Review Article

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Water quality and its multidimensional impact on broiler chicken production: growth performance, health, immunity, and carcass characteristics - A comprehensive review

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Water is one of the most important nutrients for physiological functions but is frequently undervalued in commercial broiler production and influences digestion, metabolism, immunity and performance. This review compiles evidence on the effect of critical water quality parameters such as pH, alkalinity, salinity, total dissolved solids (TDS), hardness, mineral composition, and microbiological contamination on the broiler growth, feed efficiency, gut health, immune status, carcass traits, and mortality. Elevated alkalinity, primarily due to bicarbonate, carbonate, and hydroxide ions, disrupts gastric acidification, reducing pepsin activity and impairing protein digestion while promoting pathogenic microbial proliferation. Similarly, high TDS (>3,000 mg/L) and salinity are associated with reduced body weight gain, poor feed conversion ratio, osmotic diarrhoea and increased mortality. Alternatively, mild acidification of water (pH 5.5-6.5) increases the enzymatic efficiency, calcium and phosphorus utilization and promotes a favourable gut microbiota by encouraging beneficial microorganisms such as Bacillota and Bacteroidetes and suppressing pathogens such as *Salmonella* and *Escherichia coli*, thus improving immune responses. Poor water quality also negatively impacts carcass yield, dressing percentage and breast muscle development due to osmotic stress, inefficient nutrient utilization and increased protein catabolism. Overall, the findings highlight that systematic, source-specific water quality monitoring and evidence-based interventions including acidification, mineral management and microbiological treatment are key elements of precision poultry nutrition to optimize gut health, disease resistance, carcass quality and economic sustainability.

Keywords: Alkalinity, Broiler chickens, feed conversion ratio, gut health, immune function.

Introduction

Poultry production, especially the commercial broiler systems, is the central, growing component of global food security. The world population is expected to reach 9.7 billion by 2050 (United Nations, 2022), which will increase the demand for affordable and high-quality animal protein. Broiler meat is now the meat of choice with global output increasing from about 70 million tonnes in 2000 to an estimated 103.5 million tonnes in 2023 (USDA, 2023). Projections suggest continued growth to about 145 million tonnes by 2030, with the fastest growth expected in South and Southeast Asia, sub-Saharan Africa and Latin America (OECD FAO, 2024). India is projected to lead the growth with a compound annual growth rate (CAGR) of around 5.5% due to rising incomes, urbanisation and the shift to poultry as the main protein in the diet.

Even with the size and sophistication of the sector, production efficiency is still subjected to seemingly routine factors. Of these, water quality is arguably the most consequential and least carefully managed variable in commercial broiler operations. Water constitutes about 65-70% of the body weight of a broiler (Leeson and Summers, 2009) and is involved in almost all physiological processes such as thermoregulation, nutrient absorption and transport, metabolic reactions, waste excretion and immune function. Broilers drink water at a rate of approximately twice the amount of feed consumed (water-to-feed ratio ≈1.6-2.0:1 under thermoneutral conditions) and therefore the quality of drinking water has a direct and continuous effect on bird physiology from day zero to market age.

However, historically water has been regarded as a passive medium rather than an active nutrient with specified quality requirements. The consequences are profound and so significantly affect the farm economics and production. Poor water quality has been linked to reduced average daily gain (ADG), worsened Feed Conversion Ratio (FCR), increased mortality, compromised immune organ development, higher susceptibility to enteric pathogens, and poor carcass quality, leading to measurable economic losses (Augusto et al., 2022; Biswas et al., 2024).

This review addresses a structured, scientifically supported, comprehensive coverage of importance of water quality as a whole and its impacts on broiler production outcomes. The specific objectives are to: (i) describe the major physicochemical and microbiological water quality parameters relevant in broiler production; (ii) review the mechanistic and empirical evidence linking each parameter to growth performance, gut health, immune function, and carcass characteristics; (iii) examine the influence of water source on quality variability; and (iv) outline evidence-based water quality management and treatment strategies.

Water: The Quintessential but Overlooked Nutrient

Precision nutrition in commercial broiler production has evolved into complex scientific research that demands a careful and balanced formulation of macronutrients and micronutrients. Water, on the other hand, is the fundamental and systematically neglected nutrient. Water is much more than a simple solvent, it plays a role in physiological homeostasis in thermoregulation, in the absorption and transport of nutrients, and in the many metabolic reactions that are essential for cellular function (Leeson and Summers, 2009).

Broilers are especially susceptible to heat stress because they lack sweat glands and depend on evaporative cooling by panting to regulate their body temperature, which can lead to them consuming 4–8 fold more water than they usually do (Borges et al., 2003). Water is the solvent for enzymatic catalysis at the cellular level and even mild dehydration (1–2% of body weight) obviously reduces metabolic efficiency and feed intake. Modern poultry farming now treats water as a main nutrient with strict quality standards, rather than just an extra resource. If water quality is poor, bird body weight gain can drop by 5% to 20%, and FCR can worsen by 0.1 to 0.3 points (Augusto et al., 2022)

Water Intake Patterns and Feed-to-Water Ratio

Water intake (WI) patterns of broiler chicken depend on age-related patterns, environmental effects, dietary effects, and genetic and strain effects. Age related: Broiler WI increases linearly with age, a long-established trend confirmed in recent measurements; the average bird consumes ~7.8 L between 14-42 d with substantial individual variation (Aggrey et al., 2023), and earlier commercial data also show WI is a strong linear function of age (Pesti et al., 1985).

The water to feed intake ratio of broiler chickens is a dynamic and diagnostically significant indicator of flock health. Under thermoneutral conditions this ratio is usually between 1.6:1 to 2.0:1 but varies widely with age, temperature, diet composition, genetic strain and management practices (Pesti et al., 1985; May and Lott, 1992). The ratio changes from about 1.93:1 on day 11 to 1.72:1 on day 46, showing the changing metabolic needs (Williams et al., 2013). Environmental effects: heat stress increases WI and the WI/FI ratio as birds depend on evaporative cooling via panting and decreases Feed Intake (FI) (de Baets et al., 2026; Oluwagbenga & Fraley, 2023; Donkoh, 1989). Birds under heat stress have higher WI during hot periods even when corrected for light hours (de Baets et al., 2026). Environmental temperature is perhaps the most acute modulator, with water intake increasing by approximately 7% for each 1°C rise above the thermoneutral zone. Water temperature effects are less consistent, though cold water may improve comfort in heat conditions (Erensoy et al., 2020). Dietary effects: moisture-rich feed ingredients (e.g., live Black Soldier Fly larvae) reduce WI from drinkers (Dorper et al., 2024); dietary sodium, a potent osmotic stimulus, increases water intake proportionally; several water-delivered supplements increase WI especially under heat stress or via osmoregulatory effects (Fathima et al., 2025; Hamdi et al., 2026) and high-salinity drinking water stimulates thirst at low levels but may reduce WI at high concentrations (Biswas et al., 2024). Genetic and strain effects: males drink more than females, and strains differ significantly in WI patterns and in water conversion ratio (WCR) performance, though differences do not align strictly with "fast-growing" versus "high-yielding" types (Hiltz et al., 2025). Monitoring the water-to-feed ratio daily provides a sensitive, non-invasive early-warning indicator of flock health; a sustained ratio below 1.5:1 may signal water quality problems reducing palatability, while a ratio persistently above 2.5:1 may indicate heat stress, high dietary salt, diarrhoea, or renal disease (Pesti et al., 1985; May and Lott, 1992).

Water-to-feed intake ratio (WI/FI) in broiler chickens shows consistent baseline values and predictable responses to environmental, dietary, and genetic factors. Baseline ratios for conventional broiler diets cluster around 1.75–1.77 g/g (Pesti et al., 1985; Edge et al., 2025), and historical flock-level studies report comparable averages of 1.77 g/g (Edge et al., 2025). Factors that increase WI/FI include heat stress, which raises WI while depressing FI (de Baets et al., 2026; Oluwagbenga & Fraley, 2023), and certain supplements—most notably *Pluchea indica* extract at 6 mL/L—reported to raise WI/FI to 2.77 (Hamdi et al., 2026). Unrestricted water access during rearing increased breeder pullet WI/FI to 2.3 versus 1.8 under restricted access (Van Emous, 2024). Factors that decrease WI/FI include diets with high-moisture inputs such as live black soldier fly larvae, which supply water from feed and reduce drinker intake (Dorper et al., 2024), and water deprivation, which alters dynamics because FI often falls faster than WI (Mhmoud et al., 2023; Ndlela et al., 2020). Water conversion ratio (WCR = water consumed/weight gained) varies among strains but shows no sex × strain interaction (Hiltz et al., 2025), with higher-performing strains generally exhibiting lower (more efficient) WCR. Practically, monitoring WI provides a sensitive early indicator of flock health because sudden drops signal problems (Edge et al., 2025); heat mitigation (cooler water, additives, ventilation) is essential to stabilize WI/FI, diet formulations should be adjusted when WI/FI deviates markedly from baseline, and breeding for water efficiency is feasible since selection lines differ in WCR and neuroendocrine profiles (Roach et al., 2025). In conclusion, convergent evidence indicates broilers maintain a typical WI/FI near 1.75–1.77 under standard conditions; environmental stressors—especially heat—are the strongest drivers of elevated WI and WI/FI, while diet composition and management can modulate the ratio, and strain/sex contribute additional variation (Pesti et al., 1985; Dorper et al., 2024; de Baets et al., 2026; Hiltz et al., 2025).

Commercial poultry operations typically rely on inline water meters on drinking lines as the standard method for monitoring flock water intake (Edge et al., 2025). All poultry houses in developed countries are reported to be equipped with such water meters, which often provide electronic pulse outputs that integrate with house controllers to enable automated daily or hourly logging of WI per line or per whole house (Edge et al., 2025). These water intake patterns serve as real-time health diagnostics because disease produces sharp drops in WI and dietary salt problems cause elevated WI (Edge et al., 2025). Large-scale flow meters installed on commercial-style houses have been used successfully to monitor WI over the life of the flock, validating the method for both industry and scientific analyses (Edge et al., 2025). Where farms lack flow meters, some studies estimated water demand indirectly from feed consumption (e.g., 1 kg feed ≈ 2 L water), a suboptimal approach that underscores the importance of meter installation (Williams et al., 2013).

Automated systems that integrate meter pulse outputs with environmental controllers allow logging by row or entire house and support early detection of problems such as disease, salt toxicity, or leaking drinkers (Xin & Liu, 2017; Edge et al., 2025). While specialized research tools—novel low-flow monitoring systems, pressure-transducer drinking stations integrated with balances, and isotope dilution techniques—can measure individual bird water turnover, they are costly and impractical for routine commercial use (Puma et al., 2001; Riek et al., 2008; Hiltz et al., 2021). Similarly, RFID-linked stations and low-flow meters have been developed for research applications but are not used widely on commercial farms (Hiltz et al., 2021; Puma et al., 2001).

AI and precision-livestock technologies (computer vision, video action recognition, and behavior-detection systems) increasingly complement water monitoring by identifying drinking behavior, but they do not measure water volume directly and therefore depend on flow meters for quantitative intake data (Demmers et al., 2022; Wu et al., 2022; Nasiri et al., 2024). Reviews and recent field studies confirm that water meters remain the simplest, most reliable way to measure drinking performance in commercial operations (Bao & Xie, 2022; Edge et al., 2025). Daily meter-based measurements expressed as WI per house or per 1,000 birds are widely used for benchmarking and provide sensitive early warning of health and management issues, making meter installation and integration with data logging a practical priority for commercial broiler and layer farms (Williams et al., 2013; Edge et al., 2025).

Sources of Drinking Water on Poultry Farms

Municipal (Treated) Water

Municipal water sources assure the most consistent baseline quality. Residual chlorine (0.2–0.5 mg/L) can interfere with live vaccines, some medications, and probiotics administered through the water line (Kalita et al., 2020). pH fluctuations associated with treatment may reduce solubility of water-soluble vitamins and medications. The significant water quality parameters with their acceptable ranges for broilers and various characteristic challenges faced by different sources available has been shown in Table 1.

Groundwater (Well Water)

Groundwater is the primary source for the majority of global poultry operations. Its quality is highly variable and mostly depends on the geographical location of the farm. TDS frequently exceed 3,000 mg/L in well water from arid and semi-arid regions, and elevated sodium, sulphate, calcium, magnesium, and iron concentrations are common (Augusto et al., 2022; Raut et al., 2025). Nitrate contamination from agricultural runoff also represents an increasing problem for the only available drinking water source for the poultry farms.

Surface Water

Surface water sources are presented as the water sources with the most susceptible microbiological and chemical risks. Surveys indicate that up to 87% of stream samples in agricultural catchments exceed E. coli limits for poultry use (Derose et al., 2020). Surface water should never be supplied to broilers without comprehensive treatment.

Table 1: Key water quality parameters-acceptable ranges for broilers and characteristic challenges by source type

Parameter	Acceptable Range (Broilers)	Municipal	Well Water	Surface Water
pH	6.5-8.5	Variable	Often alkaline	Variable; seasonal
TDS (mg/L)	<1,500 (<3 weeks); <3,000 (>3 weeks)	Generally OK	Often >3,000	Moderate
Total Hardness				
(mg/L $CaCO_3$)	60–300	Variable	Often very high	Variable
Sodium (mg/L)	<200	Generally low	Often elevated	Usually, OK
Iron (mg/L)	<0.3	Usually, <0.1	Frequently elevated	
Elevated after runoff				
Nitrate (mg/L)	<15	Usually, low	Variable	Agricultural runoff risk
Total Coliforms				
(CFU/mL)	<100	Low (treated)	Contamination risk	High risk
E. coli (CFU/mL)	Absent (<1)	Low (treated)	Risk of contamination	Frequently positive
Turbidity (NTU)	<5	Low	Usually, low	Often elevated

(Do Amaral, 2004; Augusto et al., 2022; Raut et al., 2025; Munster and Kemper, 2024)

Key Physicochemical Water Quality Parameters and Their Effects on Broiler Production

Total Dissolved Solids (TDS) and Salinity

Total dissolved solids (TDS) is a comprehensive measure of all dissolved inorganic and organic substances in water (mg/L or ppm). Salinity refers specifically to the concentration of dissolved salts, predominantly sodium chloride, and forms a component of TDS. Both parameters are operationally measured via electrical conductivity (EC), with 1 µS/cm approximately equivalent to 0.5-0.7 mg/L TDS (Mirsalimi and Julian, 1993).

The physiological consequences of elevated TDS and salinity are dose-dependent. High osmotic load induces increased water consumption at low to moderate salinity as an attempt to dilute excess ions, followed by paradoxical reduction in water intake at high salinity as palatability deteriorates (Biswas et al., 2024). Experimental exposure of broilers to saline water at 0, 5, 10, and 15 g/L demonstrated a significant inverse relationship between salinity concentration and feed intake and BWG (Biswas et al., 2024; Mushtaq et al., 2013). Increasing drinking-water salt level from 0 to 15 g/L produced progressive negative effects: compared with the control (0 g/L), T1 (5 g/L) showed reduced body weight a moderate decline in antibody titers, a rise in *E. coli* antibiotic resistance to 47.22%, and minimal organ damage; T2 (10 g/L) caused further reductions in weight and intake, significant antibody decline, 50.00% *E. coli* resistance and fibrotic changes; T3 (15 g/L) produced the lowest body weight and feed intake, severe antibody decline, 55.56% *E. coli* resistance, and severe fibrosis-indicating a dose-dependent deterioration in production, immunity, and organ health associated with higher water salinity (Biswas et al., 2024). FCR worsens proportionally with increasing salinity. At the renal level, elevated dietary sodium imposes a significant excretory burden, and histopathological evidence of renal stress has been documented in experimental birds exposed to saline water (Mirsalimi et al., 1993). Salt-induced pulmonary hypertension and right ventricular hypertrophy-precursors to ascites syndrome are particularly prominent in rapidly growing broilers under three weeks of age (Mirsalimi and Julian, 1993).

Figure 1 represents graphical synthesis of the dose-response relationship between Total Dissolved Solids (TDS) and key production outcomes (BWG and FCR) across a range of published experimental values while Table 2 is depicting the general classification of drinking water for broiler chicken as per the TDS and showing its implications on health and performance.

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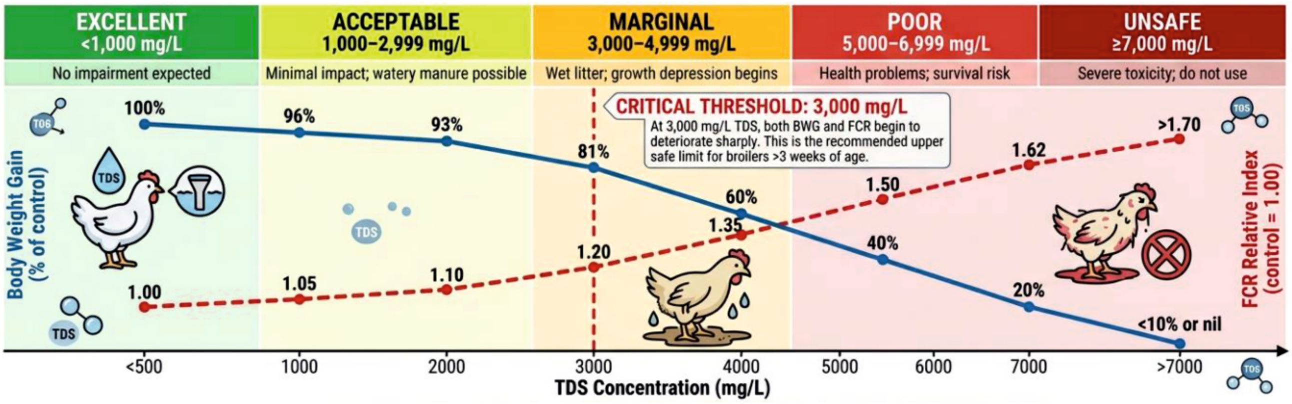

Figure 1: Dose-response relationship between drinking water total dissolved solids (TDS) concentration and broiler production outcomes. Body weight gain (BWG) is expressed as percentage of control (<500 mg/L TDS = 100%); feed conversion ratio (FCR) is expressed as a relative index with control=1.00. Data points represent means synthesised from published experimental and field studies. The critical threshold at 3,000 mg/L TDS marks the point beyond which both BWG and FCR deteriorate sharply. Zone classifications follow Hess and Macklin (2025).

Table 2: Classification of drinking water by TDS and associated health and performance implications for broiler chickens

TDS (mg/L)	Classification	Expected Effects on Broilers	Recommended Action
<1,000	Excellent	No health or performance impairment expected	No treatment required
1,000-2,999	Acceptable	Watery manure possible at upper range; no significant growth effect	Monitor closely; test regularly
3,000-4,999	Marginal	Wet litter, increased mortality risk, stunted growth	Treatment advised; limit to mature birds
5,000-6,999	Poor	Health problems, poor growth, survival concerns near upper limit	Treatment required; avoid for young chicks
7,000-10,000	Unsafe for Poultry	Severe dehydration, salt toxicity, organ failure	Do not use without full desalination
>10,000	Unsuitable	Lethal for poultry; unsuitable for most livestock	Must not be used

(Hess and Macklin, 2025; Mirsalimi and Julian, 1993; Biswas et al., 2024)

Drinking Water pH: Acidity, Neutrality, and Alkalinity

Water pH is among the most consequential and practically modifiable parameters in broiler water management. The gastrointestinal tract of broilers requires an acidic microenvironment-particularly in the proventriculus (pH 2.5-3.5) and gizzard (pH 2.0-3.5) to activate pepsinogen to pepsin, initiate protein denaturation, and create bacteriostatic conditions (Yadav et al., 2010). When drinking water pH is elevated, it contributes to buffering of gastric acid, raising luminal pH and impairing these critical early digestive processes.

Numerous studies have demonstrated that water acidification to pH 5.0-6.5 improves broiler BWG, ADG, and FCR relative to birds receiving neutral or alkaline water (Chaveerach et al., 2002; Hamid et al., 2018; Samudovská et al., 2018). The performance-enhancing effects of acidifiers are attributed to stimulation of pancreatic enzyme secretion (Dibner et al., 2002), enhanced mineral solubility and absorption, improved protein digestibility, and direct antimicrobial effects on enteric pathogens. The antimicrobial mechanism involves undissociated acid molecules penetrating bacterial cell membranes and dissociating intracellularly, releasing protons that acidify the cytoplasm and inhibit acid-sensitive metabolic enzymes (Davidson et al., 2012; Carpenter and Broadbent, 2009).

The claim that "alkaline water = health" for humans does not hold reliably for poultry. Raising drinking-water pH alone generally does not improve growth, feed or water intake, FCR, or amino-acid digestibility (Bassi et al., 2022; Raut et al., 2025), and highly alkaline water (pH > 8) can impair pepsin activity, protein digestion, and palatability (Azizi et al., 2026). Reported benefits typically come from ionized/electrolyzed reduced waters that alter ORP, TDS, and have mild antimicrobial effects properties that, not pH per se, seem responsible for improvements in weight or antioxidant markers (Khalil et al., 2025; El-Sabrout et al., 2026) yet these benefits are inconsistent under commercial stressors such as cyclic heat (de Baets et al., 2026). Mildly acidified water more consistently supports performance and gut health as depicted in Figure 2 (Hamid et al., 2018; Mahmoud et al., 2024). Practically, maintain drinking water at pH ~5.5 to 7 with low TDS, good hygiene, and balanced minerals rather than pursuing alkalinity (Bassi et al., 2022; Raut et al., 2025; Azizi et al., 2026).

On the other hand, highly alkaline water (pH >8.5), especially when induced by sodium bicarbonate supplementation, consistently affects the health and productivity of broilers, resulting in poor productive development, increased ascites incidence, higher mortality, and negative impacts on immune organ weights and caecal pH (Hamid et al., 2018). In practice, the pH of drinking water should be aimed at between 6.0 and 7.0, which represents the best compromise between digestive efficiency, mineral solubility, antimicrobial activity and palatability.

Water Alkalinity

Alkalinity frequently gets equated with pH but these are two different parameters. pH is a measure of the instantaneous concentration of hydrogen ions, while alkalinity is the ability of the water to buffer or resist changes in pH when acids are added. The buffering capacity is mainly provided by bicarbonate (HCO_3^-), carbonate (CO_3^{2-}) and hydroxide (OH^-) ions expressed in mg/L as calcium carbonate ($CaCO_3$). Operationally, alkalinity defines the

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practical difficulty and expense of pH adjustment with acidifiers: it takes significantly more acid to bring the pH of high-alkalinity water down to 6.0 than of low-alkalinity water, with the same initial pH (Hamid et al., 2018).

Broiler drinking water high in alkalinity has effects other than increasing pH. An excess of bicarbonate and carbonate ions buffers gastric acid in the crop, proventriculus, and gizzard, inhibiting the activation of pepsinogen to pepsin. This impairment reduces the efficiency of protein digestion and absorption of amino acids downstream with direct consequences on muscle adherence and growth performance. Furthermore, a high luminal pH favours the growth and colonisation of acid-sensitive pathogens such as *Clostridium perfringens* and *Campylobacter spp*. (van Bunnik et al., 2012).

At the microbiome level, acidified water induces a compositional change in favour of beneficial microbial communities. Gao et al., (2021) observed an increase in the relative abundance of *Firmicutes* and *Bacteroidetes* and a decrease in *Proteobacteria* in acidifier-treated broilers. These birds showed decreased intestinal pro-inflammatory cytokines, Tumor Necrosis Factor-α and Interleukin-1β (TNF-α, IL-1β) and increased serum immunoglobulins (IgG, IgA, IgM). Morphologically, acidified water leads to a significant increase in intestinal villus height and villus-to-crypt ratio, both of which indicate an increase in absorptive surface area (Gao et al., 2021). Acidifiers, used alone or in combination with essential oils, consistently reduce viable counts of *E. coli* and *Salmonella* in caecal microbiota while enhancing proliferation of beneficial *Lactobacillus* populations (Dong et al., 2024).

Water Hardness

Water hardness is defined by the combined dissolved concentration of calcium (Ca^{2+}) and magnesium (Mg^{2+}) ions, expressed in mg/L as calcium carbonate ($CaCO_3$) or German degrees of hardness (°dH). Hard water (>14°dH or >250 mg/L $CaCO_3$) promotes scale deposition in water distribution lines, nipple drinkers, filters, and evaporative cooling systems as shown in Table 3 (Munster and Kemper, 2024). The resulting blockages reduce water flow rates and create stagnant zones harbouring biofilm-forming bacteria. Scale deposits also significantly reduce the solubility and antimicrobial efficacy of disinfectants and impair the dissolution of water-soluble medications and vitamins.

Magnesium levels above 125 mg/L in drinking water can have a strong laxative effect by increasing osmotic activity in the intestine, resulting in wet litter and related problems such as footpad dermatitis (Munster and Kemper, 2024). Even lower magnesium concentrations, around 50 mg/L, may cause similar effects when sulphate or chloride levels are also high. Water hardness caused by excess magnesium can be reduced through chemical precipitation methods, but ion-exchange systems are generally more effective. However, when sodium levels in water are already high, potassium-based softeners or reverse osmosis (RO) systems are considered better alternatives.

Table 3: Water hardness classification and practical management implications for poultry operations

Hardness	Classification	Practical Implications	Management
<8.4°dH (<150 mg/L $CaCO_3$)	Soft	Minimal risk; suitable for most applications	No treatment required
8.4-14°dH (150-250 mg/L $CaCO_3$)	Moderately Hard	Moderate scale risk; monitor drug solubility	Periodic acidic flushing
>14°dH (>250 mg/L $CaCO_3$)	Hard	High scale/clogging risk; Mg laxative effects; reduced disinfectant/drug efficacy	Ion exchange or RO softening strongly advised

°dH = German degrees of hardness (1°dH = 17.8 mg/L $CaCO_3$). (Munster and Kemper, 2024.)

Specific Minerals and Trace Elements

Apart from general water quality measures such as TDS and hardness, specific minerals and trace elements can independently influence broiler physiology through different biological mechanisms. Table 4 summarises their acceptable limits, biological effects, interactions with equipment, and suitable treatment approaches.

Sodium and chloride require special attention because of their synergistic effects on bird health. High sodium levels (>300 mg/L), especially when accompanied by chloride or sulphate, can lead to wet droppings due to their osmotic laxative action and may also encourage the growth of *Enterococcus* in water lines.

Iron is another important concern in poultry drinking water. At concentrations above 0.3 mg/L, it supports the growth of biofilm-forming bacteria in the water system, gives water a metallic taste that can reduce voluntary intake, and may interfere with vaccine stability and the effectiveness of medications.

Nitrate contamination (>15 mg/L) is also becoming a growing global issue. In young chicks, intestinal bacteria can convert nitrate into nitrite, which changes haemoglobin into methaemoglobin and reduces the blood's oxygen-carrying capacity. This condition, known as methemoglobinemia, may appear clinically as dullness along with a bluish-purple discoloration of the combs and wattles.

Table 4: Key minerals and elements in drinking water-recommended thresholds, biological effects, and treatment strategies for broiler operations

Mineral/Parameter	Threshold (mg/L)	Biological/Equipment Effects	Treatment Options
Sodium (Na)	<200	Wet manure (laxative); >600: eggshell issues; promotes *Enterococcus*	Reverse osmosis; blend with low-Na water
Chloride (Cl^-)	<250	Laxative (synergistic with Na, SO_4^{2-}); wet manure; reduced feed intake	Reverse osmosis; address Na concurrently
Sulfate (So_4^{2-})	<200	Laxative; 'rotten egg' odour (H_2S from bacteria); reduced performance	Aeration; chlorine shock treatment; RO

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Iron (Fe)	<0.3	Metallic taste; biofilm formation; impairs vaccines/medications	Oxidation (Cl_2, ClO_2, ozone) + aeration + filtration
Manganese (Mn)	<0.05	Black deposits in drinkers/filters; slow to remove	Extended Cl_2 contact + filtration; greensand filter
Magnesium (Mg)	<125	Laxative at >125 mg/L (>50 mg/L with high SO_4^{2-} or Cl^-)	Ion exchange; RO; blend with low-Mg water
Nitrate (No_3^-)	<15	Methemoglobinaemia; apathy; reduced weight gain (young chicks)	Reverse osmosis; anion exchange
Nitrite (No_2^-)	<1	Highly toxic; severe oxygen transport impairment	Reverse osmosis; ion exchange
Copper (Cu)	<0.6	Pipe corrosion source; oral/gizzard lesions; taste alteration	Filtration; replace corroded plumbing
Fluoride (F^-)	<2	Skeletal fluorosis; impaired bone mineralisation at high levels	Activated alumina; bone char; RO
Alkalinity	<100 mg/L $CaCO_3$	Buffering reduces acid efficacy; bitter taste; pipe corrosion	Acidification (target pH <6.5); anion exchange
TDS (Total)	<1,500 (<3 wks) <3,000 (>3 wks)	Osmotic diarrhoea; reduced growth; mortality at >5,000 mg/L	Filtration; RO for high TDS

(Munster and Kemper, 2024; Hess and Macklin, 2025; Mirsalimi and Julian, 1993) RO = reverse osmosis.

Microbiological Water Quality

Microbiological contamination of drinking water is a major, yet often overlooked, aspect of water quality management in broiler production. Contaminated water can easily spread enteric pathogens within and between flocks, leading to higher disease incidence, mortality, antibiotic usage, and increased food safety concerns (Di Martino et al., 2018; Derose et al., 2020). The most commonly implicated waterborne pathogens include *E. coli*, *Salmonella spp.*, *Campylobacter spp.*, *Clostridium perfringens*, and *Pseudomonas aeruginosa* (Di Martino et al., 2018). Surveys conducted on commercial poultry farms indicate that water contamination is a common concern. For example, Osei et al. (2019) found that the total *coliforms* and faecal *Enterococci* were present in 97% and 56% samples respectively. Along with these, *Escherichia coli*, *Salmonella typhi*, *Staphylococcus aureus* and non-coagulase *Staphylococci* were also isolated from four samples an found that 58% of water samples collected from small-scale layer farms exceeded recommended chemical limits, while 47.4% failed to meet microbiological quality standards.

Biofilm proliferation within water distribution systems presents a particularly insidious challenge to microbiological control. These structured communities of microorganisms reside within a self-produced extracellular polymeric matrix that confers substantial resistance to conventional disinfection protocols. Consequently, the biofilm functions as a persistent reservoir, continually seeding the water flow with planktonic bacteria (Zhu et al., 2021). To achieve effective biofilm management, a rigorous remediation regimen is required; this entails periodic line cleaning with alkaline detergents to disrupt the organic matrix, followed by acidic descaling, and culminating in terminal disinfection with chlorine dioxide, peracetic acid, or hydrogen peroxide-based products (Demkina et al., 2023).

While systemic biofilm management is critical, the continuous disinfection of drinking water remains the cornerstone of microbiological quality management. Chlorination is the most widely practiced method, typically maintaining a free residual chlorine concentration of 0.5–3.0 mg/L at the drinker. However, the biocidal efficacy of this practice is highly contingent upon water chemistry, being fundamentally pH-dependent and significantly reduced by the presence of organic matter (Gani et al., 2024; Jiang et al., 2024).

Effects of Water Quality on Carcass Characteristics and Meat Quality

Dressing Percentage and Carcass Yield

Poor water quality over a long period reduces dressing percentage by lowering body weight gain and muscle growth. Broilers exposed to high TDS or high-salinity water exhibit reduced live weights at any given age, and their carcasses tend to show proportionally lower yields of breast and thigh meat due to the diversion of metabolic resources from anabolic processes to osmotic regulation and immune activation (Biswas et al., 2024; Mushtaq et al., 2013). Experimental comparisons between control and saline-water groups have reported reductions in dressing percentage of 2-5 percentage points, with proportionally greater reductions in breast muscle yield.

Immune Organ Weights

Water quality profoundly affects the relative weights of immune organs particularly the spleen, bursa of Fabricius, and thymus. Exposure to strongly alkaline water or high-TDS water has been associated with reduced relative spleen and bursa weights, indicating impaired primary lymphoid tissue development (Hamid et al., 2018). In contrast, water acidification consistently improves immune organ development, increases antibody levels, and enhances circulating immunoglobulin concentrations (Gao et al., 2021; Dong et al., 2024).

Meat Quality Parameters

Meat quality attributes such as water holding capacity (WHC), ultimate pH (pH 24h), colour indicator as L*, a*, and b*, where L* determines the lightness of the meat surface (0 = black to 100 = white) and is used to distinguish pale from dark meat (Chmiel et al., 2018); a* denoting the redness closely related to myoglobin state while b* represents the yellowness, which increases with oxidation or bacterial growth during storage; tenderness (Sellimi et al., 2017); and oxidative stability are indirectly affected by water quality through its impact on ante-mortem physiology, muscle glycogen reserves, and oxidative stress status. Saline water induces osmotic stress in broilers and increases plasma corticosterone concentrations, which promotes protein catabolism and reduces muscle glycogen, resulting in the change of muscle fiber composition, ultimately leading to impaired WHC and increased

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drip loss of the processed carcass (Mushtaq et al., 2013). High dietary sodium and chloride from poor quality water may also contribute to pre-slaughter electrolyte imbalances that accelerate post-mortem glycolysis, lower ultimate muscle pH, and produce pale, soft, exudative (PSE)-like meat characteristics.

Water Quality Monitoring and Management Strategies

Routine Monitoring Protocols

Water chemistry (pH, hardness, TDS, salts, metals) changes slowly but has major, cumulative effects on bird health, so chemical testing twice yearly is justified. Broad panels capture corrosion, underground shifts and seasonal trends, and long-term surveys show chemical exceeding levels are common (Augusto et al., 2022; Djeffal et al., 2025; Mohebbi et al., 2023; Münster & Kemper, 2024).

Microbiological monitoring quarterly is appropriate, as microbial loads change rapidly due to temperature, season, distribution conditions and hygiene. Biofilms and contamination re-establish themselves within a single cycle, so more frequent checks are useful for early detection of problems (Mustedanagic et al., 2023; Schroeder et al., 2024; Raut et al., 2024). Collecting water samples from the source, storage tank/header, and drinker points provides a realistic assessment of water quality throughout the supply system. Source samples indicate the baseline water quality, tank or header samples help identify any deterioration during storage and distribution, while drinker-end samples often reflect the highest level of contamination that birds are actually exposed to (Augusto et al., 2022; Kamal et al., 2024; Raut et al., 2024).

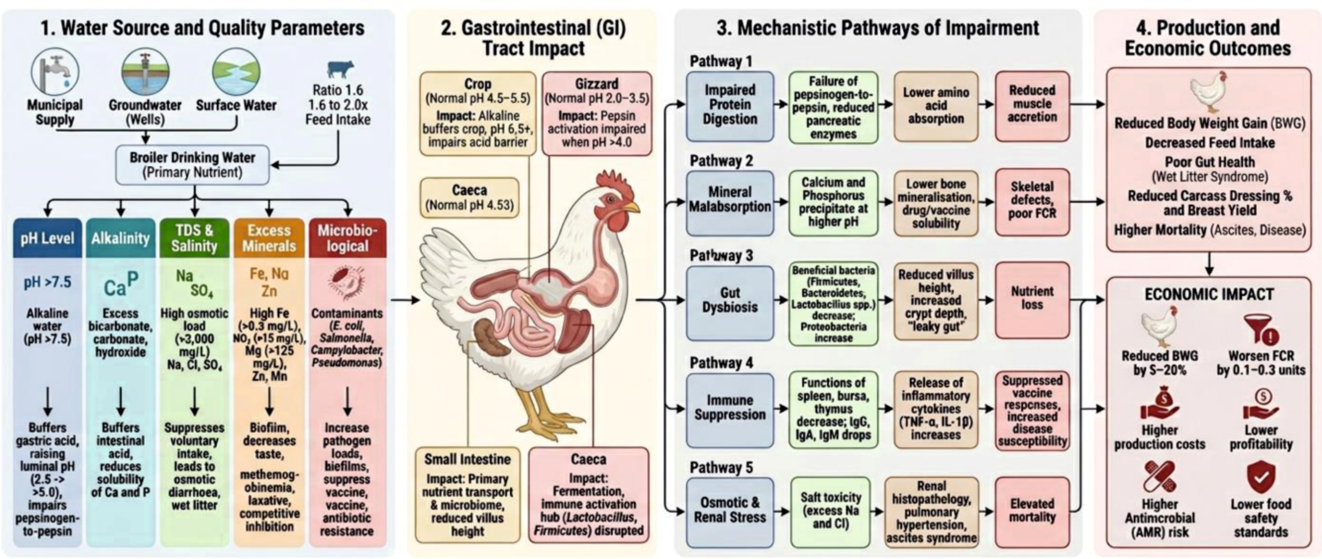

Figure 2. Integrated mechanisms through which drinking water quality affects broiler gastrointestinal function, nutrient utilisation, immune competence, and production performance.

(ADG, average daily gain; AMR, antimicrobial resistance; BWG, body weight gain; Ca, calcium; FCR, feed conversion ratio; Fe, iron; IgA/G/M, immunoglobulins; IL-1β, interleukin-1 beta; P, phosphorus; TDS, total dissolved solids; TNF-α, tumour necrosis factor alpha)

Knowledge Gaps and Future Research Directions

Carcass and meat quality research: The direct impact of various drinking water quality parameters on broiler carcass composition, meat quality traits such as pH, colour, water-holding capacity, tenderness, shelf life, and food safety has not been studied as extensively as their effects on growth performance. Therefore, well-designed controlled studies using standardised carcass evaluation methods are urgently required to better understand these relationships.

Interactive effects of multiple parameters: Mostly the experimental studies have focused to examine single water quality parameters in isolation, but in field conditions invariably involve complex combinations and situation during poultry production. Studies employing factorial or response surface methodology designs to examine interactive effects would substantially improve applicability to real-world and field level production systems.

Age-dependent sensitivity: Young chicks (0 to14 days) are extremely sensitive to osmotic, ionic, and microbiological water quality challenges. Systematic research demarcating the age-dependent thresholds and critical developmental strategies would enable the age-targeted management strategies.

Climate change and water quality: Rising temperatures and changing rainfall patterns are expected to influence the quality of drinking water by altering groundwater mineral concentration, increasing the risk of contamination in surface water sources, and promoting the accumulation of total dissolved solids (TDS). These effects are likely to be more pronounced in semi-arid livestock production regions, including large parts of India.

Economic modelling: A comprehensive cost-benefit analysis quantifying the return on investment for water quality testing, treatment infrastructure, and ongoing management programmes relative to losses from poor water quality is lacking in the literature and research trials in poultry production.

Conclusion

Water quality is a precision nutrition variable that needs to be systematically managed for productive and sustainable broiler production. The review presented here shows clearly, that pH, alkalinity, total dissolved solids, mineral composition and microbiological status have each mechanistically different effects on gut physiology, nutrient utilization, immune competence and

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carcass quality, effects that are comparable in magnitude quantitatively to those of dietary formulation decisions. This understanding needs to be translated to the field with the non-negotiable components of flock management being routine, source-specific water testing, alkalinity-matched acidification to maintain drinker pH in the 6.0–7.0 range, and a continuous, evidence-based microbiological sanitation program.

But these growing bodies of evidence have three critical gaps that limit the full integration of water quality into poultry nutrition science. Firstly, the interaction between drinking water mineral profiles, in particular calcium, magnesium, sulphate and bicarbonate, and the bioavailability of key dietary nutrients such as phosphorus, amino acids and fat soluble vitamins is poorly characterised. Current feed formulation models do not take into account water-derived mineral contributions, which may result in systematic errors in nutrient balance calculations and affect the precision of diet formulation. Secondly, age-stratified water quality thresholds for the critical 0–14 day brooding period are largely absent from the literature. This developmental window, characterized by intestinal immaturity and increased osmotic vulnerability, requires dedicated dose-response research to establish evidence-based guidelines for young chick management that are currently lacking. Thirdly, there are no validated economic models that measure the return on investment for water quality monitoring, treatment infrastructure and programme management relative to production losses from compromised water, leaving nutritionists and producers without the decision-support tools needed to prioritise water quality interventions within integrated flock management programmes.

By addressing these gaps with controlled factorial studies on nutrient-water interactions, age-specific threshold trials in the brooding phase, and rigorous cost-benefit modelling, water quality will become a core, quantifiable pillar of evidence-based poultry nutrition with direct implications for feed efficiency, bird welfare, food safety, and the long-term sustainability of global broiler production.

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