

Hypochlorous Acid in Goat Production Systems: Mechanistic Insights into Health, Growth Performance and Sustainability in Sub-Saharan Africa

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Abstract: Hypochlorous acid (HOCl) is an emerging antimicrobial agent with broad applications in livestock production systems. This review synthesises current evidence on the use of HOCl-based formulations, particularly Ano-Care Goat Cure (ANCGC), in improving goat health, productivity, and sustainability in Sub-Saharan Africa. HOCl demonstrates strong antimicrobial, anti-inflammatory, and wound-healing properties that contribute to reduce parasite burden, improved gut integrity, enhanced nutrient absorption, and accelerated tissue repair. Mechanistically, HOCl reduces gut pathogen load, modulates inflammatory responses, and lowers metabolic stress, resulting in improved feed utilisation and growth performance. Comparative analysis with global literature supports its efficacy as an alternative to conventional antimicrobials, particularly in the context of increasing antimicrobial resistance. However, limitations remain regarding long-term safety, scalability, and economic feasibility in smallholder systems. This review highlights future research priorities and positions HOCl as a sustainable innovation aligned with livestock productivity and resilience goals in Africa.

Keywords: Hypochlorous Acid; Goat Production; ANCGC; Parasite Control; Mechanistic Review; Sub-Saharan Africa.

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I. INTRODUCTION

Goat production plays a critical role in the livelihoods of smallholder farmers in Sub-Saharan Africa, contributing to food security, income generation, and climate resilience. However, productivity is significantly constrained by disease burden, including gastrointestinal parasitism, footrot, and neonatal infections, which reduce growth performance and increase mortality rates. Conventional disease control strategies, including antibiotics and

anthelmintics, are increasingly limited by antimicrobial resistance, environmental concerns, and cost implications. Hypochlorous acid (HOCl), a naturally occurring reactive oxygen species produced by neutrophils during immune responses, has emerged as a promising alternative due to its strong antimicrobial activity and low toxicity profile (Sydor, Zhang, and Wang, 2019). This review aims to synthesise current knowledge on the applications of HOCl in goat production systems, with particular emphasis on its mechanistic effects on animal health and productivity.

II. PROPERTIES AND MODE OF ACTION OF HYPOCHLOROUS ACID

Hypochlorous acid (HOCl), as described by Block and Rowan (2020), is a relatively unstable compound formed when chlorine reacts with water. It is also synthesised endogenously in mammals as part of their innate immune defence system and occurs naturally when chlorine dissolves in water, as illustrated in Figure 1. Within mammalian systems, HOCl is generated during oxidative reactions involving nicotinamide adenine dinucleotide phosphate (NADPH) in the mitochondria of phagocytic cells. This process enables immune cells to neutralise engulfed microorganisms by damaging their DNA and essential cellular structures (Ateş, 2020). From a synthetic perspective, HOCl can be produced through several methods, including acidification of hypochlorite, electrolysis of saline solutions, the reverse reaction between sodium hypochlorite and hydrogen peroxide, and the hydrolysis of chlorine gas (Sakarya *et al.*, 2014; Gold *et al.*, 2020). Although exogenous production of HOCl dates back to 1894, its widespread application was initially limited by its chemical instability (Natarelli *et al.*, 2022). More recently, stabilised forms of HOCl have been developed, particularly through the production of electrolysed (EO) water, which involves passing an electric current through a dilute salt solution (Bajgai *et al.*, 2020).

Electrolysed HOCl solutions have been widely used in environments requiring high levels of active chlorine, such as in medical and industrial sanitation (Bajgai *et al.*, 2020). However, due to certain limitations associated with electrolytic production, newer non-electrochemical HOCl formulations are being developed for broader applications, including agriculture, livestock production, and food processing. Additionally, non-electrochemical HOCl has been proposed for use in drinking water treatment, partly due to concerns over the formation of harmful by-products, such as metals and trihalomethanes, associated with other methods. Despite these advancements, there remains limited literature on non-electrochemically synthesised HOCl, highlighting the need for further research to establish its efficacy and safety. HOCl exhibits a redox potential comparable to that of ozone, underpinning its strong broad-spectrum antimicrobial activity against bacteria, viruses, and fungi (Rahman *et al.*, 2016). Huang *et al.*, (2008) suggested that its antimicrobial mechanism involves interference with microbial glucose metabolism through the oxidation of sulphhydryl groups in key enzymes. This disruption impairs essential metabolic processes and leads to structural damage of microbial cell membranes, ultimately resulting in cell death.

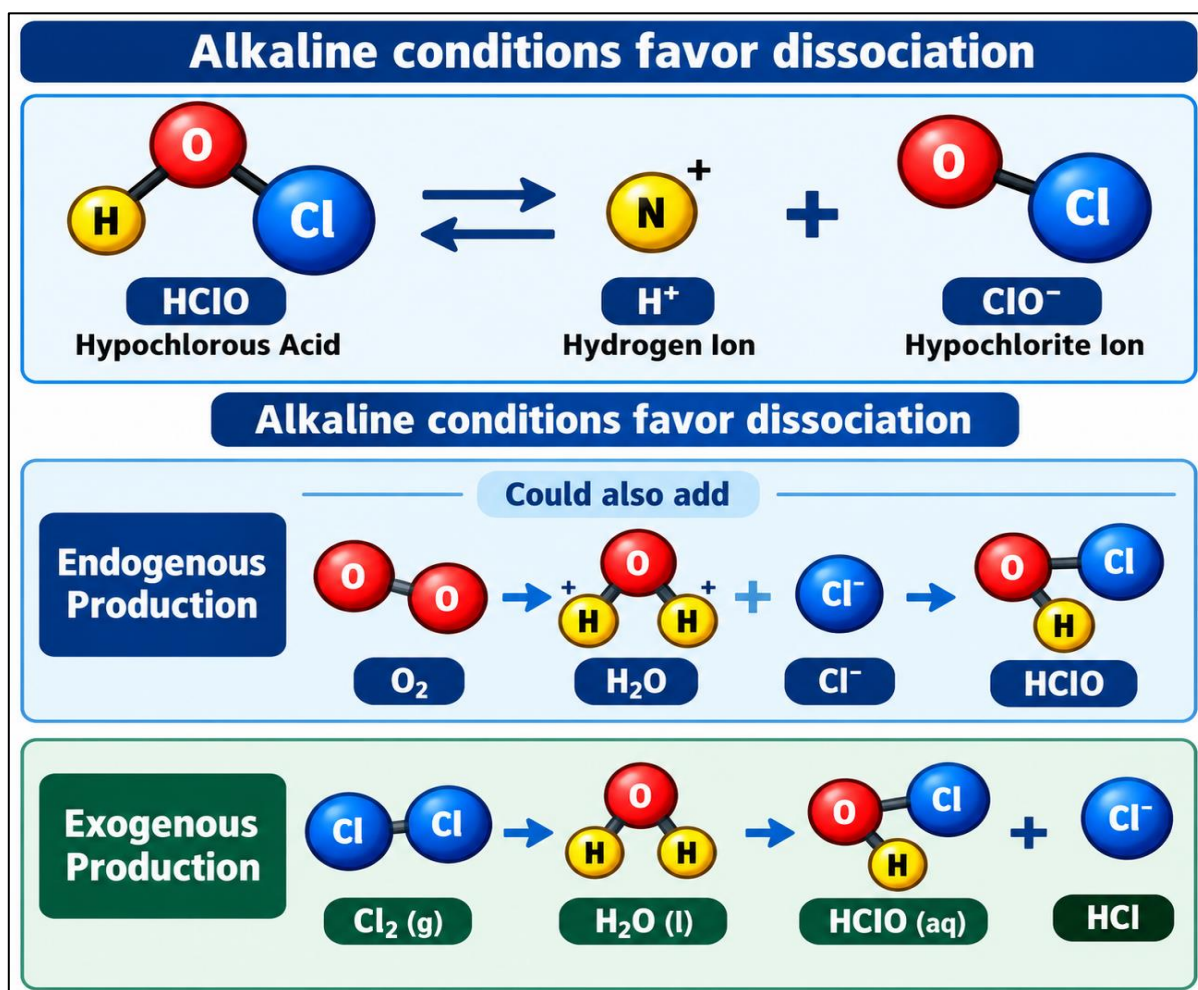


Fig 1 Hypochlorous Acid Structure and Formation Adopted from Natarelli *et al.*, 2022

➤ Antimicrobial Mechanisms

Hypochlorous acid (HOCl) exerts its antimicrobial activity through multiple synergistic biochemical mechanisms that target essential components of microbial cells. Firstly, HOCl induces oxidative damage to cell membranes, leading to increased permeability and structural disintegration. This compromises the integrity of the lipid bilayer, resulting in leakage of intracellular contents and eventual cell lysis. Secondly, HOCl causes denaturation and inactivation of proteins and enzymes by oxidising sulphhydryl groups and other functional moieties critical for enzymatic activity. This disruption interferes with key metabolic pathways, including energy production and nutrient

utilisation. In addition, HOCl inflicts direct damage to microbial DNA and nucleic acids, thereby inhibiting replication, transcription, and cellular repair mechanisms. The combined effects of oxidative membrane disruption, enzymatic inactivation, and genetic damage lead to rapid microbial death. These non-specific and multi-targeted actions underpin the broad-spectrum efficacy of HOCl against a wide range of pathogens, including bacteria, viruses, fungi, and protozoa, and reduce the likelihood of resistance development (Gold, Andriessen, Bhatia, Bitter, Chilukuri, Cohen, and Robb, 2020).

➤ Mechanism of Action of Hypochlorous Acid Flow

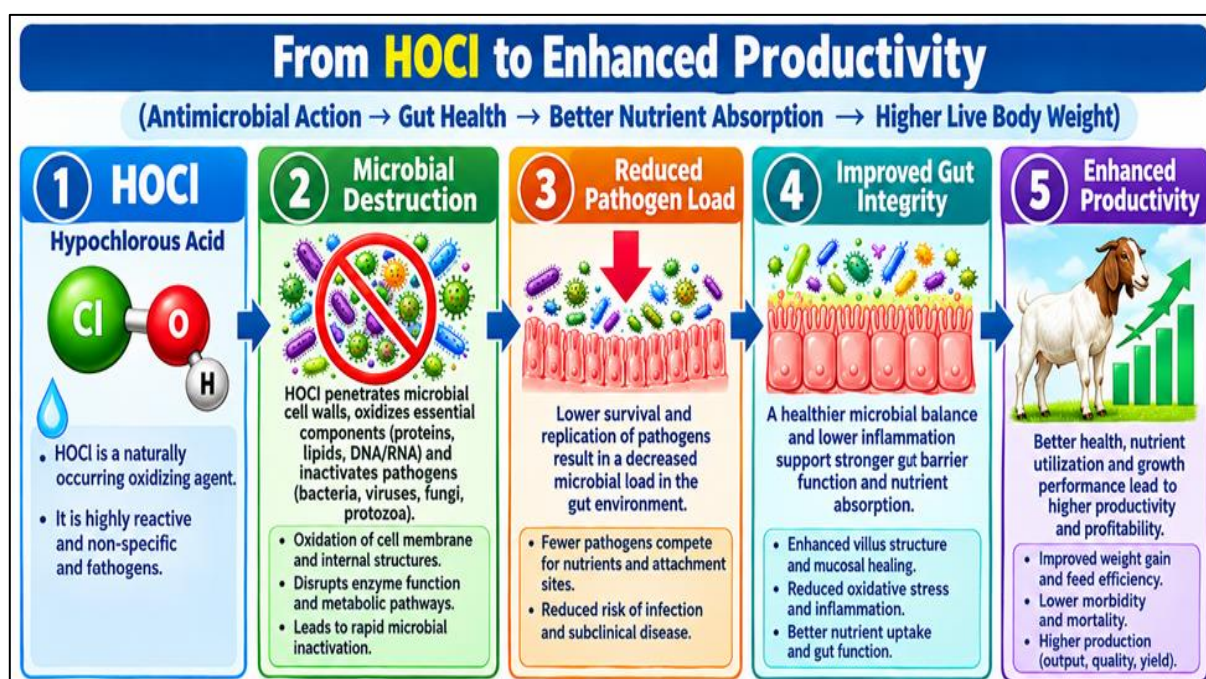


Fig 2 Mechanism of Action of Hypochlorous Acid Flow (Flow Diagram: HOCl → Microbial Destruction → Reduced Pathogen Load → Improved Gut Integrity → Enhanced Productivity)

III. APPLICATIONS OF HOCL IN GOAT PRODUCTION SYSTEMS

➤ Parasite Control and Gut Health

Hypochlorous acid (HOCl) plays a critical role in improving gut health in goats through its broad-spectrum antimicrobial activity, which reduces both microbial and parasitic load within the gastrointestinal tract. HOCl disrupts microbial cell membranes, oxidises essential enzymes, and interferes with metabolic pathways of pathogens, thereby limiting their proliferation (Sakarya, Gunay, Karakulak, Ozturk, & Ertugrul, 2014; Gold, Andriessen, Bhatia, Bitter, Chilukuri, Cohen, & Robb, 2020).

In goat production systems, gastrointestinal parasites such as *Haemonchus contortus* and *Trichostrongylus spp.* compromise intestinal integrity, leading to villi damage, reduced absorptive surface area, and impaired nutrient uptake. These pathological effects result in substantial nutrient losses, reduced feed efficiency, and poor growth performance (Gatiti, Mwebaza, & Mwangi, 2021; Dey & Paul, 2014). Evidence supporting the influence of

hypochlorous acid (HOCl) on gastrointestinal health and nutrient utilisation in goats remains limited. Studies conducted in livestock production systems have demonstrated that HOCl can effectively reduce microbial contamination in water systems, housing environments, and animal-contact surfaces. However, direct evidence linking HOCl application to improved gut microbial balance, nutrient assimilation, or productivity in goats is currently unavailable. Consequently, any potential benefits of HOCl on gastrointestinal function and nutrient utilisation in goats remain hypothetical and require validation through controlled in vivo studies. Future research should investigate whether reductions in environmental pathogen pressure translate into measurable improvements in gut health, feed efficiency, growth performance, and productivity in goat production systems.

➤ Growth Performance and Feed Efficiency

Improved growth performance observed in HOCl-treated goats can be explained by the combined effects of enhanced feed utilisation, reduced disease burden, and improved physiological stability. By lowering microbial

contamination in feed and water, HOCl improves the hygienic quality of inputs, thereby enhancing digestibility and reducing gastrointestinal disturbances (Barker, Andrews, & Smith, 2018; Bajgai, Kim, Rahman, Fadrique, 2020). Furthermore, reduced disease burden leads to lower metabolic energy expenditure associated with immune responses. Animals are therefore able to allocate more nutrients toward growth processes such as muscle development and maintenance of body condition (Kumar, Gupta, & Mehmood, 2020; Tyasi *et al.*, 2022). In smallholder and semi-arid production systems, where

nutritional resources are often limited, this improved feed conversion efficiency is particularly important. It enables goats to maintain growth performance even under conditions of environmental stress and fluctuating forage availability. The positive effects of HOCl on growth performance are therefore likely mediated through an integrated pathway linking gut health, reduced disease incidence, and improved nutrient utilisation.

➤ Conceptual Pathway Linking HOCl to Growth Performance

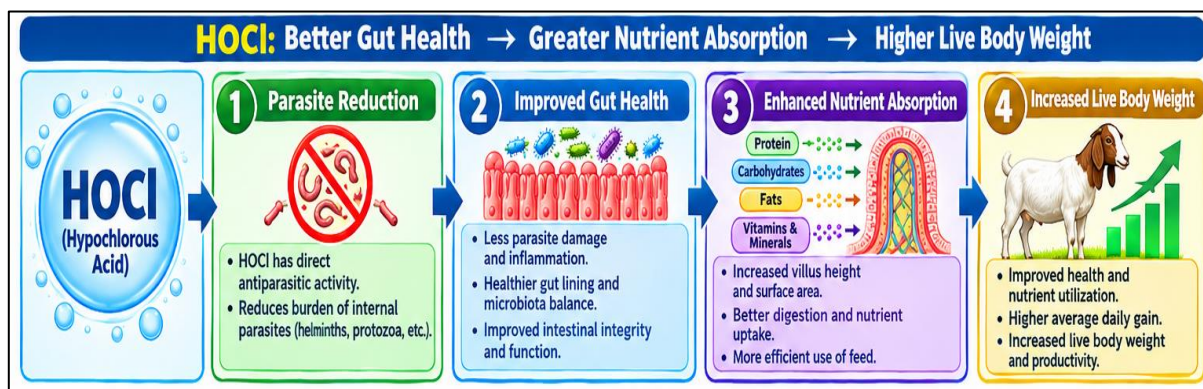


Fig 3 Conceptual Pathway Linking HOCl to Growth Performance (Parasite Reduction → Improved Gut Health → Nutrient Absorption → Increased Live Body Weight)

➤ Footrot Management and Wound Healing

HOCl has demonstrated significant potential in the management of footrot and other infectious conditions in goats due to its combined antimicrobial and tissue-regenerative properties. It exhibits rapid bactericidal activity against pathogens such as *Dichelobacter nodosus* and *Fusobacterium necrophorum*, which are primary causative agents of footrot (Sakarya *et al.*, 2014; Gold *et al.*, 2020). In addition to its antimicrobial action, HOCl enhances wound

healing by promoting fibroblast proliferation, angiogenesis, and collagen synthesis, all of which are essential for tissue repair (Baloyi, Njobeh, & Mankge, 2021; Gray, Foster, Cruz, Kane, Toomey, & Bay, 2016). Clinical observations indicate that HOCl treatment results in a progressive reduction of inflammation, suppression of infection, and rapid tissue regeneration, culminating in complete recovery within a short period under field conditions.

Table 1 Healing Progression of Footrot Following ANCGC (HOCl) Treatment, (Clinical trial at Grasslands Research Institute Marondera Zimbabwe, 2024)

Day	Clinical Condition
Day 1	Severe infection (necrosis, pus)
Day 3	Reduced inflammation
Day 5	Granulation tissue formation
Day 7	Tissue repair
Day 14	Complete recovery

Table 1 demonstrates a clear and progressive healing trajectory of footrot lesions following treatment with ANCGC (HOCl) over a 14-day period, transitioning from severe infection to complete recovery. At Day 1, lesions are characterised by necrosis and purulent discharge, reflecting active microbial infection and tissue damage; however, by Day 3, a marked reduction in inflammation indicates effective antimicrobial action and initiation of healing. Granulation tissue formation becomes evident by Day 5, signaling active tissue regeneration under improved wound conditions, followed by tissue repair and structural restoration by Day 7. By Day 14, complete healing is achieved with full resolution of clinical signs. Overall, this progression highlights the efficacy of HOCl in rapidly

controlling infection, promoting tissue regeneration, and shortening the healing period in footrot-affected animals.

➤ Navel Disinfection in Kids

Navel infections are a major cause of neonatal morbidity and mortality in goat production systems, particularly under conditions of poor hygiene. The umbilical cord serves as a direct entry route for pathogenic organisms such as *Escherichia coli* and *Clostridium spp.*, leading to omphalitis and systemic infections (Bukar & Mabu, 2023; Zhao, Liu *et al.*, 2020). HOCl-based formulations provide an effective alternative to traditional antiseptics by rapidly reducing bacterial contamination at the umbilical site. Their antimicrobial action prevents infection establishment, while

their non-irritating and regenerative properties promote faster drying and healing of the navel stump. Evidence from controlled trials indicates that higher concentrations of

ANCGC significantly improve healing rates and reduce infection-related complications in neonatal goats, thereby enhancing survival rates and early growth performance.

Table 2 Summary of Navel Treatment Outcomes (Clinical trial at Grasslands Research Institute Marondera Zimbabwe, 2025)

Treatment	Product	Mean Healing (%)	Key Outcome
Control	Iodine	—	Effective; irritation concerns
N2	Diluted ANCGC	44.7	Delayed healing
N3	100% ANCGC	82.5	Rapid, complication-free healing

Table 2 shows a clear concentration-dependent effect of hypochlorous acid (HOCl)-based ANCGC on navel healing in neonatal goats. While iodine remains an effective standard disinfectant, its potential to cause tissue irritation may compromise optimal wound recovery. In contrast, ANCGC exhibited variable outcomes depending on concentration. The 100% ANCGC treatment achieved the highest healing rate (82.5%), indicating superior efficacy compared to both iodine and diluted ANCGC. This enhanced performance is attributed to the potent broad-spectrum antimicrobial activity of HOCl, which reduces microbial colonisation while preserving healthy tissue. Additionally, HOCl supports anti-inflammatory processes and tissue regeneration, creating favourable conditions for rapid and complication-free healing. Conversely, the diluted ANCGC treatment (44.7%) resulted in delayed healing, suggesting that insufficient HOCl concentration limits antimicrobial effectiveness and allows persistent infection and inflammation. Full-strength ANCGC is a highly effective and tissue-compatible alternative to iodine for umbilical cord care in goats. The study highlights the importance of maintaining adequate HOCl concentrations to maximise both bio-decontamination and wound-healing outcomes, supporting its adoption as a welfare-friendly navel care strategy in goat production systems.

➤ Environmental and Farm Hygiene

HOCl is widely applied in livestock production systems for environmental sanitation, including water treatment, feed hygiene, and disinfection of housing facilities and equipment. Its strong oxidising properties enable rapid inactivation of a wide range of pathogens, thereby reducing environmental contamination and disease transmission risks (Bajgai *et al.*, 2020; Islam, Hossain, & Ahmed, 2019). In smallholder farming systems, where animals are often exposed to contaminated water sources and poorly sanitised environments, the use of HOCl can significantly improve biosecurity. By reducing microbial loads in drinking water, feed, and housing systems, HOCl contributes to lower disease incidence, improved animal health, and enhanced productivity. Additionally, HOCl offers advantages over conventional disinfectants due to its lower toxicity, minimal residue formation, and reduced environmental impact, aligning with sustainable livestock production principles.

IV. MECHANISTIC INTERPRETATION

➤ Reduction in Gut Pathogen Load

Hypochlorous acid (HOCl) exerts a broad-spectrum antimicrobial effect within the gastrointestinal environment

by disrupting microbial cell membranes, oxidising essential cellular proteins, and inhibiting enzymatic activity required for pathogen survival. This oxidative mechanism results in rapid inactivation of bacteria, viruses, and fungi, thereby significantly reducing microbial colonisation within the gut (Sakarya, Gunay, Karakulak, Ozturk, & Ertugrul, 2014; Gold, Andriessen, Bhatia, Bitter, Chilukuri, Cohen, & Robb, 2020).

In livestock systems, reduction in gut pathogen load is critically associated with improved intestinal integrity and microbial balance, which enhances nutrient digestion and absorption efficiency. The application of HOCl-based formulations such as ANCGC in feed and water has been shown to reduce pathogenic contamination, thereby lowering the incidence of enteric infections and improving gut health in goats (Barker, Andrews, & Smith, 2018; Gatiti, Mwebaza, & Mwangi, 2021). Improved gut integrity allows for efficient nutrient assimilation, which translates into enhanced growth performance and physiological stability under field conditions. This mechanism provides a plausible biological basis for the observed improvements in live body weight and health status in goats treated with ANCGC.

➤ Reduction in Inflammation and Improved Feed Utilisation

HOCl plays a dual role not only as an antimicrobial agent but also as a modulator of inflammatory responses. It has been demonstrated to reduce localised tissue inflammation by neutralising inflammatory mediators and inhibiting excessive immune activation, thereby promoting a balanced immune response (Njobeh, & Mankge, 2021; Gray, Foster, Cruz, Kane, Toomey, & Bay, 2016). In livestock production systems, chronic inflammation is associated with increased metabolic energy expenditure, as animals divert nutrients toward immune responses rather than growth and production processes. By reducing inflammatory stress, HOCl effectively minimises this metabolic diversion, leading to improved feed conversion efficiency and enhanced utilisation of dietary nutrients (Sydor, Zhang, & Wang, 2019; Dey & Paul, 2014). Furthermore, the anti-inflammatory and tissue-healing properties of HOCl contribute to improved intestinal mucosal integrity, which enhances digestive efficiency and nutrient absorption. This mechanism is particularly important under semi-arid conditions, where animals are subjected to nutritional stress and must optimise nutrient utilisation for survival and productivity. Consequently, the application of HOCl-based products supports improved feed efficiency and growth performance by maintaining a balance

between immune function and metabolic resource allocation.

➤ Reduction in Parasite Burden and Metabolic Stress

Parasitic infections are a major cause of metabolic stress in goats, negatively affecting growth, reproduction, and overall productivity. Gastrointestinal parasites impair nutrient absorption, increase maintenance energy requirements, and induce physiological stress responses that compromise animal performance (Grimard, Lichtenberg, & Deslauriers, 2017; Kumar, Gupta, & Mehmood, 2020). The use of HOCl-based interventions contributes to reduce parasite burden through indirect and supportive mechanisms, including improved environmental hygiene, reduced microbial contamination, and enhanced host immunity. By lowering infection pressure, HOCl helps

reduce the overall parasite load within goat production systems, thereby alleviating the negative effects associated with parasitism. Reduced parasite burden leads to decreased metabolic stress, allowing animals to allocate more nutrients toward growth, tissue repair, and productive functions. This is particularly significant in smallholder systems where livestock are exposed to high parasite challenges and limited nutritional resources. Moreover, the reduction in physiological stress contributes to improved resilience during adverse conditions such as the dry season, supporting weight stability and consistent productivity. This relationship between reduced parasitism, improved nutrient utilisation, and enhanced performance is well documented and aligns with observed field responses in HOCl-treated goats.

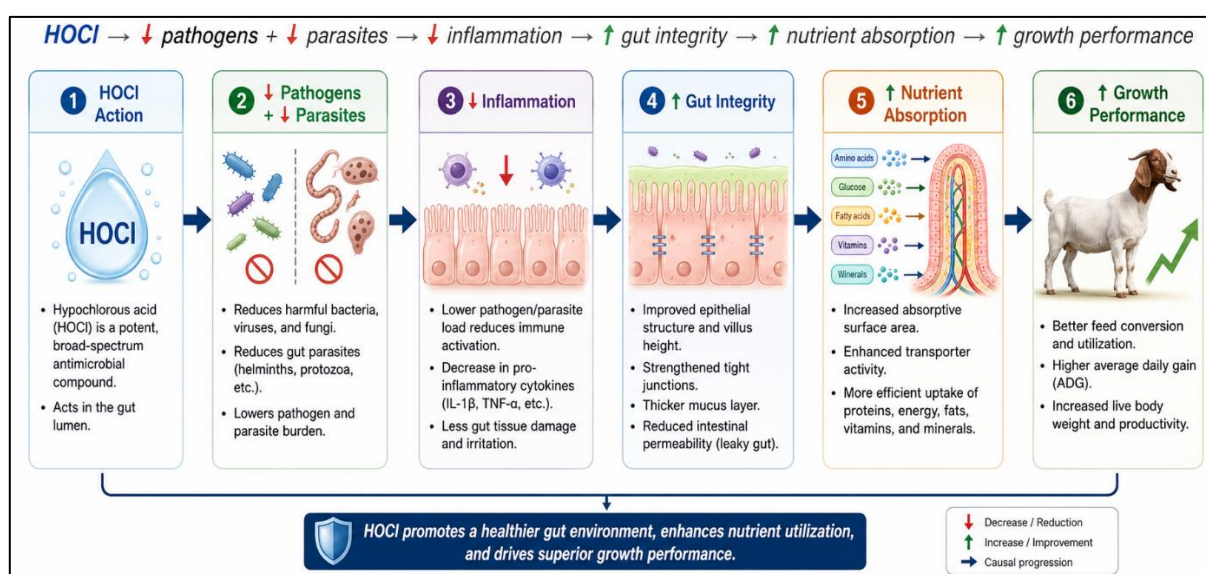


Fig 3 Integrated Mechanistic Model of HOCl Effects (HOCl → ↓ Pathogens + ↓ Parasites → ↓ Inflammation → ↑ Gut Integrity → ↑ Nutrient Absorption → ↑ Growth Performance)

V. DISCUSSION

The effects of HOCl observed in goat systems are consistent with global findings on its antimicrobial and wound-healing properties. Studies across veterinary and biomedical contexts confirm its ability to reduce microbial burden and improve tissue recovery (Gold *et al.*, 2020). The relationship between reduced parasite burden and improved productivity is also well established in ruminant systems (Gatiti *et al.*, 2021), supporting the observed improvements in live body weight and feed efficiency. Mechanistically, the reduction in inflammation represents a critical pathway linking disease control to productivity gains. Chronic inflammation is known to impair growth by diverting energy from anabolic processes, and its reduction through HOCl application enhances overall metabolic efficiency (Sakarya *et al.*, 2014). However, despite its potential, limitations remain. Current evidence is largely derived from small-scale studies, with limited long-term evaluation of safety and microbiome effects. Additionally, economic feasibility under smallholder conditions has not been sufficiently quantified.

VI. IMPLICATIONS FOR SUSTAINABLE LIVESTOCK PRODUCTION

Hypochlorous acid (HOCl) offers a significant advancement in sustainable livestock production systems due to its combined antimicrobial and immunomodulatory properties (Block and Rowan, 2020; Rahman *et al.*, 2016). One of its most important contributions is the potential to reduce dependence on synthetic antimicrobials, particularly antibiotics that are routinely used for disease prevention and treatment in intensive livestock operations (Natarelli *et al.*, 2022). As an effective broad-spectrum biocide, HOCl provides an alternative intervention that can minimise the frequency of antibiotic use, thereby enhancing antimicrobial stewardship (Bajgai *et al.*, 2020).

Closely associated with this benefit is the mitigation of antimicrobial resistance (AMR), which remains a critical global challenge affecting both human and animal health (Rahman *et al.*, 2016). Unlike conventional antibiotics that act on specific microbial targets, HOCl exerts a non-selective oxidative mechanism that disrupts microbial cell

membranes, proteins, and nucleic acids, thereby reducing the likelihood of resistance development (Huang *et al.*, 2008; Atem and Ateş, 2020). This position HOCl as a valuable tool in strategies aimed at controlling AMR within livestock production systems. From an environmental sustainability perspective, HOCl is characterised by a favourable ecological profile. It degrades into relatively benign end-products, including water and chloride ions, thus reducing the risk of environmental contamination when compared with persistent veterinary pharmaceuticals and chemical disinfectants (Block and Rowan, 2020; Bajgai *et al.*, 2020). This property contributes to reduced chemical residues in soils, water systems, and animal-derived food products, aligning HOCl use with principles of climate-smart agriculture and environmental conservation.

In addition to these benefits, HOCl supports improved animal welfare outcomes. Its applications in wound management, sanitation, and parasite control are associated with reduced infection pressure and improved healing without causing significant tissue irritation or toxicity when used at appropriate concentrations (Rahman *et al.*, 2016; Gold *et al.*, 2020). Consequently, healthier animals experience reduced physiological stress, improved growth performance, and enhanced overall productivity. Collectively, these attributes align closely with global Sustainable Development Goals priorities (SDG's), including:

- SDG 2 (Zero Hunger): through enhanced livestock productivity and improved food security
- SDG 3 (Good Health and Well-being): via reduced zoonotic disease risks and mitigation of AMR
- SDG 12 (Responsible Consumption and Production): through minimisation of chemical residues in production systems
- SDG 13 (Climate Action): by promoting environmentally sustainable and low-impact livestock practices

VII. LIMITATIONS AND KNOWLEDGE GAPS

Despite increasing interest in HOCl applications within animal agriculture, relatively little information is available regarding its use in goat production systems. Most published evidence has focused on antimicrobial efficacy, wound management, environmental sanitation, and food-processing applications, with limited goat-specific data. Consequently, there is insufficient evidence to fully evaluate the long-term efficacy, safety, and economic feasibility of routine HOCl use in goats. Furthermore, few studies have investigated repeated exposure under commercial production conditions or assessed potential impacts on animal-derived products. Additional field-based investigations are therefore required to determine the effectiveness of HOCl under diverse production systems and environmental conditions.

Another significant gap is the insufficient economic evaluation of HOCl technologies. Adoption by farmers is

highly dependent on cost-effectiveness. However, there is limited empirical evidence on production costs, return on investment, and comparative economic advantages relative to conventional treatments. This lack of cost-benefit analysis hinders informed decision-making at both farm and policy levels. Furthermore, limited adoption and behavioural studies exist to assess farmer awareness, perceptions, and willingness to integrate HOCl into existing management systems. Socio-economic, cultural, and institutional barriers may influence the uptake of such innovations, particularly in developing countries where access to technology and extension services is constrained. Addressing these gaps is essential for transitioning HOCl from a promising experimental intervention to a validated, scalable, and widely accepted livestock health management solution.

VIII. FUTURE RESEARCH DIRECTIONS

To unlock the full potential of HOCl in livestock systems, future research should focus on several strategic areas:

• *Large-Scale, Multi-Location Field Trials*

Comprehensive field studies across diverse agro-ecological zones are necessary to evaluate the efficacy, robustness, and scalability of HOCl under real-world farming conditions. These trials should include different livestock species, production systems (intensive vs extensive), and disease challenges to generate context-specific recommendations.

• *Microbiome and Long-Term Safety Studies*

Advanced research using molecular and omics technologies should examine the impact of HOCl on the animal micro biome, including gut, skin, and respiratory microbial communities. Long-term studies are also required to assess chronic exposure effects, tissue integrity, immune responses, and potential residues in animal products.

• *Economic and Cost-Benefit Analyses*

Detailed economic evaluations should be conducted to determine the financial feasibility of HOCl adoption. This includes analysing input costs, labour requirements, productivity gains, disease reduction benefits, and overall profitability compared to conventional antimicrobial and parasitic control strategies.

• *Integration Into Parasite and Disease Control Programmes*

Future work should explore how HOCl can be effectively incorporated into integrated livestock health management systems, including vaccination, biosecurity, and ethnoveterinary practices. Its role in integrated parasite control programmes, particularly in reducing reliance on chemical anthelmintics, is of high relevance given increasing resistance issues.

• *Adoption, Extension, and Policy Research*

Studies on farmer perceptions, knowledge dissemination pathways, and extension approaches are needed to facilitate adoption. Additionally, policy

frameworks and regulatory guidelines should be developed to support safe and standardised use of HOCl in livestock production.

IX. CONCLUSION

Hypochlorous acid represents a promising innovation in goat production systems due to its antimicrobial, anti-inflammatory, and regenerative properties. Its mechanistic effects on pathogen reduction, inflammation control, and nutrient utilisation provide a strong scientific basis for its role in improving productivity and sustainability in Sub-Saharan Africa.

➤ Author Contributions

Conceptualization, writing of original draft - Wesly Bvirwa, data collection and curation- Marlon Chawarika, Review and writing and editing of manuscript, supervision, Soul Washaya, Godfrey B. Nyamushamba.

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➤ Conflicts of Interest

The authors declare no conflict of interest.

➤ Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

➤ Declaration of Generative AI and AI-Assisted Technologies in Diagrams and Figures Preparation

- During the preparation of this work, the author(s) used Copilot for diagrams

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