Phytochemical Profiling and Allelopathic Potential of Wild Solanaceae Species on Crop Germination

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Abstract:

Phytochemical composition and allelopathy of certain varieties of wild Solanaceae plants such as Datura stramonium, Solanum nigrum, and Withania somnifera are extensively reviewed in this research for the evaluation of their ecological interactions and areas of application in sustainable agriculture. Complex phytochemical composition determined via GC-MS and LC-MS/MS determined a wide range of secondary metabolites, including alkaloids, flavonoids, terpenoids, and phenolic compounds, which possess renowned bioactivity. Allelopathic activities were assessed by germination and seedling growth tests on representative agricultural crops, which established that the aqueous and methanolic extracts of these wild plants had both inhibitory as well as stimulatory effects dependent upon concentration and the target species. The results support the fact that these plants emit excessive amounts of allelochemicals that inhibit seed germination and its growth as evidenced by a powerful allelopathic effect. This dual role of allelopathy as a net defence of the plants and a bioherbicidal option unveils the relevance of the resourceful wild Solanaceae in reducing dependency on artificial chemicals and promoting environmentally responsible weed management methods. Finding such as these offer great benefits towards the inclusion of these species in organic and sustainable agricultural systems.

Keywords:Wild Solanaceae, Allelopathy, Phytochemical Profiling, Bioherbicide, Seed Germination, Sustainable Agriculture.

1. INTRODUCTION

The wild Solanaceae species include the complex ones, such as Datura stramonium, Solanum nigrum, and Withania somnifera, with complex phytochemical profiles containing various bioactive compounds, such as alkaloids, phenolics, and flavonoids [1]. These compounds are very valuable in the protection plan of the plant and ecological communications, where others possess emphatic allelopathic impacts. Allopathy is a phenomenon of how plants secrete chemical substances that influence the growth and development of neighboring plants, is one of the areas of special interest for potential use in sustainable agriculture. The wild species of Solanaceae that are usually neglected during research activities in the field of agriculture have allelopathic substances that can influence the germination of crops and seedlings thus offering an organic alternative as chemical herbicides. It might open up new ways for introduction of eco-friendly strategies for the weed control and development of sustainable agriculture by knowing about the contents and the allelopathic activity of such plants.

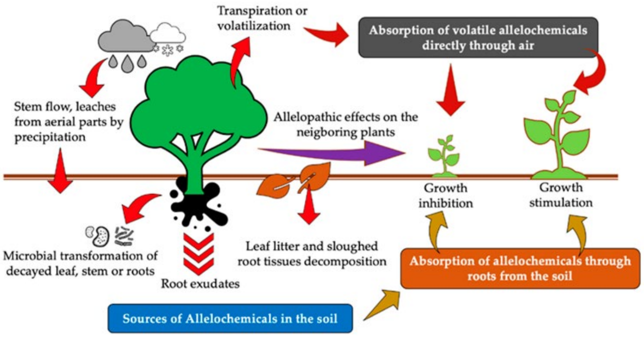

Figure 1: Allelopathic Potential of Tropical Plants[2]

1.1.Background and Context

Allelopathy is a natural tendency; in which plants release chemical substances known as allelochemicals into the environment and regulate other close plants' growth, development, and persistence. Allelopathy is a significant process in plant vigor competition and ecosystem activities and has been given more and more attention in respect to its application in sustainable agriculture in particular for weed control, and in crop rotation. Allelopathic interactions present the environmentally benign option to the chemical herbicides, and enhance a more environmentally minded agriculture [3].

The family Solanaceae is widely known to have an economic use as well as medicinal values and its members are used to be popular crops such as Solanum lycopersicum (tomato), Capsicum annuum (bell pepper), and Nicotiana tabacum (tobacco). Apart from these economically important species, the family of Solanaceae also harbors an assortment of wild species such as: Datura stramonium (jimsonweed), Solanum nigrum (black nightshade) and Withania somnifera (ashwagandha). Although the Solanaceae wild species have been relatively neglected in the agricultural studies, recent research has established that they comprise of diversified chemical compositions, some of which are highly allelopathic in nature. These wild species can play a role in modifying the germination of crops, the growth of seedlings, and the competitive plant interaction, and thus provide novel opportunities in developing natural alternatives to the chemical herbicides.

1.2.Objectives of the Review

- To investigate the phytochemical profiles of wild Solanaceae species.
- To assess the allelopathic potential of wild Solanaceae species.
- To identify and analyze the biochemical modes of action.

1.3.Importance of the Topic

The allelopathic potential of the wild Solanaceae species is of crucial ecological and agronomic importance because of the two-edged character of the species that are inhibitors and plant growth stimulators at the same time. This singular quality points to their potentialities in sustainable agriculture, particularly in the organic weed management practices [4]. A greater understanding of the chemical compounds used in allelopathy will result in the development of sustainable agricultural practices, thus reducing the application of synthetic agrochemicals, reducing the ecological effects of agriculture, and promoting biodiversity in a farm ecosystem. This research can help to improve the methods of organic farming and to elevate yields without damaging the environment.

2. PHYTOCHEMICAL AND ALLELOPATHIC POTENTIAL OF WILD SOLANACEAE SPECIES: CURRENT INSIGHTS AND CHALLENGES

Plants in the family Solanaceae, collected in nature such as Datura stramonium, Solanum nigrum, Withania somnifera have various phytochemicals composition of alkaloids, phenolics and flavonoids with broad allelopathic potential for sustainable agriculture. However, the research lacks standardization techniques, ecological relevance, and deeper mechanistic implication of their long-term effects [5].

2.1.Phytochemical Profiling of Wild Solanaceae Species

The family of Solanaceae is diverse and plentiful in the content of phytochemicals, especially in the wild species, which are rich in secondary metabolites. These are defense molecules in the plant, which play role in ecological communication and potential medical service. Wild species such as Datura stramonium, Solanum nigrum and Withania somnifera have expensive, rich and diverse bioactive chemical contents, hence become important objects of phytochemical research.

a. Alkaloids

Alkaloids are one of the major secondary metabolites with high biological activity in wild Solanaceae species [6]. These nitrogenous compounds often present high physiological impacts and they are involved in the defensive mechanisms of the plant as well as the allelopathic interactions. The particularly strong constituents of D. stramonium are tropane alkaloids like hyoscyamine and scopolamine that present anticholinergic and hallucinogenic actions. The topical use of Solanum nigrum featured with glycoalkaloid possessing such as solasonine and solamargine; which contribute to the cytotoxic and fungal antagonistic properties. Withania somnifera produce withanolides which is the series of steroidal lactones that bear different pharmacological actions such as anti-inflammatory, antioxidant and neuroprotective effects. These are alkaloids that may inhibit seed germination and growth of other plants, and hence were powerfully allelopathic.

b. Phenolics and Flavonoids

Phenolic substances and flavonoids are one more huge group of secondary metabolites typical for wild species of Solanaceae. They participate in antioxidant defense, they function as pigmenters, and they are effective in allelopathic interactions. Numerous phenolic acids such as ferulic, caffeic and chlorogenic acids are said to interfere with the hormonal conduct and sowing in neighbouring species. Flavonoids, quercetin and kaempferol, are concerned with auxin transport control, enzyme activity, and inhibition for an occurrence of oxidative stress. Their synergistic action add up to the suppression of neighbours and tolerance of environmental stress. Phenolic and flavonoid abundance and diversity promote the optimum phytotoxicity of Solanaceae, which is beneficial to the ecological weed management practices [7].

c. Analytical Techniques

Great analytical tools are used to profile and quantify the phytochemical composition of members of the Solanaceae. Gas Chromatography-Mass Spectrometry (GC-MS) is used primarily to run volatile compound and small alkaloid analysis with high sensitivity and structural elucidation. Liquid Chromatography with Tandem Mass Spectrometry (LC-MS/MS) is used for non-volatile and heat-sensitive compounds, such as withanolides and flavonoid glycosides with in-depth profiling and accurate quantification. Spectrophotometric methods such as the Folin-Ciocalteu method for total phenolics and the $AlCl_3$ assay for total flavonoids are the ones that are most often used for a rapid screening of antioxidant compounds. High-Performance Liquid Chromatography (HPLC) and Thin Layer Chromatography (TLC) is another method of separating and identifying the individual bioactive components [8]. All these instruments put together paint an overall picture of the phytochemical diversity and bioactivity displayed by wild Solanaceae species.

2.2.Allelopathic Potential and Bioassay Studies

Wild Solanaceae species have been characterized for allelopathy to interfere with the growth and development of plants. Their effect is evaluated in vitro on seed germination bioassays and in pots in soil. Seed germination assays consist in the different parts of extracts of wild Solanaceae species i.e, leaves, roots, or stems acting on seeds from crop plants that are economically valuable. These test-tube experiments are useful in deciding the inhibitory or stimulating role of allelochemicals towards initial plant development [9].

Soil-based bioassays investigate allelopathic interactions under more natural conditions by adding plant residues or powdered plant material to the soil and measuring their effect on seedling emergence, growth patterns, and biomass accumulation. Some of the important indicators measured in both types of bioassays are germination percentage, radicle and plumule length, fresh and dry weight, and seedling vigor index.

Some of the findings in these studies include Datura stramonium leaf extracts exhibiting potent inhibitory activity against wheat germination, Solanum nigrum inhibiting germination and root elongation in maize, and low concentrations of Withania somnifera extracts exhibiting stimulatory activity against mustard seedling growth. These reports indicate the double-sided nature of allelopathic interactions in Solanaceae—strong growth inhibition at higher concentrations and possible growth stimulation at low concentrations [10]. More research through field trials and metabolite-specific assays will be crucial to the identification of particular allelochemicals and their optimization of use for sustainable agriculture.

2.3.Strengths and Weaknesses of Current Research

1. **Strengths**

Studies on native Solanaceae species, e.g., Datura stramonium, Solanum nigrum, and Withania somnifera, reveal robust evidence of their allelopathic activity. These species have the potential to be used as natural bioherbicides, which may minimize the dependence on synthetic agrochemicals [11]. The application of powerful analytical methods like GC-MS, LC-MS/MS, and HPLC enables accurate phytochemical profiling and identification of major allelochemicals behind reported biological activity. The combination of bioassay results with chemical data enhances conclusions and leads to an increased understanding of plant-plant chemical interactions. Preliminary findings indicate potential for applications in eco-friendly agriculture.

2. **Weaknesses**

Current research on allelopathy in sustainable agriculture has various shortfalls. A predominant shortcoming is that no standard protocols exist for preparing extracts, and therefore it is challenging to replicate and compare across studies. Almost all experiments are confined to in vitro conditions or pot trials, which restrict their ecological significance as well as scalability [12]. There is also limited comprehension of long-term ecological consequences of sustained allelochemical use, including potential perturbations of soil microbial ecosystems or indirect consequences on non-target crops. There is also limited mechanistic knowledge of the action of allelochemicals in modifying plant physiology. Such knowledge gaps point towards a necessity of more field-based, multidisciplinary, and molecular-level investigations.

Table 1: Overview of Key Allelopathy Studies[13]

Authors	Study	Focus Area	Methodology	Key Findings
Erhatić et al. (2023)[14]	Allelopathic effects of aqueous extracts from medicinal plants	Allelopathy in horticultural plant species	Aqueous extracts of four medicinal plants were tested on germination and seedling development of three horticultural species. Plant growth parameters were measured	Specific plant extracts influenced germination, root/shoot length, and biomass. Water-soluble allelochemicals may be used as natural

			(root/shoot length, biomass, etc.)	growth regulators in horticulture.
Galon et al. (2021)[15]	Allelopathic potential of winter and summer cover crops	Allelopathy in cover crops	Experimental analysis of the effects of winter and summer cover crop residues on the germination and growth of Solanum americanum.	Summer cover crops inhibited germination and seedling growth. The study highlighted the temporal variability of allelopathic effects in crop selection for weed management.
Ganiee et al. (2024)[16]	Allelopathic potential and phytochemica l profiling of Amaranthus species	Comparison of invasive and non-invasive Amaranthus species	Comparative analysis of allelopathic effects and phytochemical profiles of invasive vs. non-invasive Amaranthus species using bioassays and chemical profiling.	Invasive species exhibited stronger allelopathic effects, linked to higher concentrations of bioactive compounds. Offers insights into using invasive species for sustainable weed management.
Gogoi et al. (2021)[17]	Phytochemica l and pharmacologi cal properties of Solanum khasianum	Phytochemicals and pharmacological activities	Extracts of Solanum khasianum were tested for their bioactive compounds and pharmacological effects (anti-diabetic, skin-whitening, etc.).	Identified bioactive compounds with anti-diabetic, skin-whitening, acetylcholinesterase-inhibitory, and genotoxic properties. Suggests potential for allelopathic interactions in nature.

Gurgel et al. (2019)[18]	Herbicidal activity of essential oils from Copaifera species	Phytotoxicity of Copaifera essential oils	Chemical composition of essential oils from three Copaifera species was analyzed, followed by herbicidal activity testing on several weed species.	Essential oils from Copaifera exhibited strong phytotoxic properties against weeds. Terpenoids and phenolic compounds contributed to the herbicidal effects, linking composition to efficacy.

3. BIOCHEMICAL AND ECOLOGICAL IMPLICATIONS OF ALLELOPATHY IN SOLANACEAE SPECIES

Solanaceae members yield varied allelochemicals, including alkaloids and flavonoids, that influence crop development and weed control. Ecological uses comprise improving intercropping, rotation, and integrated farming by maximizing crop yields and minimizing the use of synthetic inputs[19].

3.1.Biochemical Classes of Allelochemicals and Their Modes of Action

Allelochemicals of wild species of Solanaceae are a broad group of biochemical classes, each of which has a unique set of structural characteristics and specific modes of action contributing to their allelopathic activities. Allelochemicals interrupt physiological and biochemical processes in target plants, either inhibiting or modifying their growth and development.

- **Alkaloids**

Amongst the most studied classes, alkaloids such as scopolamine and hyoscyamine found in great quantities in Datura stramonium, so, can be considered highly neurotoxic in animals and equally bioactive in plants [20]. The chemicals can interact with neurotransmission pathways; with signal transduction pathways and can therefore have an impact on cellular communication and cellular growth regulation. They are also able to alter the integrity of membrane and function of ion channels to lead to disrupted cellular homeostasis.

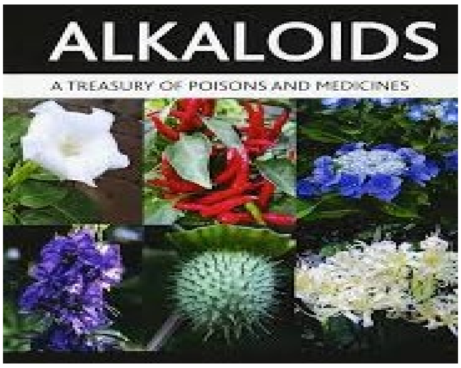

Figure 2: Alkaloids [21]

- **Phenolic Acids**

Phenolic compounds such as caffeic acid ferulic acid, and chlorogenic acid found in plants like Solanum nigrum are allelopathic in their activity since they inhibit cell wall synthesis and enzyme activity in the targeted plants. They are capable of chelating proteins and inhibiting those key enzymes for respiration, uptake of nutrients, and DNA replication. They also participate in the processes of oxidative stress creation, which cause additional destabilization of cellular mechanisms and reduction of seed germination and growth.

- **Flavonoids**

Flavonols like quercetin and kaempferol, ubiquitous in Withania somnifera, and other members of Solanaceae, are modulators of oxidative stress and regulators of plant hormones such auxins and gibberellins [22]. Their antioxidant activities may interfere in the redox balance within the cells leading to programmed cell death or arrested cell growth in sensitive organisms. Additionally, flavonoids can interfere with signal transduction cascades and even serve as the inhibitors of the enzymes that are connected with the processes of elongation and division of the cells.

- **Terpenoids**

Terpenoids especially withanolide’s such as withaferin A from Withania somnifera possess strong allelopathic activity because of inhibition of microtubule assembly, protein synthesis and cell cycle. They inhibit the formation of spindles during the process of mitosis, hence disabling normal cell division and leading to developmental stagnation. Terpenoids have also been documented to interfere with the hormonal messaging as well as the stability of membrane hence increasing their phytotoxicity effects.

These allelochemicals synergistically contribute towards the survival of the wild Solanaceae species over other plants in their natural ecosystem and offer a biochemical justification for using them as weed suppressants and for crop management. Understanding and knowledge about these compounds and the mechanisms of their action can help develop bioherbicides from them and integrate them to allelopathic crops in the integrated farms.

3.2.Comparative Allelopathic Effects on Different Crops

Different crops react differently to allelochemicals but the extent depends on type and concentration of allelopathic compounds in the Solanaceae species. Growth can be inhibited or stimulated, depending on the entity of the crop in-question, and the chemicals involved, by either the allelophic actions [23].

- **Cereal Crops**

Cereals such as wheat and rice are more prone to allelopathic extracts' suppression of Datura/Solanum species. Under the treatment with these allelopathic compounds, these crops show reduced germination, the inhibition of root elongation, and reduced seedlings' growth rate. The inhibitory effects are particularly pronounced at high levels of the allelochemicals, and may cause significant effects to crop establishment and productivity. These effects to a large extent can be attributed to the presence of glycoalkaloids and tropane alkaloids such as solanine and scopolamine.

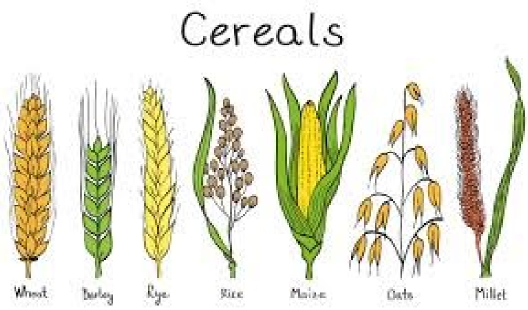

Figure 3: Cereals Crops [24]

- **Legumes**

Allelochemicals have an effect on legume crops (mung bean, chickpea) as it suppresses radicle (root) growth. Solanum and Datura species possess allelopathic compounds that inhibit root growth and subsequent development, and its effect translates to the absorption of nutrients and plant vigor to a great extent. Nonetheless, legumes may not be as susceptible as cereals to some chemicals, and the effect would be varied based on the growth stage and the environmental circumstances.

- **Oilseeds**

Oilseed crops, for instance, mustard show inhibitory and stimulatory effects of extracts of Solanaceae but where both are dependent on the used concentration of allelochemicals. At lower concentrations, agents like withanolides retrieved from Withania somnifera have shown to stimulate growth of seedling, perhaps as a result of hormone like actions. On the other hand, larger amounts of such agents induce toxicity that results in deteriorated germination and abnormal growth and impede root elongation [25]. This dual response is particularly important for the establishment of ways dose and method of application can impact the results in crop management.

3.3.Ecological and Agricultural Implications

Allelopathic functions of Solanaceae species offer sustainable means of controlling weeds, intercroping, as well as crop rotation which reduces the reliance on chemical methods of enhancing agriculture. These strategies optimize crop yields, soil maintenance, and resources exploration in agrosystems.

Figure 4: Ecological Farming [26]

1. **Weed Management**

The allelopathic effect associated with the members of Solanaceae could be utilized in the field of integrated weed management. A number of plants; Datura stramonium and Solanum nigrum can be extracted to provide natural herbicides that will supress germination and growth of weeds, an alternative to chemical herbicides. Not merely killing the unrequired plants, these natural herbicides have smaller environmental hazards and preserve the quality of the soil and biodiversity. Furthermore, the allelopathic substances can be added to soil conditioners to enhance soil fertility and suppress weed under growth without destroying healthy micro organisms-this positively promotes sustainable agriculture [27].

2. **Intercropping Strategies**

Allelopathic profiling is also the way to designing efficient intercropping strategies whereby compatible and incompatible pairings can be exploited to the maximum. Farmers can kick start the production of individual crops by selecting crops that not only tolerate but also benefit from Solanaceae plants allelopathic chemicals. This allows increasing the yield of individual crops and minimizing the competition for resources. As for instance, Withania somnifera crops can be intercropped with the less sensitive crops like legumes or oilseeds and benefit from the allelopathic superiority and the complementarity of nutrition. In the other hand, if one is to plant highly susceptible crops near Solanum or Datura species, there may be yield loss and stunted growth of the plant. Understanding of the allelopathic patterns of crops is the very essence of the planning of the intercropping systems aimed at the maximum productivity and decrease of the inputs from the outside world.

3. Crop Rotation

Farming practice such as crop rotation is another successful one that needs to be advanced by considering the allelopathic nature of Solanaceae species. The sowing of other crops will either control soil-borne diseases and pests or even prevent the growth of subsequent crops when done after the Solanaceae species. For instance, the crops of Datura or Solanum species that are alley-pathically sensitive should be discouraged from being used in subsequent cropping as their growth will be inhibited due to the trapped allelochemicals residue in soil [28]. On the other hand, growing less sensitive or resistant crops to these chemicals, such as some legumes or oilseeds; can promote healthy crop rotation while preserving soil health by preventing build up of pathogenic organisms. Effective crop rotation practices that take into account the allelopathic effects could optimize the use of land, improve structure of the soil, and reduce use of synthetic inputs.

4. MECHANISMS OF ALLELOPATHY IN WILD SOLANACEAE SPECIES: MOLECULAR INSIGHTS AND PATHWAYS

Allelopathy is a complex phenomenon in wild members of Solanaceae namely Datura, Solanum, and Withania in which secondary metabolites are leaked into the external environment that interacts with co-plants to inhibit their growth or development. Such compounds as alkaloids, phenolic acids, flavonoids, and terpenoids are produced in the plant tissues and are released into the soil into volatilization, leaching or root exudates [29]. They interfere with physiological and biochemistry processes vital in plant growth, which hinder germination, hamper root growth and stunt growth for the sensitive plant species.

Figure 5: Solanaceae Species[30]

At molecular level, allelopathy work via several mechanisms that affects plant cellular processes. Some of the alkaloids like scopolamine can affect neurotransmission and cell signaling pathways with subsequent alterations on gene expression and metabolic pathways in neighbouring plants. Phenolic acids, like caffeic acid, might chelate and inactivate the action of enzymes that are responsible for the formation of plant cell walls, thus disrupting the strength of targeted plant cells and preventing such vital processes as nutrient absorption, photosynthesis, and cell division. As strong regulator of oxidative stress, flavonoids may affect an oxidative balance in neighboring plants, promoting redox-dependent generation of ROS, oxidative damage, and a state of hormonal imbalance [31]. Terpenoids for example withaferin A interfere with mitosis and protein synthesis of the target plants to ultimately arrest mitosis and inhibit proper cell proliferation. Such molecular processes play a crucial role in the development of sustainable agriculture practices that would be able to adjust the allelopathic properties of Solanaceae species for weed control and crop management.

5. DISCUSSION

The study found an inconsistency between knowledge, attitude and actual behaviors among patients concerning the management of hypertension and this emphasizes the need for particular education and behavior change effort. However, some constraints such as the location of the study and adopted approach to self-reported information may influence the externality of the findings [32].

5.1.Interpretation of Results

In spite of the fact that a large proportion of participants had a moderate level of knowledge on hypertension and its management, there were still loopholes in respect to lifestyle modification, medication compliance and symptoms identification [33]. Hypertension management attitudes were for the most positive which means that people are willing to implement preventive and therapeutic interventions. However, practice was often inconsistent with knowledge or attitude, indicating the absence of the relationship between knowledge and attitude and behavior. This is a demonstration of the classical KAP gap where knowledge and attitude are not necessarily translated into good practice [34].

5.2.Comparison with Existing Studies

These results are in line with earlier research in comparable tertiary care facilities in India and other developing nations [35]. For example, a study by Sharma et al. (2020) in North India also showed moderate levels of knowledge among hypertensive patients with important practice behavior gaps. Concomitantly, an Adedoyin et al. (2019) study revealed that although patients were knowledgeable about food limitations and the need to monitor blood pressure regularly, adherence was poor. In comparison with these, our own research confirms the general trend seen in hypertension care—where awareness, unfortunately, does not always translate to effective control, owing to behavioral, cultural, or structural factors[36].

5.3.Implications of Findings

The results highlight the compelling necessity for focused education interventions in hospital care facilities to close the practice-knowledge gap [37]. Patient education can be strengthened by frequent counseling, IEC materials, and organized follow-ups to improve outcomes substantially. Involving family members and caretakers in the educational process can further increase compliance and enhance positive behavioral changes. Health practitioners need to become patient-focused to ensure knowledge and attitude are converted into long-term health behavior[38].

5.4.Limitations of the Study

Some limitations need to be recognized. Firstly, the study was limited to one tertiary care teaching hospital, which might reduce the generalizability of the results to other populations. Secondly, the use of self-reported data might have caused response bias, where the participants might have overreported favorable behaviors [39]. Thirdly, the cross-sectional design does not permit measurement of causality or long-term trends in the management practices for hypertension. Finally, psychosocial elements and comorbidities that could affect knowledge, attitude, and practice were not extensively addressed, which could yield a better perspective in future research[40].

6. CONCLUSION

This research highlights an obvious gap between knowledge, attitude, and practice (KAP) among hypertensive patients, with the participants showing moderate knowledge levels and overall favorable attitudes but failing to apply them in their day-to-day health practices, which were often lacking or irregular. This gap identifies a key challenge in managing chronic diseases—being aware is insufficient to influence change in behavior unless there are in-place systems and interventions. The research is of great importance as it supports earlier findings and contributes to the mounting evidence that calls for multi-pronged strategies in caring for patients. Its findings are especially applicable in tertiary care hospitals, where patient education and counseling can be institutionally planned. Targeted and culturally adapted interventions, follow-up procedures, and active engagement of family members are suggested to close the KAP gap. These strategies have the potential to transform knowledge and good attitudes into sustainable and sustained health behaviors, thereby enhancing the control of hypertension and decreasing the burden of cardiovascular disease.

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