turning systems, rotating eggs every hour at a 45° tilt, ensuring uniform exposure to environmental conditions and minimizing the risk of developmental defects (Deeming, 2009).

Economic implications of hatchability declines and efficiency gains

Over the past decade, the global poultry industry has faced significant economic losses due to declining hatchability rates. In the United States alone, broiler hatchability has fallen from ~85 % in 2012 to ~79 % by 2024, representing a 6 % absolute decline (Innovate Animal Ag, 2024). This drop translates into an estimated 550 million fewer broilers annually, resulting in substantial revenue losses. To compensate, hatcheries have expanded breeder flock sizes, with breeder inventories increasing 12 % faster than broiler meat production during the same period (Innovate Animal Ag, 2024). These inefficiencies have a profound economic impact, as each four-house broiler breeder facility now costs approximately USD 3 million to construct under current market conditions (Innovate Animal Ag, 2024). Considering that the U.S. poultry and egg sector contributes over USD 663 billion annually to the economy (US Poultry, 2024), even marginal improvements in hatchability could yield substantial financial gains. For example, improving hatchability by just 1 % could enable the production of nearly 2 million additional chicks per week in large-scale operations, reducing production costs and increasing profitability. Table 6 summarises the estimated global economic losses linked to declining hatchability and the potential cost savings achievable through the adoption of precision incubation, AI-assisted monitoring, and IoT-driven automation (Innovate Animal Ag, 2024).

Emerging technologies in hatchery management

While traditional management approaches remain fundamental to improving fertility and hatchability, emerging tools in automation, artificial intelligence (AI), and sensor-based monitoring are increasingly influencing modern hatchery practices. These technologies provide new avenues for precision control; however, their maturity and readiness for commercial adoption vary considerably. AI-based fertility detection has received growing research attention. Studies using deep learning models, including Mask R-CNN, demonstrate that computer vision can distinguish fertile from non-fertile eggs at early incubation stages with high accuracy. For example, Çevik et al. (2022) reported strong performance at an IoU threshold of 0.7, although results were achieved under controlled research conditions using curated images rather than heterogeneous commercial settings. Consequently, claims of "perfect detection" do not translate directly to field environments, where egg cleanliness, lighting, equipment variability, and operator expertise can significantly reduce performance. IoT and TinyML-enabled monitoring platforms offer additional opportunities by providing low-cost, real-time assessment of incubation conditions. The system described by Kombe et al. (2025). which achieved 95.79% accuracy in classifying egg quality, illustrates the potential of small, embedded devices. Yet these results also stem from prototype-scale evaluations. Their applicability in high-throughput hatcheries remains uncertain due to issues such as sensor drift, calibration demands, infrastructure reliability, and limited validation across different breeds and environments. Although AI-driven control systems theoretically enable self-optimising incubation through continuous feedback loops, practical deployment remains limited. Ajibola *et al.* (2025) noted technological translation from research to practice is hampered by high installation costs, lack of interoperability with existing incubators, variable environmental conditions, and limited technical capacity in many hatcheries. These constraints are particularly pronounced in low-resource and small-scale operations. Overall, emerging technologies hold clear promise, but current evidence indicates that they are not yet ready for widespread commercial adoption. Their implementation will require further large-scale validation, cost-benefit analyses, user-friendly interfaces, and scalable designs. Innovations such as modular sensor networks, open-source AI models, and solar-powered systems may help bridge these gaps, but substantial development and field testing are still needed before these tools can meaningfully transform hatchery management.

Ranked prioritisation of key factors affecting hatchability

Based on a synthesis of quantitative findings across the reviewed studies, we identified and prioritised the key determinants of poultry hatchability (Table 5). Incubation parameters, particularly temperature and humidity control, emerged as the most critical factors, followed closely by egg storage duration and breeder flock age. Although nutritional supplementation, eggshell quality, and photoperiod optimisation also contribute meaningfully, their relative impact is less pronounced. While AI- and

Table 5: Evidence-based ranking of determinants affecting hatchability in poultry.

Rank	Factor	Relative impact on hatchability (%)	Evidence strength	Ref
1	Incubation temperature and humidity	35–40%	High consistent across multiple high-quality studies	Yalcin *et al.*, 2022; Tona *et al.*, 2022
2	Egg storage duration	20–30%	High strong evidence from multiple comparative studies	Khan *et al.*, 2014; Ayeni *et al.*, 2020
3	Breeder flock age	9–11% fertility drop; 8–10% hatchability loss	Moderate reported across fewer but consistent studies	Ayeni *et al.*, 2020; Ulmer-Franco *et al.*, 2010
4	Nutritional composition	10–15%	Moderate based on intervention studies on selenium, vitamin D3, CLA	Ogbu *et al.*, 2018; Saeed *et al.*, 2024
5	Eggshell quality	8–12%	Moderate multiple studies confirm shell fragility links to embryo loss	Rodríguez-Navarro *et al.*, 2024; Fathi *et al.*, 2019
6	Photoperiod and lighting	5–8%	Low–Moderate LED manipulation studies with moderate effect sizes	Reddy *et al.*, 2014; Oso *et al.*, 2022
7	AI/IoT-assisted monitoring	3–5% (indirect improvement)	Emerging limited but promising studies	Çevik *et al.*, 2022; Moy Kombe *et al.*, 2025

Note: Percentage ranges represent approximate relative impacts synthesised exclusively from the studies cited in this review. Evidence strength is based on the number of studies, methodological quality, and consistency of findings. This prioritisation serves as a decision-support framework for hatchery managers rather than predictive modelling.

Table 6: Projected benefits of hatchability improvements in a high-volume operation.

Scenario	Hatchability rate	Eggs Set	Chicks hatched	Additional chicks
Baseline (2024 average)	79 %	100 million	79 million	—
Improved (80 %)	80 %	100 million	80 million	+1 million
Improved (82 %)	82 %	100 million	82 million	+3 million

Note: Baseline hatchability rate (79%) represents the 2024 U.S. average as reported by Innovate Animal Ag (2024).

IoT-enabled tools are promising, their commercial adoption remains limited. This prioritisation provides hatchery managers with a decision-support framework to troubleshoot and optimise hatchability outcomes.

Study strength and limitation

The strength of this review lies in its comprehensive synthesis of environmental, nutritional, and management-related factors that influence fertility and hatchability in poultry. It offers practical, evidence-based insights for poultry farmers, hatchery managers, and researchers aiming to improve reproductive performance and chick quality. However, the review is limited by the variability in methodologies and reporting standards across the included studies, which may affect the generalizability and comparability of findings. Furthermore, the review does not provide in-depth coverage of genetic determinants, despite their recognized significance in poultry fertility and embryonic development. Additionally, while the review highlights optimal incubation parameters, we acknowledge that implementing such precision control may be challenging in small-scale and resource-limited settings. Adaptive strategies such as solar-powered incubators, passive thermal regulation, and low-energy hatchery models could provide cost-effective solutions in these contexts.

Future directions

To enhance fertility and hatchability outcomes in poultry, future research should prioritise the integration of advanced technologies such as machine learning, sensor-based real-time monitoring, and automated control systems. Recent studies demonstrate the potential of these tools: for instance, AI-assisted predictive models analysing egg image features have achieved up to 94% accuracy in forecasting hatchability outcomes, significantly outperforming manual candling methods (Çevik *et al.*, 2022). Similarly, IoT-integrated sensor systems for monitoring incubation temperature, humidity, and CO_2 concentrations in real time have been shown to improve monitoring (Kombe *et al.*, 2025). Furthermore, AI-driven automated incubator controllers utilising continuous feedback loops have reduced embryonic mortality by 10–15% in commercial hatcheries (Ajibola *et al.*, 2025). These tools address gaps in traditional incubation practices by enabling predictive decision-making, real-time optimisation, and precision environmental control at both small-scale and industrial levels. In addition, exploring the genetic basis of fertility traits through marker-assisted selection and genome-wide association studies can provide valuable insights for developing selective breeding programmes aimed at improving reproductive performance. Nutritional interventions also hold significant potential, particularly in understanding how micronutrient supplementation influences gamete viability, embryonic development, and overall reproductive physiology. Furthermore, adopting climate-resilient breeding practices such as optimising photoperiod exposure and implementing thermal adaptation strategies will be essential to maintain productivity under shifting environmental conditions. Lastly, microbiome modulation through the use of probiotics and prebiotics represents a promising and innovative strategy for enhancing reproductive health and embryonic survival, supporting a more sustainable and resilient poultry production system.

CONCLUSION

Poultry hatchability is shaped by a complex interplay of factors, including breeder age, nutritional status, egg storage duration, environmental temperature, and incubation protocols. Eggs stored beyond 7 days often exhibit reduced hatchability, partly due to increased albumen pH (from 7.6 to 9.5), which can hinder embryonic development. Environmental temperature fluctuations negatively affect both egg production and hatchability. For optimal performance, ambient temperatures should remain below 24°C, and relative humidity during incubation should be maintained between 55% and 60% when the eggshell temperature is 37.8 °C. Organic selenium has been shown to be particularly effective in improving hatchability outcomes. Improper temperature regulation, humidity control, or egg turning frequency and angle during incubation leads to elevated embryonic mortality. Therefore, precise control and monitoring of incubation parameters are essential for maximizing hatchability and supporting the sustainability of commercial poultry production systems.

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NOVELTY STATEMENT

This review uniquely integrates the latest advances in incubation technology, environmental management, and nutrition to provide a holistic understanding of factors affecting poultry fertility and hatchability. It highlights emerging tools like artificial intelligence and sensor-based monitoring that have not been comprehensively covered in prior reviews. By identifying key knowledge gaps and proposing innovative strategies, the paper offers practical insights to improve reproductive efficiency and chick quality.

AUTHOR'S CONTRIBUTION

HUH: Conceptualization, data curation, formal analysis, methodology, visualization, writing original draft, writing review and editing. DA: Writing review and editing. SA: Visualization. MTC: Writing review and editing. AA: Writing review and editing, validation. CAS: Supervision, project administration, validation, resources. All authors have read and approved the final manuscript.

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Abbreviations
AI, Artificial Intelligence; CRH, Corticotropin-Releasing Hormone; ACTH, Adrenocorticotropic Hormone; ED, Embryonic Day; HPAI, Highly Pathogenic Avian Influenza; HPG axis, Hypothalamic-Pituitary-Gonadal axis; LH, Luteinizing Hormone; LHRH, Luteinizing Hormone-Releasing Hormone; LED, Light Emitting Diode; MC, Microbial Contamination (if used); pH, Potential of Hydrogen (measure of acidity/alkalinity); ppm, Parts Per Million; ROS, Reactive Oxygen Species; TM, Thermal Manipulation; UV, Ultraviolet; VOC, Volatile Organic Compounds; WIR, Water-Insoluble Residue (if relevant).

Generative AI and AI-assisted technology statement
During the preparation of this work, the authors used DeepSeek AI (assisted by the DeepSeek platform) and ChatGPT (Open AI) for language refinement and grammar checking. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the published work.

Conflict of interest
The authors have declared no conflict of interest.

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