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Short Communication

Evaluating Homeopathy as an Alternative to Antibiotics for Surgical Wound Management

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ABSTRACT

Background and objectives: Postoperative wound management commonly relies on antibiotics and anti-inflammatory drugs; however, increasing antimicrobial resistance (AMR) has prompted interest in complementary approaches. This pilot study aimed to explore the effects of selected homeopathic remedies in postoperative wound management and to compare observed outcomes with conventional allopathic therapy in a goat surgical model. Methods: Six healthy female Black Bengal goats were randomly allocated into two groups (n=3 each): a control group receiving standard allopathic postoperative care (antibiotics, anti-inflammatory and antihistaminic drugs) and a treatment group managed with homeopathic remedies (*Calendula officinalis*-Q, *Arnica montana*-200, *Hypericum perforatum*-200, and Staphysagria 200). Animals underwent skin incision, laparotomy, and rumenotomy under aseptic conditions. Wound healing time, duration of acute pain, and infection status were monitored. Data were analyzed descriptively due to the small sample size. Results: All wounds healed in both groups without postoperative infection. However, the control group showed shorter mean healing times (6.7, 9.3, and 9.7 days for skin incision, laparotomy, and rumenotomy, respectively) compared to the homeopathic group (8.3, 11.7, and 15.0 days). Duration of postoperative pain was also shorter in the control group. Delayed recovery in the homeopathic group was more evident in major abdominal procedures. Conclusion: In this small exploratory study, conventional antibiotic-based postoperative management was associated with faster healing and earlier pain resolution. Homeopathic remedies supported eventual wound closure but were associated with delayed recovery, particularly in more invasive procedures. These findings suggest that such approaches may have limited or adjunctive roles rather than serving as replacements for standard therapy. Larger, controlled studies with objective outcome measures are required to validate these observations.

Introduction

Surgical site infection and delayed wound healing remain major challenges in both human and veterinary medicine. Despite advances in aseptic technique and perioperative care, postoperative complications continue to contribute substantially to morbidity, prolonged hospitalization, increased treatment cost, and compromised welfare outcomes. A cornerstone of modern surgical management is the prophylactic and therapeutic use of antibiotics to prevent infection and control inflammation. While this strategy has dramatically improved surgical success, the growing global crisis of antimicrobial resistance (AMR) now threatens the effectiveness of routine postoperative care across medical and veterinary disciplines (Marshall and Levy, 2011; O'Neill, 2016).

Antimicrobial resistance is recognized as one of the most serious public health threats of the twenty-first century. The widespread and often indiscriminate use of antibiotics in human hospitals, veterinary clinics, and agricultural systems has accelerated the emergence of multidrug-resistant pathogens that compromise infection control after surgery (Ventola, 2015; WHO, 2017). Resistant organisms increase the risk of surgical site infections, prolong recovery, and limit therapeutic options for both human and animal patients. In human

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medicine, postoperative infections caused by resistant bacteria are associated with longer hospital stays, higher mortality, and greater economic burden (Allegranzi et al., 2016). Similarly, in veterinary surgery, resistance reduces the reliability of conventional prophylaxis and forces clinicians to rely on increasingly restricted antimicrobial agents.

Because of this escalating crisis, there is strong international emphasis on reducing unnecessary antibiotic exposure while maintaining safe and effective postoperative management. Global action plans advocate the development of alternative or adjunctive strategies to minimize antibiotic dependence without compromising wound healing and patient comfort (WHO, 2017; O'Neill, 2016). These strategies include improved local wound care, immunomodulation, phytotherapy, and complementary approaches such as homeopathy.

Homeopathy is a complementary medical system based on the principles of similitude and potentization, using highly diluted substances to stimulate endogenous healing responses. Although controversial, homeopathy is widely applied in both human and veterinary practice, particularly where reduction of drug residues and side effects is desired (Bellavite et al., 2006; Mathie et al., 2014). In veterinary medicine, homeopathy has gained attention as a potential adjunct in wound management, postoperative recovery, and pain control, especially under organic and low-input health management systems (Hovi, 2001; ECCH, 2007). However, scientific evaluation of homeopathy in surgical contexts remains limited, particularly in large animal models.

Among homeopathic and phytotherapeutic agents, several remedies have been repeatedly associated with tissue repair and postoperative comfort. *Calendula officinalis* has long been recognized for its wound-healing (Preethi et al., 2009; Parente et al., 2012), antimicrobial (Efstratiou et al., 2012), anti-inflammatory (Parente et al., 2012), and angiogenic properties (Parente et al., 2011). Experimental and clinical studies demonstrate that Calendula enhances fibroblast proliferation, collagen synthesis, epithelialization, and wound contraction (Preethi et al., 2009; Parente et al., 2012). It has been shown to reduce microbial load and improve granulation tissue formation, supporting its use in surgical and traumatic wounds (Süntar et al., 2012). *Arnica montana* is traditionally used to reduce postoperative edema, bruising, and inflammation. Its bioactive compounds inhibit inflammatory mediators and improve microcirculation at injured sites. Clinical and experimental data suggest that Arnica may reduce swelling and pain after trauma and surgery, contributing to faster functional recovery (Iannitti et al., 2016; Ross, 2000). *Hypericum perforatum* (St. John's Wort) is especially valued for injuries involving nerve-rich tissues. It exhibits analgesic, anti-inflammatory, and neuroprotective effects and is commonly indicated for sharp, shooting, or neuralgic pain following trauma or incision (Süntar et al., 2010). Hypericum also supports epithelial regeneration and reduces hypersensitivity at wound margins. Staphysagria is classically associated with clean incised wounds and postoperative irritation. It is widely used to promote healing after surgical trauma, minimize pain at incision sites, and improve tissue tolerance following suturing. Experimental work suggests its role in modulating stress and cellular repair mechanisms in injured tissues (Khuda-Bukhsh, 2003; Bellavite et al., 2006). Together, these remedies form a logical multimodal approach targeting inflammation, pain, and tissue regeneration.

Despite increasing interest in such alternatives, most wound-healing research still relies heavily on rodent models. Rats and mice provide valuable mechanistic insight but have important limitations for translational surgical research. Their small body size, thin skin, rapid metabolism, and restricted capacity for layered surgical manipulation limit realistic simulation of clinical procedures such as laparotomy, organ handling, suturing, and postoperative wound care. Large incisions, standard surgical closure, and infection dynamics observed in routine surgery cannot be fully reproduced in rodents.

Goats offer a practical and clinically relevant experimental surgical model. Their body size allows realistic execution of surgical techniques, including skin incision, laparotomy, rumenotomy, and layered closure under conditions comparable to routine clinical surgery. The structure of goat skin, inflammatory response, and wound repair mechanisms permit direct observation of healing patterns applicable to both veterinary and translational research. In addition, goats are manageable, economical, ethically acceptable, and widely available, making them suitable for evaluating postoperative interventions aimed at reducing antibiotic dependence. Using goats as an experimental surgical model therefore bridges the gap between laboratory studies and clinical practice, allowing assessment of alternative wound-management strategies under realistic operative conditions. In the context of antimicrobial resistance affecting both human and veterinary medicine, exploring non-antibiotic postoperative approaches in such a model is particularly relevant.

The present study was designed to compare conventional allopathic (antibiotic-based) postoperative management with a homeopathic treatment protocol in goats undergoing different surgical procedures. By evaluating wound healing time, pain duration, and infection status, this work aims to explore whether selected homeopathic remedies can support postoperative recovery while potentially reducing reliance on antibiotics, thereby contributing to global efforts to combat antimicrobial resistance in surgical care.

Materials and Methods

Study Location and Ethical Considerations

The study was conducted at the Veterinary Teaching Hospital and animal shed facilities of Faculty of Animal Science and Veterinary Medicine, Patuakhali Science and Technology University (PSTU), Babugonj, Barishal-8210, Bangladesh. All experimental procedures were performed in accordance with standard animal welfare guidelines for the care and use of experimental animals. The goats were handled humanely, and all surgical and postoperative procedures were carried out to minimize pain and distress.

Ethical statements

All animal experiments were approved by the Institutional Ethical Committee of Patuakhali Science and Technology University (Reference No.: PSTU/IEC/2026/64, Dated: 12.04.2026).

Experimental Animals and Management

A total of six (n= 6) apparently healthy, young female Black Bengal goats were used in this study. The goats had a mean age of approximately 2.6 months and a mean body weight of 12.11 kg. Animals were collected from the local market and acclimatized at the PSTU animal shed prior to experimentation. Before the experiment, the goats were vaccinated against tetanus, goat pox, and peste des petits ruminants (PPR). They were maintained under uniform management conditions with adequate housing, ventilation, and hygiene. All animals were provided with a balanced diet and clean drinking water ad libitum throughout the experimental period.

Experimental Design

The goats were randomly allocated into two equal groups: Group A (Antibiotic group, n= 3); Group B (Homeopathic group, n= 3). Both groups underwent similar surgical procedures under aseptic conditions. Postoperative management differed only in the type of medications used for wound management and systemic therapy.

Anesthesia and Premedication

All animals were fasted for 12 hours prior to surgery. Premedication was performed using atropine sulphate at 0.04 mg/kg body weight intravenously (Tropin Vet®, ACME Laboratories Ltd.). Sedation was achieved with xylazine at 0.02 mg/kg intravenously (Xylazine Injection USP®, Farmer's Pharma Pvt. Ltd.). Local anesthesia was provided using lignocaine hydrochloride 2% (G-Lidocaine®, Gonoshasthaya Pharmaceuticals Ltd.) by infiltration at the surgical site according to the type of procedure.

Surgical Preparation and Procedures

The left or right flank area was clipped and shaved, followed by thorough cleaning. In Group A, the surgical site was prepared with povidone iodine solution (Povisep® 10% w/v), whereas in Group B, *Calendula officinalis*-Q was used for skin preparation. Standard aseptic techniques including draping were applied in both groups. Depending on the case, procedures such as skin incision, laparotomy, and rumenotomy were performed under regional anesthesia. After completion of surgery, muscle and skin layers were sutured routinely using standard suture materials.

Postoperative Treatment Protocol

Group A (Antibiotic group)

Animals in Group A received conventional allopathic postoperative management as follows: Surgical site antisepsis with Povisep® (Povidone iodine 10% w/v). Local antibacterial application using Sumid-Vet® (Sulphanilamide powder) beneath the skin sutures. Systemic antibiotic: Renacef® Vet (Ceftriaxone sodium) administered intramuscularly according to body weight. Anti-inflammatory drug: Tufnil Vet® (Tolfenamic acid). Antihistaminic drug: AstaVet® (Pheniramine maleate). All medications were administered following recommended veterinary dosages for postoperative care.

Group B (Homeopathic group)

Animals in Group B were managed using homeopathic remedies. Skin preparation was performed using *Calendula officinalis*-Q (Q= mother tincture; New life & Co. (Pvt.) Ltd., (Homeo), Mirpur, Dhaka, Bangladesh). The wound was soaked with *Calendula officinalis*-Q before skin suturing, and a topical spray of *Hypericum perforatum*-200 (New life & Co. (Pvt.) Ltd., (Homeo), Mirpur, Dhaka, Bangladesh) was applied to the wound margins prior to closure.

Postoperatively, *Calendula officinalis*-Q spray was applied topically three times daily for 7 days. Immediately after suturing, two oral doses of Staphysagria-200 (New life & Co. (Pvt.) Ltd., (Homeo), Mirpur, Dhaka, Bangladesh) were administered at 30-minute intervals. One hour later, *Hypericum perforatum*-200 was given orally in two doses at 30-minute intervals. Thereafter, *Arnica montana*-200 (New life & Co. (Pvt.) Ltd., (Homeo), Mirpur, Dhaka, Bangladesh) was administered orally at midday, and Calendula-200 (New life & Co. (Pvt.) Ltd., (Homeo), Mirpur, Dhaka, Bangladesh) was administered orally in the morning and evening for seven consecutive days.

All oral medicines were diluted with water (one drop in 10 mL of water, with 2 mL administered per dose) prior to administration, except *Calendula officinalis*-Q, which was used only for external application. *Calendula officinalis*-Q and *Calendula officinalis*-200 were used as healing agents to promote primary intention wound healing. Staphysagria-200 was used to facilitate recovery from clean surgical incisions, *Hypericum perforatum*-200 to alleviate neuralgic pain, and *Arnica montana*-200 to reduce inflammation and muscular pain.

Monitoring and Evaluation of Wound Healing

All animals were observed daily for postoperative recovery. Parameters recorded included: Presence of swelling and inflammation, Pain response, Discharge or infection, Time required for complete wound healing, and any postoperative complications. Healing time was defined as the number of days required for complete closure of the wound with absence of pain, swelling, and discharge.

Data Recording and Analysis

Data on healing response, pain duration, and infection status were recorded in tabular form. Descriptive statistics were used to calculate mean healing time and mean duration of acute pain for each surgical category in both groups. Due to the small sample size, only descriptive analysis was performed, and no inferential statistical testing was applied. Results were compared qualitatively between treatment groups

Results

Postoperative wound healing outcomes were evaluated in goats subjected to skin incision, laparotomy, and rumenotomy and managed either with conventional allopathic therapy (control group) or homeopathic treatment. Healing success, time to recovery, duration of acute pain, and incidence of infection were recorded and compared between groups (Table 1).

Wound Healing Response

All goats in the control (antibiotic) group showed complete wound healing (3/3) following all surgical procedures, including skin incision, laparotomy, and rumenotomy. No postoperative infection, wound dehiscence, or abnormal discharge was observed in any control animal during the observation period (Table 1).

In the homeopathic group, complete healing was also achieved in all animals (3/3) across the same surgical categories. However, healing progressed more slowly compared with the control group, particularly following major abdominal procedures such as rumenotomy (Table 1).

Healing Time

Mean healing time differed between treatment groups. In the control group, skin incisions healed in a mean of 6.7 days, whereas laparotomy and rumenotomy wounds healed in 9.3 and 9.7 days, respectively. In contrast, the homeopathic group required a longer period for wound closure. Skin incision healed in 8.3 days, laparotomy in 11.7 days, and rumenotomy in 15.0 days. The greatest delay relative to the control was observed after rumenotomy, where healing time increased by approximately five days compared with antibiotic-treated goats (Table 1).

Pain and Inflammatory Signs

Duration of acute postoperative pain was shorter in the control group than in the homeopathic group. Control animals showed mean pain persistence of 3.3 days for skin incision and 5.3 days for both laparotomy and rumenotomy (Table 1). In the homeopathic group, pain lasted longer, with mean durations of 4.0 days for skin incision, 6.0 days for laparotomy, and 6.7 days for rumenotomy. Swelling and local inflammatory signs subsided earlier in the control group than in the homeopathic-treated goats (Table 1).

Infection and Complications

No surgical site infection was recorded in either group throughout the study period (Table 1). However, the control group demonstrated faster resolution of inflammation, absence of serous discharge, and earlier restoration of normal activity compared with the homeopathic group, especially following laparotomy and rumenotomy.

Comparative Outcome

Overall, the control (antibiotic) protocol resulted in more rapid wound healing and earlier pain relief (Table 1) than the homeopathic protocol (Table 1). While homeopathic management supported eventual recovery, it was associated with delayed healing and prolonged discomfort, particularly after major surgical interventions. The summarized outcomes for wound healing time, pain duration, and infection status for both groups are presented in Tables 1.

Table 1. Postoperative Wound Healing Outcomes in Goats Treated with Antibiotic and Homeopathic Therapies

Type of surgery	Antibiotic group				Homeopathic group			
	Complete Healing (Yes/No)	Mean Healing Time (Days)	Mean Acute pain observed (Days)	Infection	Complete Healing (Yes/No)	Mean Healing Time (Days)	Mean Acute pain observed (Days)	Infection
Skin incision	Yes (3/3)	6.7	3.3	No	Yes (3/3)	8.3	4	No
Laparotomy (Right flank)	Yes (3/3)	9.3	5.3	No	Yes (3/3)	11.7	6	No
Rumenotomy (Left flank)	Yes (3/3)	9.7	5.3	No	Yes (3/3)	15	6.7	No

(Note: 3/3= 3 out of 3 goats)

Legend: This table summarizes the healing responses of surgical wounds in goats managed with either conventional allopathic (antibiotic) therapy or homeopathic postoperative protocols. Parameters include the proportion of animals achieving complete healing (Yes/No), mean healing time in days, mean duration of acute postoperative pain in days, and occurrence of surgical site infection following skin incision, laparotomy (right flank), and rumenotomy (left flank). Values represent mean observations from three goats per procedure. The notation (3/3) indicates that all three animals in the group showed complete wound healing.

Discussion

Effective postoperative wound management is essential for minimizing complications, reducing pain, and ensuring rapid functional recovery in both human and veterinary surgery. In the present study, conventional allopathic management using antibiotics, anti-inflammatory, and antihistaminic drugs (control group) was compared with a homeopathic-based postoperative protocol in goats undergoing different surgical procedures. The findings demonstrate that while both approaches supported eventual wound closure, the antibiotic-based protocol achieved faster resolution of inflammation, shorter duration of pain, and earlier completion of healing, particularly in major abdominal procedures such as laparotomy and rumenotomy. The superior performance of the control group is consistent with the established role of antibiotics and non-steroidal anti-inflammatory drugs in controlling microbial contamination and modulating postoperative inflammation. Surgical trauma initiates a complex cascade involving vascular changes, inflammatory cell recruitment, and tissue remodeling. Antibiotics reduce bacterial load at the wound site, preventing prolonged inflammatory responses and secondary infection, while NSAIDs suppress prostaglandin-mediated pain and edema, thereby promoting a more favorable healing environment. Previous veterinary studies similarly report improved postoperative recovery when systemic antibiotics and anti-inflammatory agents are combined in goat surgery (Egbe-Nwiyi et al., 2000; Kumar et al., 2013).

Nevertheless, the broader significance of the present work lies not in replacing antibiotics outright but in exploring the feasibility of alternative or adjunct strategies in the context of antimicrobial resistance. AMR threatens the sustainability of current postoperative management paradigms in both human and veterinary medicine (Ventola, 2015; O'Neill, 2016). Routine prophylactic antibiotic use, although effective, exerts selective pressure that accelerates the emergence of multidrug-resistant organisms, compromising future surgical safety. Therefore, identifying complementary approaches that support wound healing while potentially reducing antibiotic exposure is of increasing importance.

In this study, the homeopathic protocol resulted in complete healing of all wounds but with delayed closure and prolonged pain, particularly after rumenotomy. This observation suggests that while homeopathic remedies may support biological repair processes, they may not provide sufficient antimicrobial protection or anti-inflammatory control to match conventional therapy in major surgeries. The difference between superficial and deeper procedures highlights an important dimension: minor skin incisions may benefit from alternative therapies, whereas complex abdominal operations demand stronger infection control and inflammatory modulation.

From a mechanistic perspective, several components of the homeopathic protocol exhibit biological plausibility. *Calendula officinalis* has been reported to enhance fibroblast proliferation, collagen synthesis, angiogenesis, and epithelialization, thereby promoting granulation tissue formation (Preethi et al., 2009; Parente et al., 2012). Its documented antimicrobial and antioxidant properties may have contributed to the absence of overt infection in the homeopathic group despite the lack of systemic antibiotic therapy (Efstratiou et al., 2012; Rigane et al., 2013). Nevertheless, Calendula alone may not provide sufficient antimicrobial coverage to control deeper contamination associated with major abdominal surgery. Furthermore, *Calendula officinalis*-Q may be considered a potential adjunct or alternative to conventional surface antiseptics, such as povidone iodine, during preoperative skin preparation; however, further controlled studies are required to confirm its comparative efficacy.

Arnica montana has been reported to exert anti-inflammatory and analgesic effects through modulation of inflammatory mediators, vascular permeability, and microcirculation (Iannitti et al., 2016). Experimental evidence further demonstrates that Arnica preparations can downregulate pro-inflammatory cytokines such as TNF-α, IL-1β, and IL-6, inhibit COX-2 expression, and reduce oxidative stress in cellular and animal models (Verre et al., 2024; Lee et al., 2025). These mechanisms provide biological support for its traditional use in reducing postoperative edema, ecchymosis, and soft tissue inflammation. Additionally, topical Arnica formulations have shown measurable reductions in experimentally induced edema and pain behavior, indicating both anti-inflammatory and analgesic activity (Lee et al., 2025). In the present study, a reduction in swelling was observed in the homeopathic group, consistent with these reported properties. However, the rate of inflammatory resolution was slower than in the antibiotic-based control group, suggesting that while *Arnica montana* may partially modulate inflammatory cascades, it may not provide sufficient magnitude or breadth of suppression to fully control the complex inflammatory response associated with major surgical trauma.

Hypericum perforatum is particularly relevant to postoperative pain modulation due to its documented anti-inflammatory and antinociceptive properties. Experimental studies demonstrate that *H. perforatum* extracts can inhibit carrageenan-induced edema, suppress pro-inflammatory mediators, and reduce nociceptive responses in validated animal pain models (Abdel-Salam, 2005; Sosa et al., 2007). Mechanistically, bioactive constituents such as hyperforin and hypericin are reported to modulate inflammatory signaling pathways and influence neurotransmitter systems involved in pain perception (Galeotti, 2017). In addition, wound-healing studies suggest that *H. perforatum* contributes to tissue repair while reducing inflammatory infiltration, supporting its traditional application in trauma-related and neuralgic pain conditions (Süntar et al., 2010). In the present study, although a degree of postoperative analgesic effect was observed in the homeopathic group, pain persisted for a longer duration compared to the NSAID-based control protocol. This finding suggests that while *Hypericum perforatum* may attenuate inflammatory and neuropathic components of pain, it does not replicate the potent cyclooxygenase inhibition and prostaglandin suppression achieved by conventional NSAIDs in the management of acute surgical inflammation.

Staphysagria is classically indicated for clean incised wounds and postoperative irritation. It is believed to influence cellular repair mechanisms and stress-related inflammatory responses (Khuda-Bukhsh, 2003). Its role may explain why incision wounds healed successfully in the homeopathic group, albeit more slowly, supporting the concept that such remedies may serve best as adjuncts rather than replacements in high-risk surgeries.

An important methodological strength of this study is the use of goats as an experimental surgical model. Unlike rodent models, goats allow realistic simulation of clinical surgery including skin incision, laparotomy, organ handling, suturing, and postoperative monitoring. Their wound size, tissue response, and healing kinetics resemble practical surgical conditions, making findings more translational to real-world veterinary and potentially comparative surgical research. This model therefore bridges laboratory experimentation and clinical application, providing meaningful insight into postoperative management strategies.

However, several limitations must be acknowledged. The sample size was small, limiting statistical power and generalizability. Consequently, no inferential statistical analysis was performed, and the findings should be interpreted as descriptive observations rather than statistically validated conclusions. The absence of blinding and objective measurement tools may introduce observational bias. The study relied primarily on descriptive outcome measures rather than histological, microbiological, or molecular assessments of healing. Additionally, the design did not evaluate combined protocols where homeopathic remedies might supplement reduced-dose antibiotics, which could be a realistic compromise in AMR-oriented strategies.

Future studies should incorporate larger populations, quantitative bacterial cultures, cytokine profiling, histoplanimetry, and controlled statistical comparisons to better elucidate mechanisms and clinical relevance.

The results also highlight a key conceptual point: alternatives to antibiotics should not necessarily aim to replace conventional therapy in all contexts but rather to optimize and rationalize antibiotic use. In human surgery, there is growing emphasis on antimicrobial stewardship programs that minimize exposure while maintaining patient safety (Allegranzi et al., 2016). A similar philosophy applies in veterinary practice, where integrating non-antibiotic wound-supportive therapies may reduce reliance on broad-spectrum agents without compromising outcomes.

In conclusion, the present study demonstrates that while conventional antibiotic-based postoperative management remains superior in ensuring rapid healing and pain control, selected homeopathic remedies can support biological repair processes and may have value as complementary tools. Within the broader context of antimicrobial resistance affecting both human and veterinary surgery, such approaches deserve further investigation using robust experimental models like goats. Refining these strategies may contribute to safer, more sustainable postoperative care with reduced antibiotic dependence in the future.

Conclusion and Recommendations

This pilot study provides preliminary observations on postoperative wound management using conventional allopathic therapy and a homeopathic protocol in a goat surgical model. While complete wound healing was achieved in all animals, antibiotic-based management was associated with faster healing and shorter duration of pain, particularly in major surgical procedures. The findings indicate that although the selected homeopathic remedies may support basic wound repair processes, they do not match the efficiency of standard postoperative care in controlling inflammation and promoting rapid recovery. Their potential role may therefore be limited to adjunctive use or less complex clinical situations rather than replacement of antibiotics in major surgeries. Given the small sample size, absence of statistical analysis, and reliance on observational parameters, these results should be interpreted with caution. Further studies with larger sample sizes, appropriate controls, blinding, and objective outcome measures such as histopathology, microbiological assessment, and validated wound scoring systems are necessary to establish clinical relevance. Future research may also explore combined or reduced-antibiotic protocols integrating supportive therapies to contribute to antimicrobial stewardship without compromising surgical outcomes.

Contributions of the authors

MTH designed the experiments. SMH, TAS, AD, and BKP conducted the experiment, collected, and analyzed the data. SMH prepared the initial draft. MTH and MAJ critically revised the manuscript.

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