ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/25aug1258

Herbal and Enzymatic Therapeutics in Modern Drug Delivery: The Case of Bromelain

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Publication Date: 2025/09/03

Abstract: This review examines the incorporation of bromelain, a proteolytic enzyme complex derived from pineapple, into advanced drug delivery systems. Bromelain has demonstrated anti-inflammatory, analgesic, fibrinolytic, and wound-healing properties, but its therapeutic use is limited by its poor stability and low bioavailability. The pharmacological profile, mechanisms of action, and conventional dosage forms of bromelain are also discussed. Advanced delivery approaches using nanocarriers, such as nanoparticles, liposomes, and nanoemulsions, have been explored as strategies to enhance the stability, bioavailability, and targeted delivery of bromelain. Clinical applications in areas such as anti-inflammatory therapy, wound healing, and cancer treatment are reviewed, along with challenges in translating nano-formulations to commercial products. The integration of bromelain into novel drug delivery platforms and combination therapies represents a promising strategy for expanding its therapeutic potential. Further research is needed to optimize these formulations and to demonstrate the clinical efficacy of advanced bromelain delivery systems.

Keywords: *Bromelain, Drug Delivery Systems, Nanocarriers, Anti-Inflammatory, Proteolytic Enzyme, Pineapple-Derived Enzyme, Clinical Applications.*

How to Cite: Parnika P. Kadam ; Dr. Lalita S. Nemade ; Apeksha C. Rahate (2025). Herbal and Enzymatic Therapeutics in Modern Drug Delivery: The Case of Bromelain. *International Journal of Innovative Science and Research Technology*, 10(8), 2121-2128. https://doi.org/10.38124/ijisrt/25aug1258.

I. INTRODUCTION

Recently, pharmaceutical research has increasingly focused on the incorporation of herbal and enzymatic agents into contemporary drug delivery systems. Natural therapeutics, particularly enzymes derived from plants, present a broad range of pharmacological benefits with minimal side effects, making them appealing alternatives or supplements to traditional synthetic medications. Among these, Bromelain, a proteolytic enzyme complex sourced from Ananas comosus (pineapple), has attracted significant interest because of its ability to reduce inflammation, alleviate edema, provide pain relief, promote fibrinolysis, and aid wound healing.

Bromelain has long been utilized in oral formulations to manage inflammation, aid post-surgery recovery, and treat digestive issues. Recently, it has also been incorporated into topical products, such as gels and ointments, for healing wounds and treating soft tissue injuries. Despite its potential, its broader use has been limited by factors, such as poor stability, enzymatic breakdown in the digestive tract, and low systemic bioavailability. To overcome these obstacles, advanced drug delivery systems, particularly those based on nanotechnology, have been developed as promising methods to improve their stability, bioavailability, and therapeutic efficacy [3].

This review seeks to deliver a critical and up-to-date summary of Bromelain's use in both traditional and modern drug delivery systems, focusing particularly on nano-formulations and topical applications.

II. PHARMACOLOGICAL PROFILE OF BROMELAIN

Bromelain is a crude extract rich in various thiol endopeptidases, primarily obtained from the stem of the pineapple plant (*Ananas comosus*), although it can also be sourced from fruit. Its molecular composition includes multiple proteolytic enzymes, phosphatases, glucosidases, peroxidases, cellulases and glycoproteins. The stem extract, referred to as stem bromelain, is particularly potent and have been widely studied. The molecular weight of bromelain ranges between 20 to 35 kDa, depending on the specific isoenzyme and the extraction method.

Proteolytic action is centered around cysteine residues, which interact with peptide bonds in target proteins. This underscores the ability of bromelain to modulate numerous physiological pathways. It is also known to downregulate

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/25aug1258

pro-inflammatory mediators, such as tumor necrosis factor-alpha (TNF-α), interleukins (IL-1β, IL-6), and prostaglandins (PGE-2), establishing its role as an anti-inflammatory and analgesic agent.

In addition to proteolysis, bromelain exhibits antimicrobial, anticoagulant, and immunomodulatory activities. This enzyme has demonstrated efficacy in various in vitro and in vivo models, supporting its application in multiple therapeutic domains.

➢ *Mechanism of Action*

Bromelain exerts its effects primarily through the following mechanisms.

- Proteolytic activity, breaking down of proteins, and fibrin to reduce inflammation and edema.
- Modulation of inflammatory mediators, including downregulation of prostaglandins, bradykinin, and cytokines such as IL-1β and TNF-α.
- Fibrinolytic and anticoagulant properties aid the breakdown of fibrin clots and enhance blood circulation.
- Immunomodulatory activity promotes T-cell activation and reduces oxidative stress through its antioxidant properties.

➢ *Therapeutic Applications*

Bromelain has been extensively studied for .

- Anti-inflammatory activity in conditions such as arthritis, sinusitis, and sports injuries.
- Wound healing, especially in burn therapy and debridement.
- Post-operative recovery, pain reduction, swelling, and bruising.
- Digestive aid, improving protein digestion, and relieving bloating and indigestion.
- The anticancer potential is still largely under experimental evaluation.

➢ *Safety and Toxicity*

Bromelain is widely regarded as safe and non-toxic, and exhibits a high LD50 value in animal studies. Although adverse effects are uncommon, they can include gastrointestinal discomfort, allergic reactions (particularly in those allergic to pineapple or latex), and mild skin irritation when topically used. Additionally, bromelain may interact with anticoagulant or antiplatelet medications; therefore, caution is advised in patients undergoing such treatments.

➢ *Limitations*

Despite its therapeutic potential, bromelain has certain formulation-related limitations.

- Enzymatic degradation in the gastrointestinal tract after oral administration.
- Instability under high-temperature and pH fluctuations.
- Its short half-life and low bioavailability compromise its systemic effectiveness.

III. CONVENTIONAL DOSAGE FORMS OF BROMELAIN

Bromelain has traditionally been incorporated into various standard dosage forms for oral, topical, and parenteral administration. Although these methods have facilitated clinical application, they frequently encounter challenges concerning enzyme stability, bioavailability, and precise delivery.

➢ *Oral Dosage Forms*

Bromelain, a mixture of proteolytic enzymes derived from pineapple stems, is widely available in oral formulations such as tablets, capsules, and granules. These formulations are popular owing to their convenience and ease of administration.

- *The primary therapeutic applications of oral Bromelain include the following.*

✓ Anti-inflammatory action Bromelain has shown efficacy in reducing inflammation associated with arthritis, sinusitis, and sports injuries. This may help to alleviate pain and swelling under these conditions.
✓ Post-operative recovery: Bromelain is used to reduce pain and swelling following surgical procedures, potentially accelerating healing, and improving patient comfort.
✓ Digestive support: As a proteolytic enzyme, Bromelain aids in protein breakdown, potentially improving digestion, and reducing gastrointestinal discomfort.

- *Despite these benefits, the oral bioavailability of Bromelain remains a significant challenge.*

✓ *Enzymatic degradation:*

The acidic environment of the stomach can degrade Bromelain, reducing its effectiveness.

✓ *First-pass metabolism:*

The liver metabolizes a portion of the absorbed Bromelain before it reaches systemic circulation, further reducing its bioavailability.

- *Several Strategies Have Been Explored To Address These Issues:*

✓ *Enteric coating:*

This technique involves coating the Bromelain formulation with a material that resists stomach acid, allowing the enzyme to be released in the small intestine where absorption can occur more efficiently.

✓ *Co-formulation with protease inhibitors:*

Bromelain degradation in the gastrointestinal tract may be reduced by including compounds that inhibit proteolytic enzymes in the formulation.

✓ *Lipid-based systems*:

These formulations protect Bromelain from degradation and potentially enhance its absorption through the intestinal wall.

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/25aug1258

Although these approaches show promise in improving the stability and bioavailability of oral Bromelain, they are not yet widely commercialized. Further research and development are needed to optimize these formulations and to demonstrate their clinical efficacy and safety before they can become mainstream products.

➢ *Topical Dosage Forms*

Topical formulations of Bromelain offer several advantages for treating skin conditions and wounds:

- *Burn Wound Debridement:*

Bromelain proteolytic enzymes play a crucial role in wound healing by breaking down damaged or necrotic tissues. This action aids in the removal of dead skin and debris from burn wounds, thereby effectively cleansing the affected area. By facilitating a cleaner wound bed, bromelain creates an optimal environment for the healing process, potentially accelerating recovery and reducing the risk of complications.

- *Skin Inflammation and Pain Relief:*

Bromelain is known for its significant anti-inflammatory effects, which help minimize swelling and redness in the affected regions. This enzyme can also assist in easing the pain associated with various skin ailments or injuries. Its potential therapeutic uses include the management of inflammatory skin conditions such as psoriasis or eczema. Additionally, proteolytic enzymes in bromelain are vital for wound healing, as they break down damaged or dead tissue. This process aids in clearing dead skin and debris from burn wounds and effectively cleaning the affected area. Bromelain establishes an ideal environment for healing by promoting a cleaner wound bed, which may accelerate recovery and lower the risk of complications.

- *Wound Healing:*

The ability of bromelain to break down proteins is vital for wound healing, as it efficiently removes dead tissue, fostering a more conducive environment for recovery. This enzymatic function not only purifies the wound site but might also encourage the development of new tissue, aiding the regeneration process. By establishing ideal conditions for healing and potentially promoting tissue growth, proteolytic characteristics of bromelain could accelerate the overall healing process. This comprehensive approach to wound care highlights the potential therapeutic benefits of bromelain in various medical settings, especially in treating burns, ulcers, and other skin injuries, where effective debridement and tissue regeneration are crucial for healing.

- *Benefits of Topical Application*

Bypass first-pass metabolism, avoiding degradation of the digestive system.

Allows targeted and localized delivery to the affected area.

Particularly effective in burn therapy owing to its direct application to damaged skin.

➢ *Challenges in Formulation and Application*

- *Enzyme Stability In Aqueous Systems:*

Bromelain is degraded in water-based formulations, with reduced enzymatic activity in aqueous environments. To maintain its proteolytic capabilities for wound healing, formulators must consider pH, temperature, and stabilizing agents. Encapsulation or non-aqueous carriers protect the enzyme, whereas antioxidants reduce the degradation of metal ions. These factors require specialized formulations to ensure the stability of bromelain in pharmaceuticals.

- *Skin Permeability*:

Bromelain faces challenges in topical use owing to its large molecular size, which limits skin penetration and therapeutic effectiveness. To overcome this, advanced formulation methods, such as nanoencapsulation, could reduce the effective size of bromelain, while penetration enhancers can modify skin barrier properties. These approaches aim to enhance the bioavailability of bromelain for topical applications.

- *Retention Time:*

When developing topical bromelain products, the formulation must remain on the skin long enough for it to be effective. If removed too soon, its therapeutic benefits may diminish owing to insufficient penetration time. To address this, formulations must either adhere to the skin or gradually release the enzyme. Adhesive formulations can use polymers to improve skin adherence, whereas slow-release systems can encapsulate bromelain in a matrix for gradual release, potentially enhancing its therapeutic effects.

Future research may focus on addressing these challenges through advanced formulation techniques and delivery systems to enhance the efficacy of topical Bromelain preparations.

➢ *Parenteral/Injectable Forms*

Parenteral delivery is a promising method for the administration of bromelain in anticancer and thrombolytic applications. It involves the introduction of the enzyme directly into the bloodstream or tissues, bypassing the gastrointestinal tract. Its main advantages include rapid systemic absorption, higher bioavailability, and avoidance of gastrointestinal degradation.

Rapid systemic absorption is a key benefit of parenteral administration of Bromelain. When injected into the bloodstream or tissues, the enzyme quickly reaches the target sites without delays in oral absorption. This rapid onset is crucial in time-sensitive situations such as thrombolytic therapy, where prompt intervention can significantly impact outcomes.

A higher bioavailability is a key advantage of parenteral Bromelain delivery. By circumventing the digestive system, most of the administered dose remains intact for therapeutic action. This increased bioavailability allows for lower dosages and more predictable therapeutic effects compared with oral administration.

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Avoiding gastrointestinal degradation is the third major benefit of parenteral Bromelain delivery. It is protected from stomach acid and intestinal enzymes, which can degrade oral Bromelain. This preservation ensured that the more active compounds reached the intended target sites.

Despite these advantages, the clinical adoption of parenteral Bromelain faces several limitations. Safety concerns are paramount, as direct bloodstream introduction risks adverse reactions including allergic responses and systemic effects. The immune response is another major challenge, as the body may recognize Bromelain as foreign and mount an immune response, potentially reducing efficacy or causing immunological complications.

The limited regulatory approval has hindered the widespread use of parenteral Bromelain. The stringent requirements for injectable medications and the need for extensive clinical trials to demonstrate safety have slowed the progress of bromelain from experimental treatments to approved options. These regulatory hurdles reflect the complexity of developing parenteral enzyme therapies and the need for evidence to support their clinical use.

IV. ADVANCED DRUG DELIVERY SYSTEMS FOR BROMELAIN

Recent advancements in nanotechnology and targeted delivery systems have revolutionized the formulation of bioactive agents such as bromelain. These systems are designed to overcome conventional limitations, such as poor stability, low solubility, enzymatic degradation, and lack of targeted delivery. In the case of bromelain, nanocarrier-based formulations have shown promise in enhancing their bioavailability, protecting enzymatic activity, and improving therapeutic outcomes.

➢ *Nanoparticles*

Nanoparticles made from biodegradable polymers such as chitosan and PLGA have been investigated for the encapsulation of bromelain, offering several advantages. These nanoparticles protect bromelain from pH degradation, enable controlled release, and target specific tissues such as inflamed joints or tumors. Chitosan nanoparticles are particularly noteworthy due to their mucoadhesive and permeation-enhancing properties, making them suitable for both oral and topical delivery methods. These characteristics make biodegradable polymer nanoparticles a promising approach for improving the efficacy and versatility of bromelain-based treatments.

➢ *Liposomes and Niosomes*

Vesicular systems such as liposomes (phospholipid bilayers) and niosomes (non-ionic surfactant vesicles) can encapsulate Bromelain and deliver it via topical and oral/mucosal routes. The topical route is beneficial for wound healing and anti-inflammatory applications, whereas the oral/mucosal route offers enhanced protection and absorption. These systems provide a biocompatible environment, prevent enzymatic degradation, and can be tailored for site-specific drug delivery. By encapsulating Bromelain in these vesicular structures, the therapeutic potential can be maximized through improved stability, targeted delivery, and enhanced bioavailability.

➢ *Nanoemulsions and Nanoemulgels*

Nanoemulsions, characterized by their thermodynamically stable composition of oil, water, surfactant, and co-surfactant with droplet sizes below 200 nm, serve as the foundation for incorporation into gels. This innovative drug delivery platform offers several advantages for topical anti-inflammatory therapies. Nanoemulgels enhance skin permeation, improve drug solubility and spreadability, and allow dual-drug compatibility. Moreover, these formulations demonstrated good patient acceptability and ease of application, making them a promising approach for effective topical treatment. The unique properties of nanoemulgels make them particularly suitable for addressing inflammatory conditions through localized drug delivery, potentially improving therapeutic outcomes and patient compliance.

➢ *Other Systems*

- *Hydrogels* offer a sustained release of therapeutic agents, providing a controlled and prolonged delivery mechanism. This characteristic is particularly beneficial for the maintenance of consistent drug levels over extended periods. However, hydrogels may lack penetration enhancement capabilities, potentially limiting their effectiveness in drug delivery across biological barriers.
- *Microspheres* have shown promise for oral delivery of various therapeutic agents. Their small size and encapsulation properties render them suitable for protecting drugs from degradation in the gastrointestinal tract. However, microspheres have not been extensively explored for the delivery of enzymatic agents, presenting an opportunity for further research and development in this area.
- *Solid lipid nanoparticles* (SLNs) provide stability to encapsulated drugs, protecting them from degradation, and enhancing their shelf life. This stability is particularly advantageous for the development of sensitive therapeutic agents. However, SLNs typically have a lower drug-loading capacity for hydrophilic proteins, such as bromelain, which may limit their efficiency in delivering such agents at therapeutic doses.

V. CLINICAL APPLICATIONS

Bromelain, a mixture of proteolytic enzymes derived from pineapple stems, has demonstrated significant therapeutic potential in the clinical setting. Its anti-inflammatory and anti-edematous properties make it effective in reducing swelling and inflammation, whereas its wound-healing capabilities contribute to faster tissue repair. These benefits have been observed in various medical applications, including post-surgical recovery and treatment of inflammatory conditions. Despite promising preclinical and in vitro studies, the development of advanced bromelain delivery systems has not yet been fully translated into clinical

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/25aug1258

practice. This gap between laboratory findings and clinical implementation may be attributed to several factors including bioavailability challenges, stability issues, targeted delivery limitations, regulatory hurdles, and cost considerations. Ensuring consistent and effective absorption of bromelain in the human body, maintaining the enzyme's activity throughout the delivery process and within the body, developing systems that can deliver bromelain to specific sites of action, meeting stringent safety and efficacy requirements for novel delivery systems, and balancing the expenses of advanced delivery technologies with potential clinical benefits are all critical aspects that need to be addressed. Overcoming these challenges could unlock the full therapeutic potential of bromelain and improve its clinical efficacy in various medical applications.

➢ *Anti-inflammatory and Pain Management*

Bromelain has been shown to be effective in reducing inflammation under several conditions.

- *Osteoarthritis and Rheumatoid Arthritis:*

Clinical studies have reported that oral Bromelain (500–2000 mg/day) can reduce joint pain, stiffness, and swelling, with tolerability comparable to NSAIDs.

- *Post-operative Inflammation:*

Trials of dental and orthopedic surgeries have demonstrated faster recovery and reduced pain and edema.

- *Sports Injuries*:

Bromelain, either alone or in combination with flavonoids, has been shown to accelerate recovery from soft tissue trauma.

- *Most of these studies used conventional oral forms;*

Few have evaluated topical or nanoformulated bromelain, particularly in comparison to NSAIDs or enzyme combinations.

➢ *Wound Healing and Burn Debridement*

Topical Bromelain formulations, including enzymatic debriding agents, were used as follows:

- *Burn wound management:*

Selective enzymatic debridement of necrotic tissue in deep burns improves healing time.

- *Chronic wounds and ulcers:*

Some clinical case reports suggest improved healing and granulation.

A commercial product (e.g., NexoBrid®, containing Bromelain) has been approved in Europe for topical burn debridement, indicating the clinical acceptance of enzyme-based formulations.

➢ *Digestive Disorders and Systemic Use*

Orally administered bromelain is marketed as a digestive enzyme in several countries. Although clinical evidence is less robust in this domain, anecdotal and observational studies support its role.

- Protein digestion aid
- Management of bloating, indigestion, and IBS

Its systemic use in conditions such as cardiovascular disorders (e.g., fibrinolysis and platelet aggregation inhibition) remains experimental, with insufficient human trials.

➢ *Cancer and Immune Modulation (Emerging Area)*

Preclinical studies have demonstrated the multifaceted anticancer properties of Bromelain. This proteolytic enzyme induces apoptosis in cancer cells and effectively promotes programmed cell death in malignant tissues. In addition, bromelain enhances immune surveillance, potentially improving the ability of the body to detect and eliminate cancer cells. Furthermore, it has been observed to reduce tumor cell adhesion and metastasis, which may inhibit the spread of cancer to other parts of the body. Collectively, these findings suggest that bromelain is a promising agent for cancer prevention and treatment strategies [27].

However, clinical trials in oncology are scarce, and delivery system challenges (e.g., enzymatic degradation and targeting) persist.

VI. COMMERCIAL PRODUCTS

➢ *Oral Formulations of Bromelain Available Globally Are:*

- Digestive enzyme supplements and anti-inflammatory agents play a crucial role in the management of various gastrointestinal and inflammatory conditions. Digestive enzymes aid in breaking down food components, improving nutrient absorption, and alleviating the symptoms of digestive disorders.
- Anti-inflammatory agents, often combined with other compounds, such as Rutoside or Trypsin, help reduce inflammation throughout the body. These fixed-dose combinations may offer synergistic effects, potentially enhancing therapeutic outcomes. Nonsteroidal anti-inflammatory drugs (NSAIDs) are also frequently used in such combinations to provide pain relief along with their anti-inflammatory properties. The use of these supplements and medications should be guided by healthcare professionals to ensure appropriate dosing and to minimize potential side effects.
- Brands include: Bromelain Forte®, Wobenzym®, Phlogenzym®, Zymoflam-D®, etc.

➢ *Topical Preparations Included the Following:*

- *NexoBrid®*

Enzymatic debridement has gained recognition as an effective method for treating burn wounds and has received regulatory approval in the European Union. Enzymatic agents break down necrotic tissue while preserving healthy tissue, facilitating healing and reducing surgical needs. In the United States, enzymatic debridement is undergoing clinical trials to evaluate its safety and efficacy compared with traditional methods, with the aim of determining its potential as a standard treatment option for burn patients [25].

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/25aug1258

- *Bromelain*

Containing herbal wound gels show potential healing properties. Pineapple stem enzymes have anti-inflammatory and proteolytic effects. However, the lack of clinical standardization of formulation and dosage makes it difficult to establish efficacy profiles. More rigorous research is necessary to validate their therapeutic potential in wound management.

➢ *Challenges in Commercialization of Nano-formulations*

- *Stability and shelf-life concerns with protein-based nano-formulations*:

Protein-based nano-formulations may face stability issues during storage and transportation. Shelf life can be affected by factors, such as temperature, pH, and exposure to light or moisture, potentially leading to protein degradation or loss of therapeutic efficacy.

- *Scalability of nanocarrier manufacturing processes:*

Scaling up nanocarrier production from laboratory to industrial levels presents challenges for maintaining consistent size, shape, and functionality. Ensuring reproducibility and quality control across large-scale batches are crucial for commercial viability.

- *Regulatory data requirements (toxicity, immunogenicity, and stability):*

Regulatory agencies require extensive data on the toxicity profiles, potential immunogenicity, and long-term stability of nano-formulations. Comprehensive studies are necessary to demonstrate the safety and efficacy of this method for its clinical use and market approval.

- *Cost-effectiveness vs. traditional enzyme delivery methods:*

Although nanocarrier-based enzyme delivery may offer improved efficacy, the production costs and complexity of these systems must be weighed against traditional methods. Economic viability depends on superior therapeutic outcomes and reduced overall treatment costs.

- *Patent restrictions and proprietary technologies for encapsulation methods:*

Existing patents on nanocarrier technologies and encapsulation methods may limit innovation or increase licensing costs for new development. Navigating the intellectual property landscape is crucial for the commercialization and market entry of novel nano-formulations.

VII. FUTURE PERSPECTIVES

Bromelain, a natural enzymatic therapeutic, continues to gain attention for its broad pharmacological profile and minimal side effects. However, to fully harness its potential in modern medicine, especially through advanced drug delivery systems, targeted research and strategic innovations are essential.

➢ *Integrating Bromelain into Advanced Drug Delivery Platforms*

Enzyme immobilization techniques address several key challenges in biocatalysis and drug delivery. By protecting enzymatic activity from environmental degradation, these methods ensure the longevity and effectiveness of enzymes for various applications. Improved site-specific delivery enables targeted action, maximizing the impact of the enzyme where it is most needed. Enhanced bioavailability ensures that a higher proportion of the enzyme remains active and accessible to the substrates or target sites. Additionally, controlled and sustained release mechanisms allow for gradual and consistent distribution of enzymes over time, optimizing their performance and extending their therapeutic or catalytic effects. These combined benefits make enzyme immobilization a valuable approach for biotechnology, pharmaceuticals, and industrial processes.

➢ *Exploring Dual-Drug and Combination Therapies*

Combining Bromelain with synthetic agents, such as NSAIDs, in dual-drug delivery systems offers several advantages. This approach can provide synergistic anti-inflammatory effects, potentially enhancing the overall therapeutic outcomes. This allows for a reduction in the dosage of synthetic drugs, thereby minimizing the adverse effects associated with their use. Additionally, this combination can address multiple pathological pathways simultaneously, which is particularly beneficial for complex diseases, such as rheumatoid arthritis. This multifaceted approach may lead to more effective and safer treatment strategies for inflammatory conditions [30].

➢ *Application Expansion into Emerging Fields*

- Bromelain's role can be expanded as follows:

✓ *Oncology:*

Bromelain shows promise as an adjuvant to chemotherapy, potentially enhancing the efficacy of cancer treatment. Additionally, it may exhibit direct anti-tumor properties, offering a complementary approach to conventional cancer therapies.

✓ *Dermatology*:

The enzymatic activity of bromelain could contribute to skin barrier repair, potentially aiding in the treatment of various dermatological conditions. It may also be beneficial in managing acne and reducing the appearance of scars, offering a natural alternative to skincare regimens.

✓ *Veterinary Medicine*:

The anti-inflammatory properties of bromelain make it a valuable option in veterinary medicine, particularly in companion animals. It could be used to manage inflammatory conditions, potentially improving the quality of life of pets with various ailments.

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/25aug1258

VIII. CONCLUSION

This review article on bromelain and its incorporation into advanced drug delivery systems highlights the significant potential of this pineapple-derived proteolytic enzyme in various therapeutic applications. The exploration of nanocarrier-based delivery systems has shown promise for addressing the limitations of bromelain, such as its poor stability and bioavailability. These innovative approaches have demonstrated enhanced efficacy in anti-inflammatory, wound healing, and other clinical applications.

Although considerable progress has been made in understanding the therapeutic potential of bromelain and developing suitable delivery systems, further research is necessary to optimize formulations and conduct comprehensive clinical trials. The integration of bromelain into nanocarriers represents a promising avenue for improving its pharmacokinetic profile and expanding therapeutic applications. As research in this field continues, bromelain-based drug delivery systems may offer new treatment options for various inflammatory conditions and wound healing, potentially revolutionizing patient care in these areas.

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