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Review

Botanically Derived Phytochemicals in Antimicrobial Spray Formulations: Mechanism, Strategies and Future Prospects

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Abstract

The need for alternate and sustainable treatment methods has increased due to the rising incidence of microbial diseases and the quick development of antimicrobial resistance (AMR). A wealth of bioactive phytochemicals with antibacterial, anti-inflammatory, antioxidant, and wound-healing qualities can be found in medicinal plants. The benefits of spray-based topical formulations over traditional dose forms—such as ease of application, consistent distribution, better sanitation, and increased patient compliance—have drawn a lot of attention in recent years. The function of botanically derived phytochemicals in antimicrobial spray formulations is critically examined in this review, with a focus on the compounds' botanical origins, chemical makeup, antimicrobial action mechanisms, and formulation significance. There is a thorough discussion of well-known medicinal herbs such *Syzygium aromaticum, Terminalia chebula, Ocimum sanctum, Aloe vera, Curcuma longa,* and *Azadirachta indica.* Moreover, formulation strategies, benefits of plant-derived antimicrobial sprays, existing research deficiencies, and future possibilities are emphasized, highlighting the significance of combining traditional botanical knowledge with contemporary phytopharmaceutical technologies.

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Statement of Sustainability: This review contributes to the achievement of the Sustainable Development Goal 3: Good Health and Well-Being and Sustainable Development Goal 12: Responsible Consumption and Production by promoting plant-based antimicrobial spray formulations as sustainable alternatives to conventional synthetic drugs. The work addresses antimicrobial resistance through exploration of natural bioactive compounds and encourages sustainable pharmaceutical innovation. Integrating traditional botanical knowledge with modern formulation approaches may improve public health outcomes while reducing reliance on synthetic antimicrobial agents and minimizing environmental impact.

1. Introduction

Plants are playing significant role in human civilization for their well being and sustainability of life. They not only provides medicine but also other purposes food, fodder, fuel, shelter, etc. The medicinally important plants has important phytochemicals which cure different ailments including antimicrobial activities against skin infection. For centuries, traditional treatments for infections and wounds have relied on medicinal plants, primarily because of their capacity to produce a variety of secondary metabolites with strong antimicrobial effects. Recent advancements have investigated innovative approaches like nanoencapsulation, active packaging, and edible coatings to improve the stability and effectiveness of natural antimicrobial agents (Kumar et al., 2025). Infectious diseases pose a formidable global challenge, compounded by the emergence of antimicrobial resistance (Sayed et al., 2023). Infections caused by microbes that impact skin and wounds continue to pose a significant worldwide health issue. The growing occurrence of antimicrobial resistance has greatly undermined the efficacy of numerous synthetic antibiotics, leading to a revived interest in plant-derived antimicrobial options (Yang et al., 2023.) Bacterial infections pose a significant threat to public health, as many pathogenic bacteria quickly develop resistance to multiple antibiotics (Pacheco et al., 2022). Traditionally, medicinal plants have been used across the globe for various therapeutic purposes, including the treatment of microbial diseases (Alfuraydi et al., 2024, Safarzadeh et al., 2022).

In India, several plants showing antimicrobial activities which are used since ancient time and has been mentioned in ayurdevedic system of medicine. The medicinal plants like *Azadirachta indica* A.Juss. (Neem), *Curcuma longa* L. (Haldi), *Ocimum sanctum* L. (Tulsi), *Aloe vera* (Ghartkumari), *Terminalia chebula* Retz. (Harad), *Cinnamomum zeylanicum Blume* (Dalchini) and *Syzygium aromaticum* (L.) Merr. & L.M.Perry (Long) has been acknowledged for its wide-ranging antimicrobial properties including several other benefits (Wylie & Merrell, 2022; Iweala et al., 2023; Pattanayak et al., 2010; Bag et al., 2013; Pattanayak et al., 2010; Teles et al., 2019; Cortés-Rojas et al., 2014). Topical antimicrobial treatment is essential for infection prevention and wound healing promotion. Conventional formulations, such as ointments and lotions, often come with disadvantages such as a lack of easy spread, greasiness, non-uniform dosage, and risk of contamination. On the contrary, antimicrobial sprays serve as ideal carriers for plant-derived antimicrobial medications due to their ability to offer uniform coverage, reduced contact, and improved adherence by patients.

2. Employing Phytochemicals as Organic Antimicrobials

For the purpose of adaptation and defence, plants produce secondary metabolites known as phytochemicals. Many of these substances possess antibacterial properties through various mechanisms. Autotrophic organisms include plants. All living things have a secondary metabolism in addition to their primary metabolism, which enables them to create and collect a wide variety of chemical substances. Secondary metabolites (SM) are substances that are produced by secondary metabolism in plants (Mera et al., 2019).

2.1. Phenolic Compounds

Phenolic compounds, including tannins and phenolic acids, possess antibacterial properties by precipitating microbial proteins and compromising cell wall integrity. It is well known that the tannins of *Terminalia chebula* possess broad-spectrum antibacterial properties.

Using this criterion, the phenolic compounds are divided into a number of categories, including acetophenones, hydroxycinnamic acids, coumarins, flavonoids, bifavonyls, benzophenones, xhantones, stilbenes, quinones, betacyanins, simple phenols, and acidic phenols. This group also includes tannins, phlobaphenes, lignans, and neolignans. The latter have more intricate structures and are polymers. The malonate/acetate or shikimic acid pathways (or both, as in flavonoids) produce phenolic chemicals in plant cells. Phenylalanine and cinnamic acids, as well as their derivatives (simple phenols, phenolic acids, coumarins, lignans, and phenyl propane derivatives), are synthesized via the shikimic acid pathway. Quinones and xanthones are produced via the polyacetate route. Precursors of the polyacetate and shikimic acid pathways are combined in the mixed pathways.

2.2. Flavonoids

Flavonoids hinder the growth of microorganisms by interfering with cellular metabolism and the production of nucleic acids. Furthermore, while wounds heal, their antioxidant characteristics foster tissue regeneration. A class of naturally occurring compounds with a variety of phenolic structures, flavonoids can be found in tea, wine, fruits, vegetables, grains, bark, roots, stems, and flowers. The health benefits of these natural chemicals are widely recognized, and efforts are underway to separate the components known as flavonoids. Nowadays, flavonoids are regarded as an essential part of many pharmacological, cosmetic, nutraceutical, and medical uses. This is explained by their ability to modify the operation of important cellular enzymes as well as their antioxidative, anti-inflammatory, anti-mutagenic, and anti-carcinogenic qualities. The finding of the low cardiovascular death rate and the prevention of CHD gave flavonoid research a boost (Panche al., 2016).

2.3. Essential Oils and Terpenoids

Due to their lipophilic nature, essential oils and terpenoids can penetrate microbial membranes and lead to the leakage of intracellular contents. Substances such as eugenol and cinnamon aldehyde demonstrate potent antibacterial and antifungal properties.

2.4. Polysaccharides

One instance of a polysaccharide that bolsters antimicrobial defense by enhancing immunity and expediting wound healing is acemannan from *Aloe vera* (Table 1; Figures 1 and 2).

3. Mechanisms of Antimicrobial Action

3.1. Cell Wall and Membrane Disruption

Many phytochemicals derived from plants endanger the structural soundness of microbial cell walls and cytoplasmic membranes. Lipophilic substances, particularly terpenoids and essential oil components, readily traverse lipid bilayers. This increases membrane permeability, allowing intracellular ions and metabolites to leak out, disrupting membrane potential, and ultimately leading to cell lysis.

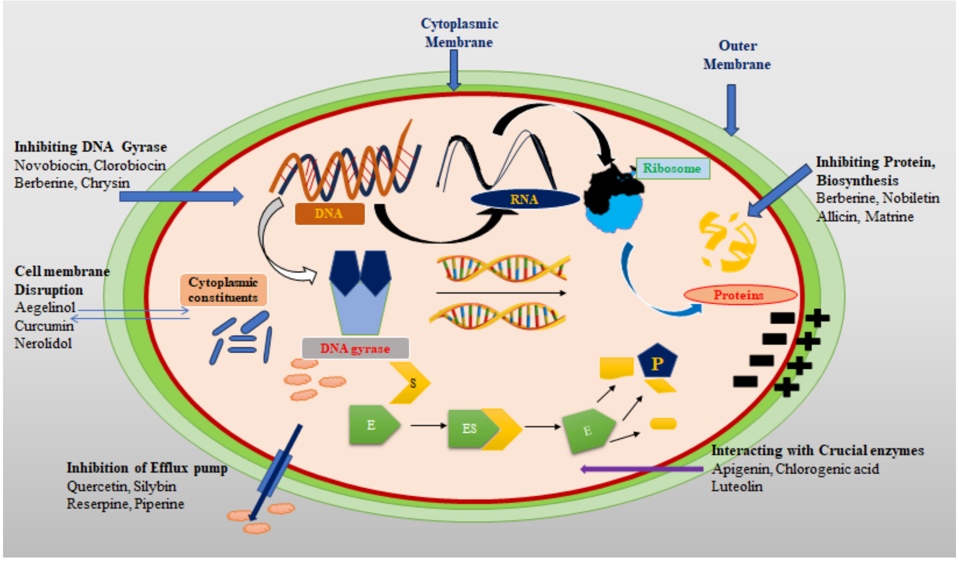
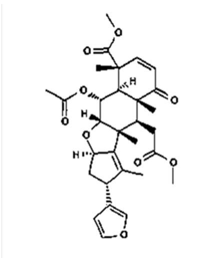


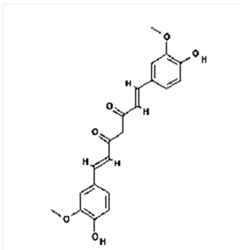
Figure 1. Antibacterial mechanism of action of plant-derivative compounds.

Table 1. Botanically important medicinal plants used in antimicrobial sprays.

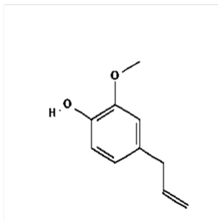
Plant	Family	Major Phytochemicals	Biological Activity	Citation
Azadirachta indica	Meliaceae	Nimbin, Nimbidin	Antibacterial, antifungal	Wylie and Merrell (2022)
Curcuma longa	Zingiberaceae	Curcumin	Antimicrobial, anti-inflammatory	Iweala et al. (2023)
Ocimum sanctum	Lamiaceae	Eugenol	Antibacterial	Pattanayak et al. (2010)
Aloe vera	Asphodela-ceae	Aloin, Acemannan	Antimicrobial, wound healing	Surjushe et al. (2008)
Terminalia chebula	Combretaceae	Tannins	Broad-spectrum antimicrobial	Bag et al. (2013)
Cinnamomum zeylanicum	Lauraceae	Cinnamaldehyde	Antibacterial	Teles et al. (2019)
Syzygium aromaticum	Myrtaceae	Eugenol	Potent antimicrobial	Cortés-Rojas et al. (2014)



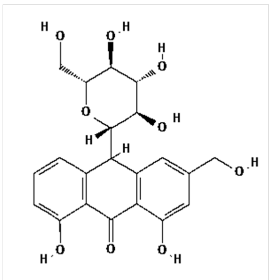
Nimbin



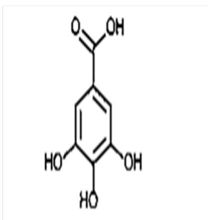
Curcumin



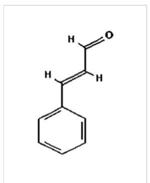
Eugenol



Aloin



Tannins



Cinnamaldehyde

Figure 2. Structure of different compounds

3.2. Inhibition of Essential Enzymes and Metabolic Pathways

A wide variety of flavonoids, phenolics, and alkaloids exert antimicrobial effects by interacting with key microbial enzymes through hydrogen bonding and hydrophobic interactions. This interaction ultimately suppresses microbial growth and survival by inhibiting essential metabolic pathways such as protein synthesis, energy production, and nucleic acid replication.

3.3. Antibiofilm Activity

Due to their innate resistance to conventional antibiotics, infections linked with biofilm are highly challenging to eliminate. A range of phytochemicals exhibit antibiofilm activity by thwarting initial microbial adhesion, disrupting extracellular polymeric substance (EPS) matrices, or interfering with quorum sensing signalling pathways (Figure 3). These actions significantly heighten the susceptibility of microorganisms to antimicrobial agents (Wang et al., 2024; Azad et al., 2023).

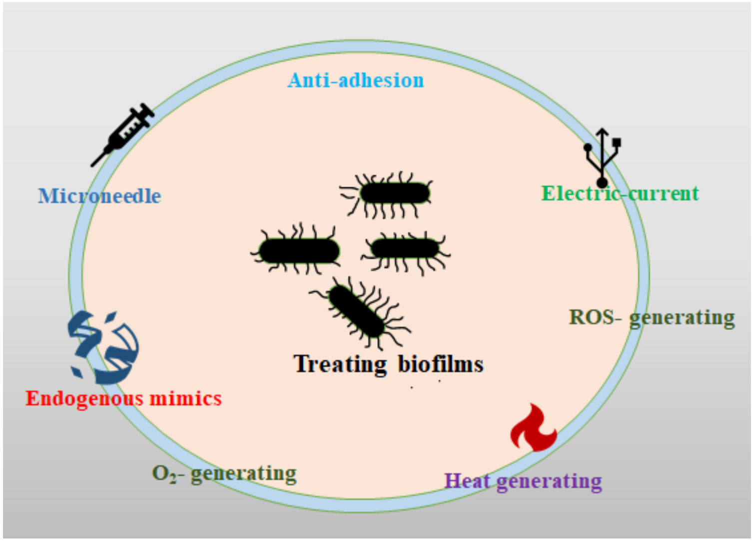


Figure 3. Schematic illustrating various approaches for treating biofilms.

3.4. Synergistic Interactions

Phytochemicals often show synergistic effects when combined with other plant compounds or traditional antibiotics. Such interactions can reduce the emergence of resistance, enhance the efficacy of antibiotics, and decrease the required therapeutic dosage. In formulations for broad-spectrum antibacterial sprays, this synergism is particularly beneficial.

4. Antimicrobial Spray Formulations: A Pharmacognostic Perspective

Antimicrobial sprays provide an effective and patient-friendly means of delivering bioactive plant-derived substances. These formulations usually use hydroalcoholic or aqueous bases that are enhanced with natural polymers, humectants, and stabilizers. Due to its natural antibacterial properties, compatibility with biological systems, ability to break down biologically, and excellent film-forming characteristics, chitosan is extensively utilized. From a pharmacognostic viewpoint, ensuring the therapeutic reliability, consistency, and reproducibility of plant-derived spray formulations hinges on phytochemical standardization and botanical authentication.

4.1. Solvent Systems

To achieve the solubilization of phytochemicals and to ensure that the formulation remains stable and safe, it is crucial to select an appropriate solvent. Water, ethanol, and hydroalcoholic mixtures are commonly used solvents that balance skin compatibility, antibacterial effectiveness, and extraction efficiency.

4.2. Emulsions and Microemulsions

In spray systems, essential oils and other hydrophobic phytochemicals are often formulated as emulsions or microemulsions to enhance their dispersion, stability, and bioavailability. These technologies ensure that active ingredients are evenly distributed and increase interaction with microbial cells.

4.3. Advanced Delivery Systems and Nanoencapsulation

Delivery technologies utilizing nanotechnology, like liposomes, polymeric nanoparticles, and nano-emulsions, enable regulated release, enhance antibacterial activity, and protect phytochemicals from environmental degradation. The field of research concerning nano-enabled antimicrobial sprays is expanding quickly and holds great promise.

4.4. Stability and Shelf-Life Considerations

Phytochemicals can degrade due to exposure to light, heat, and oxygen. To guarantee the long-term stability and shelf life of antimicrobial spray formulations, it is crucial to include antioxidants, choose suitable packaging materials, and optimize storage conditions.

4.5. Advantages of Plant-Based Antimicrobial Sprays

- Natural and eco-friendly origin
- Reduced risk of microbial resistance
- Ease of application and improved hygiene
- Uniform distribution of active compounds
- Compatibility with traditional and ethnomedicinal knowledge

4.6. Regulatory Aspects, Safety, and Toxicity

Despite the common belief that plant-derived items are safe, a comprehensive toxicological analysis is essential. It is especially important to study skin irritation, sensitization, and allergenicity for products that contain essential oils. Moreover, due to regional variations in the regulatory frameworks for botanical products, it is essential to strictly comply with established safety, effectiveness, and quality standards.

4.7. Present-Day Uses and Case Studies

Today, surface disinfection, dental hygiene, dermatology, and wound care utilize antimicrobial sprays derived from phytochemicals. Formulations based on neem, tea tree oil, and eucalyptus exemplify the successful fusion of ancient medical wisdom and modern formulation technology.

4.8. Research Gaps and Future Prospects

Botanical antimicrobial sprays, although yielding promising outcomes, remain under-researched. The lack of standard extraction procedures, a shortage of botanical studies based on formulations, and an absence of stability data pose significant challenges. For enhanced therapeutic relevance, future research should focus on translational studies, refinement of formulations, advanced delivery technologies, and comprehensive phytochemical validation.

5. Discussion

The increasing danger of antimicrobial resistance (AMR) has greatly diminished the efficacy of standard antibiotics, creating an urgent demand for alternative treatment approaches. Phytochemicals derived from botanical sources have re-emerged as promising antimicrobial agents in this context, owing to their chemical diversity, multitarget mechanisms, and long history of use in traditional medicine systems. This review critically examines the mechanistic relevance, formulation feasibility, and translational potential of phytochemical-based antimicrobial spray formulations, emphasizing their benefits and current limitations in comparison to synthetic antimicrobial products (Salam et al., 2023)

A particularly interesting aspect of phytochemicals is the multiplicity of ways in which they can act as antimicrobials. Phytochemicals, in contrast to traditional antibiotics that typically focus on one cellular process, engage multiple microbial targets at once. These include cell membranes, metabolic enzymes, genetic material, and quorum sensing pathways. This multitarget approach boosts antimicrobial effectiveness and diminishes the chances of resistance emergence. Microbial integrity is rapidly compromised by membrane-disrupting compounds like terpenoids and essential oil constituents, resulting in cell death. Simultaneously, phenolics and alkaloids disrupt enzymatic systems essential for microbial survival. It is especially beneficial for topical spray formulations to combine these mechanisms, as they aim for swift and localized antimicrobial effects (Khameneh et al., 2021)

Phytochemicals also offer the noteworthy benefit of antibiofilm properties, which tackle one of the most enduring difficulties in antimicrobial treatment. Biofilms provide increased resistance to antibiotics and are associated with chronic wounds, infections related to medical devices, and the development of dental plaque. Certain phytochemicals can inhibit initial microbial adhesion, degrade extracellular polymeric substances, or disrupt quorum sensing pathways. These abilities provide a mechanistic rationale for their inclusion in spray formulations designed for wound care and surface disinfection. The relevance of this antibiofilm characteristic for sprays is particularly pronounced, given that uniform surface coverage boosts the interaction between the active ingredient and biofilm structures (Shrestha et al., 2022).

Spray-based delivery systems provide unique pharmaco-technical benefits for plant-derived antimicrobials when viewed from a formulation standpoint. With sprays, it is possible to distribute active substances uniformly, reduce contamination from direct contact, and achieve accurate dosing on large or uneven surfaces. Incorporating phytochemicals into aqueous or hydroalcoholic spray bases allows for quick drying and improves patient adherence, especially in dermatological and wound-care contexts. Moreover, due to their non-occlusive nature, sprays lower the risk of maceration something that is often a drawback of creams and ointments (Kalelkar et al., 2022).

Natural polymers like chitosan can be included to augment the therapeutic potential of antimicrobial sprays. Besides serving as a stabilizer and film-forming agent, chitosan also provides inherent antimicrobial activity due to its cationic properties, which disrupt microbial membranes. The combined effect of chitosan and phytochemicals can enhance the inhibition of microbes while ensuring biocompatibility is preserved. These combinations illustrate the effective integration of pharmacognosy and pharmaceutical technology to create multifunctional antimicrobial formulations (Hemmingsen et al., 2021).

Even with these benefits, the transition of phytochemical-based spray translations from lab studies to clinical and commercial use is still restricted. A significant challenge is the absence of standardization for phytochemicals. Because of variations in plant species, geographical origin, harvesting conditions, and extraction methods, the chemical composition of plant extracts often varies. Without strict standardization, reproducibility and consistency across batches become major issues, especially regarding regulatory approval. This underscores how crucial it is to authenticate botanicals and conduct quantitative phytochemical profiling when developing formulations (Zhou et al., 2025).

Another key factor affecting the clinical viability of phytochemical sprays is stability. Many compounds derived from plants are sensitive to light, oxygen, and temperature changes, which can cause their degradation during storage. Essential oils are especially volatile and susceptible to oxidation, which can diminish their antimicrobial effectiveness as time passes. Utilizing sophisticated formulation methods like nanoencapsulation and antioxidant incorporation can provide promising solutions to these issues. Nanocarriers serve to shield phytochemicals from environmental degradation, facilitate controlled release, and enhance penetration at the application site (Mihociu et al., 2024).

The emergence of nano-enabled antimicrobial sprays represents a significant advancement in this field. Nano-emulsions, liposomes, and polymeric nanoparticles improve solubility and bioavailability of hydrophobic phytochemicals while maintaining formulation stability. Additionally, nanocarriers can enhance interaction with microbial cells due to their high surface area, leading to improved antimicrobial performance at lower concentrations. However, concerns related to nanoparticle safety, scalability, and regulatory approval must be addressed before widespread adoption (Finina et al., 2024).

Safety and toxicity considerations play a pivotal role in the acceptance of plant-based antimicrobial sprays. While phytochemicals are often perceived as safe due to their natural origin, this assumption is not always scientifically justified. Certain essential oils and alkaloids can cause skin irritation, sensitization, or allergic reactions when used at inappropriate concentrations. Therefore, comprehensive toxicological evaluation, including dermal irritation and sensitization studies, is essential. The balance between antimicrobial efficacy and dermal safety must be carefully optimized to ensure clinical acceptability (Pinto et al., 2023).

The creation of sprays based on phytochemicals is made more difficult by regulatory challenges. Depending on the regional frameworks, botanical products often fall into ambiguous regulatory categories that vary between pharmaceuticals, cosmetics, and traditional medicines. The absence of harmonization can lead to delays in product approval and market entry. It is vital to create unambiguous regulatory guidelines for botanical antimicrobial sprays, backed by solid scientific evidence, in order to enable their commercialization (Chauhan et al., 2022).

From a clinical and practical perspective, the combined use of phytochemicals with standard antibiotics offers a promising approach to boost antimicrobial effectiveness while lowering antibiotic dosage and resistance pressure. Spray formulations intended to provide such combinations could be especially advantageous in the contexts of wound management and infection control. However, systematic studies that assess these synergistic interactions in formulated products are still limited, representing a significant area for future research (Sánchez Hernandez, 2024).The rationale for including medicinal plants like neem, turmeric, clove, aloe vera, and eucalyptus in antimicrobial sprays is further bolstered by their ethnopharmacological significance. These plants have been used for a long time in traditional medicine systems, and emerging scientific evidence supports their antimicrobial properties. By combining traditional knowledge with contemporary formulation science, therapeutic innovation is advanced and sustainable, culturally relevant healthcare solutions are fostered (Shah et al., 2021).

Even though laboratory and preclinical findings are promising, there is still a lack of clinical evidence backing phytochemical-based antimicrobial sprays. The majority of investigations concentrate on in vitro antimicrobial effectiveness, while there is a scarcity of in vivo or clinical validation. To determine efficacy, safety, optimal dosing, and application frequency, clinical trials that are designed well are essential. In the absence of such data, the clinical uptake of these formulations will be limited (Kebede et al., 2021; Singh et al., 2019).

To summarize, antimicrobial sprays based on phytochemicals offer a promising and novel strategy for tackling the worldwide problem of antimicrobial resistance. They will be successful if they can establish a framework that integrates pharmacognosy, microbiology, formulation science, toxicology, and regulatory affairs across multiple disciplines. It will be crucial to tackle current shortcomings concerning standardization, stability, safety, and clinical validation in order to move these formulations from research environments into practical use.

6. Conclusion

Phytochemicals from plants offer a practical and sustainable alternative to synthetic antibacterial agents, especially in topical spray formulations. Their importance in modern pharmacognosy is underscored by their broad-spectrum antibacterial activity, good safety profile, and ecological sustainability. The development of effective plant-based antimicrobial treatments could be significantly supported by advanced formulation technology and rigorous botanical authentication.

Author Contributions

Vansh Gupta: Conceptualization; Data curation; Funding acquisition; Investigation; Methodology; Resources; Software; Validation; Visualization; Writing – original draft; Writing – review & editing; Gayatri Saini: Data curation; Methodology; Writing – original draft; Anshul: Methodology; Writing – original draft; Archit Kapil: Visualization; Mahvish Khan: Data curation; Software; Writing – original draft; Sandeep Kumar Barwal: Supervision; Writing – original draft; Writing – review & editing; Harsh Singh: Writing – original draft; Writing – review & editing.

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Declarations

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Ethics approval: As this study did not involve human or animal subjects, ethical approval was not required.

Consent for publication: All authors have reviewed and approved the manuscript and consent to its publication in Society for Agri-environmental Sustainability.

Data availability: The data supporting the conclusions of this study can be obtained from the corresponding author upon reasonable request.

Supplementary material: No supplementary material is associated with this manuscript.

Additional information: No additional information is provided for this study.

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