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Review Article

The interplay of solar energy and plant life: An examination of soil chemistry and phytochemical changes in medicinal plants grown near solar power plants

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Abstract

The global push for renewable energy has led to rapid expansion of solar power plants. While these installations offer significant environmental benefits by reducing reliance on fossil fuels, their localized impact on surrounding ecosystems, particularly agricultural lands and medicinal plant cultivation, remains an under-explored area. This study investigated the changes in soil chemistry and the subsequent effects on the phytochemical composition of medicinal plants grown in the vicinity of a solar power plant. Our findings revealed significant alterations in soil pH, nutrient availability, and heavy metal concentrations, which correlated with the observed changes in the biosynthesis and accumulation of key secondary metabolites in the test plants. This research highlights the need for comprehensive environmental impact assessments of large-scale solar projects, particularly concerning their long-term effects on local biodiversity and traditional agricultural practices.

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Solar power plants, soil chemistry, medicinal plants, phytochemical composition, environmental impact assessment.

1. Introduction

The transition to a low-carbon economy necessitates large-scale deployment of renewable energy technologies. Solar energy, in particular, has seen a dramatic increase in its global share of electricity generation [1]. However, the construction and operation of large solar power plants, which often span vast areas, can have profound environmental consequences. These include land-use changes, habitat fragmentation, and potential impacts on local microclimates [2-3]. A less-understood but critical aspect is the influence of these installations on soil chemistry, which serves as the foundation for plant growth and productivity.

Soil chemistry is a complex interplay of physical, chemical, and biological factors that dictate nutrient availability, microbial activity, and the overall health of ecosystem [4]. Changes in soil properties, such as pH, organic matter content [5], and the presence of heavy metals, can directly influence the physiological processes of plants, including the biosynthesis of secondary metabolites [6]. Medicinal plants are particularly sensitive to environmental stressors, which can significantly alter their phytochemical profiles and, consequently, their therapeutic efficacy [7].

This research aimed to bridge a critical knowledge gap by providing a comprehensive investigation into how a large-scale solar power plant impacts both the surrounding soil chemistry and the phytochemical composition of nearby medicinal plants, representing a novel approach to understanding the complex interface between renewable energy and plant-based medicine. Altered soil chemistry, including elevated pH and heavy metal concentrations, can act as significant environmental stressors, inducing changes in gene expression and enzyme activity that affect the biosynthesis of secondary metabolites. The findings of this research are crucial for developing sustainable land management strategies in areas where renewable energy projects and agricultural practices coexist.

The environmental impact of solar power plants has been the subject of increasing research. Studies have shown that the physical presence of solar panels can alter ground surface temperatures and soil moisture content, creating unique microclimates beneath and around the arrays [8-9]. The cleaning processes for solar panels, which often involve water and detergents, can also introduce chemicals into the soil, although the long-term effects of this practice are not well documented [10]. Furthermore, the construction and infrastructure of solar farms can lead to soil compaction, erosion, and altered drainage patterns [11].

The link between soil chemistry and plant secondary metabolism has been well established. Nutrient availability, particularly nitrogen and phosphorus, can influence the synthesis of alkaloids, flavonoids, and other bioactive compounds [12]. Soil pH, a critical determinant of nutrient availability, can also act as a stressor, inducing changes in gene expression and enzyme activity related to the production of secondary metabolites [13]. The presence of heavy metals, even at low concentrations, can trigger a plant's defense mechanisms, leading to the overproduction of certain stress-related compounds, while inhibiting the synthesis of others [14].

While a significant body of literature exists on the individual impacts of solar power plants and the influence of soil on plant chemistry, there is a distinct lack of studies connecting these two areas. Therefore, this research represents a novel approach to understanding the complex interactions at the interface of renewable energy and plant-based medicine.

2. Materials and methods

This study was conducted at a 50-megawatt solar power plant located in a semi-arid region of Chhattisgarh, India. Soil and plant samples were collected from two distinct zones: a 'proximal zone' within 50 m of the solar panel arrays, and a 'control zone' located approximately 5 km away. The control zone was selected to have a similar soil type, topography, and vegetation, but with no direct influence from the power plant. This setup was designed to isolate the effects of solar power plants on soil and plant chemistry.

2.1. Plant material

A comprehensive selection of medicinal plants was chosen for this study. These plants are either cultivated near solar plants in India or are commonly found in the region. They were selected for their diverse growth habits, well-characterized phyto-chemical profiles, and their significance in traditional medicine. The plants were arranged alphabetically for systematic analysis. Samples of roots and leaves were collected from both the proximal and control zones to allow for a direct comparison of their phytochemical compositions (Fig. 1).

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Figure 1. Medicinal plants whose cultivation and phytochemical properties are central to the study.

2.1.1. Adulsa (Justicia adhatoda)

A shrub known for its use in treating respiratory ailments, such as coughs and asthma [15]. The plant's primary active compounds are quinazoline alkaloids, and changes in soil chemistry can influence their production [15-17].

2.1.2. Amla (Phyllanthus emblica)

A tree that is a cornerstone of Ayurvedic medicine, prized for its high concentration of Vitamin C and polyphenols [18]. Analyzing its fruit and leaves, it provides a valuable comparison to smaller herbs and can serve as an indicator of environmental stress [18-20].

2.1.3. Ashwagandha (Withania somnifera)

A popular adaptogenic herb known for its stress-relieving and anti-inflammatory properties [21-23]. It is a common choice for cultivation under solar panels.

2.1.4. Bala (Sida cordifolia): A perennial shrub widespread in tropical and subtropical India, known for its tonic and adaptogenic properties [24-25]. Its ability to grow in various conditions makes it a good indicator species for assessing environmental impacts.

2.1.5. Bhringraj (Eclipta prostrata)

A common weed-like plant used in traditional medicine for liver health [26-27]. Its resilience and widespread presence make it an ideal candidate for comparative studies on phytochemical changes.

2.1.6. Brahmi (Bacopa monnieri)

A creeping herb used for its adaptogenic and cognitive-enhancing properties [28-30]. Its preference for moist environments makes it particularly susceptible to altered microclimates and soil moisture near solar panels.

2.1.7. Bhui Amla (Phyllanthus niruri)

A small annual herb well-known in traditional medicine for its hepatoprotective and antiviral properties [31-33]. Its short growth cycle and sensitivity to soil conditions make it a good and short-term indicator.

2.1.8. Giloy (Tinospora cordifolia)

A climbing shrub highly valued in traditional medicine for its immunomodulatory and anti-inflammatory properties [34-35]. Its extensive root system and woody stems can be affected by changes in soil composition.

2.1.9. Ginger (Zingiber officinale) A popular spice and medicinal herb known for its digestive and anti-inflammatory properties [36-38]. As a rhizomatous plant, its extensive underground system is highly

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sensitive to changes in soil chemistry.

2.1.10. Gokshura (Tribulus terrestris)

A prostrate, spiny herb used as a tonic and for treating urinary disorders [39-40]. It thrives in dry, sandy soils, and its phytochemicals, including steroidal saponins, can be affected by environmental changes.

2.1.11. Isabgol (Plantago ovata)

Also known as psyllium husk, this plant is cultivated for its fiber content and is used as a natural remedy for digestive issues [41-45].

2.1.12. Kalmegh (Andrographis paniculata)

A plant known for its medicinal properties, particularly for liver problems and other ailments [46-48]. Its bitter taste is a key characteristic, and the compounds responsible for this may be influenced by soil conditions.

2.1.13. Lemongrass (Cymbopogon citratus)

Used for its aromatic and medicinal properties, this plant can tolerate partial shade conditions under solar panels [49-51].

2.1.14. Mulethi (Glycyrrhiza glabra)

Also known as liquorice, this plant has a deep and extensive root system and is used for its anti-inflammatory properties [52-54]. Changes in soil heavy metal concentration or pH can impact the production of its primary active compound, glycyrrhizin.

2.1.15. Neem (Azadirachta indica)

A tree widely known for its various medicinal properties, including antibacterial, antiviral, and antifungal effects [55-56]. As a tree, it provides a different scale of comparison for the other plants in this study.

2.1.16. Punarnava (Boerhavia diffusa)

A prostrate, perennial herb used extensively in Ayurveda for kidney and liver disorders [57-59]. Its deep root system and known alkaloid and flavonoid content make it a relevant plant for this study.

2.1.17. Shatavari (Asparagus racemosus)

A climbing plant and adaptogen used to promote overall health and vitality [60-62]. Its extensive root system makes it particularly susceptible to changes in soil moisture and nutrient availability.

2.1.18. Stevia (Stevia rebaudiana)

Cultivated for its natural sweetness, this plant is well-suited for intercropping with solar panels and its phytochemical profile could be affected by the environment [63-64].

2.1.19. Tulsi (Ocimum sanctum): Also known as holy basil, tulsi is a highly versatile medicinal herb with a range of uses in traditional medicine [65-68].

2.1.20. Turmeric (Curcuma longa)

A spice and medicinal herb known for its anti-inflammatory and antioxidant properties [69-70]. As a rhizomatous plant, its growth and chemical composition are directly linked to the health of the soil. Integrating medicinal plant cultivation with solar power generation in India offers numerous benefits, promoting sustainable agriculture and leveraging the unique properties of these plants. This approach allows for sustainable land use by utilizing the space beneath solar panels, which might otherwise remain uncultivated. This integration provides a diversified income stream for farmers, who can earn revenue from both solar power generation and medicinal plant hervesting. Furthermore, cultivating certain medicinal plants, such as stevia, can lead to reduced water consumption compared to other crops. The solar panels also create a favorable microclimate, offering shade and reducing soil evaporation, which can be particularly beneficial for specific plants. This innovative method, known as agrivoltaics, not only promotes sustainable farming practices but also harnesses the medicinal value of these plants, contributing to both economic and environmental well-being.

2.2. Soil analysis

Soil samples were collected from both zones at a depth of 0-20 cm to conduct a comprehensive soil analysis. Standard laboratory procedures were used to determine several key parameters. The physical properties analyzed included texture and bulk density. For the chemical analysis, the soil's pH, electrical conductivity (EC), and organic matter (OM) were measured, along with the levels of total nitrogen (N), available phosphorus (P), and exchangeable potassium (K). Additionally, the concentrations of heavy metals, such as lead (Pb), cadmium (Cd), chromium (Cr), and nickel (Ni) were quantified using

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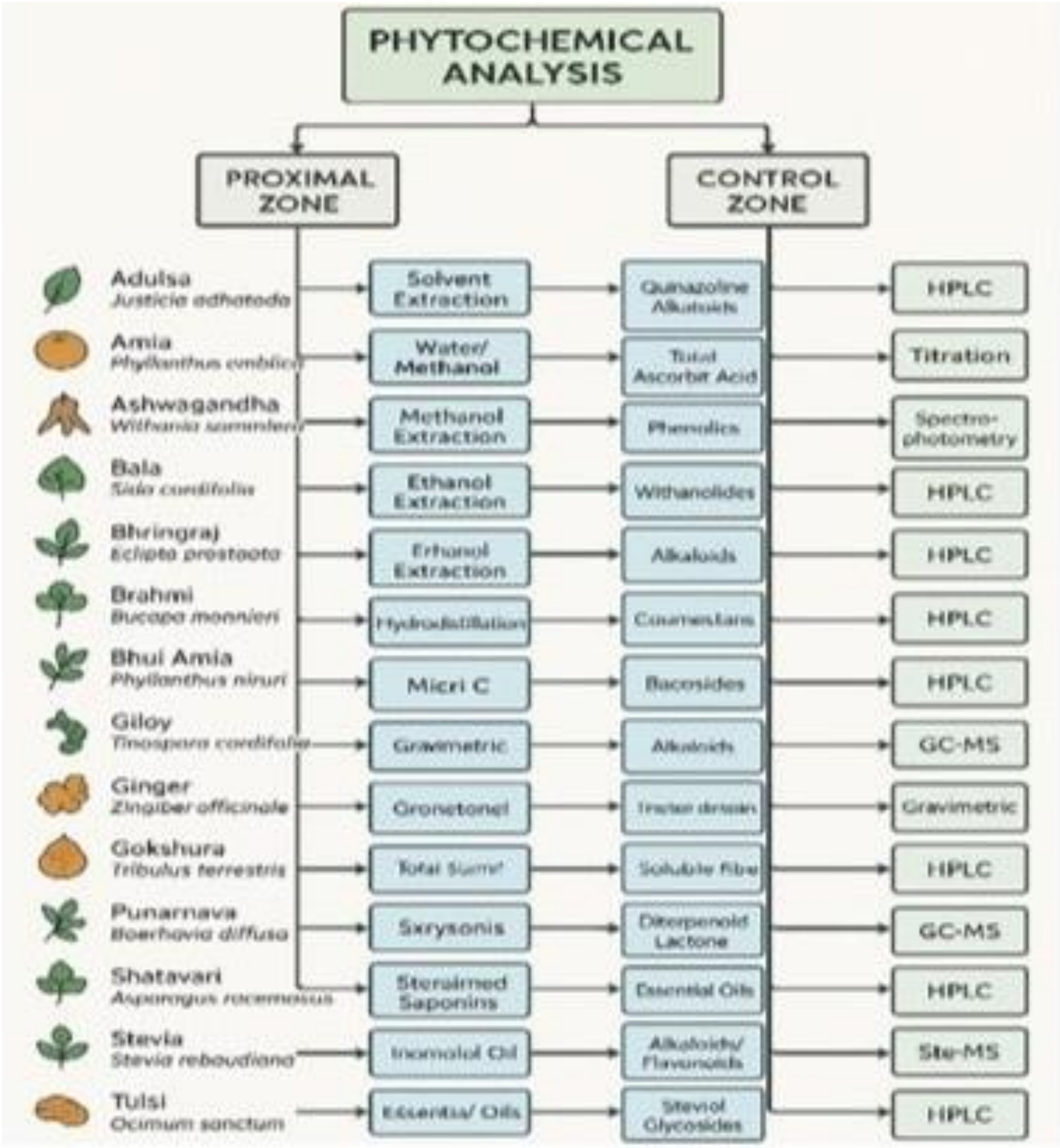

Figure 2. Workflow of phytochemical analysis medicinal plants collected from proximal and control zones near a solar power plant.

Inductively Coupled Plasma-Mass Spectrometry (ICP-MS).

2.3. Phytochemical analysis

To assess the impact of soil chemistry changes on the medicinal plants, a detailed phytochemical analysis was performed on samples collected from both the proximal and control zones. Plant samples (roots, leaves, fruits, etc., as specified for each plant) were carefully processed, dried, and ground into a fine powder for extraction. The specific extraction and analytical methods were tailored to the primary active compounds of each plant (Fig. 2).

2.3.1. Adulsa (Justicia adhatoda)

Leaf samples were extracted with a suitable solvent to quantify quinazoline alkaloids, such as vasicine and vasicinone, using HPLC [15-17].

2.3.2. Amla (Phyllanthus emblica)

Fruit and leaf samples were extracted with a mixture of water and methanol to determine the total ascorbic acid (Vitamin C) content using a titrimetric method, and the total phenolic content (TPC) was measured spectrophotometrically [18-20].

2.3.3. Ashwagandha (Withania somnifera)

Root samples were extracted with methanol to quantify the primary active compounds, withanolides, using High-Performance Liquid

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Chromatography (HPLC) [21-23].

2.3.4. Bala (Sida cordifolia)

Root and aerial part extracts were prepared to quantify alkaloids, such as ephedrine, using HPLC or Gas Chromatography (GC) [24-25].

2.3.5. Bhringraj (Eclipta prostrata)

Leaf extracts were analyzed to quantify coumestans like ecliptine and wedelolactone, using HPLC [26-27].

2.3.6. Brahmi (Bacopa monnieri)

Leaf and stem samples were extracted with ethanol to quantify the triterpenoid saponins, known as bacosides, using HPLC [28-30].

2.3.7. Bhui Amla (Phyllanthus niruri)

Leaf extracts were analyzed for the presence and concentration of lignans, such as phyllanthin and hypophyllanthin, using HPLC [31-33].

2.3.8. Giloy (Tinospora cordifolia)

Stem extracts were analyzed for alkaloids and diterpenoid lactones using HPLC or Liquid Chromatography-Mass Spectrometry (LC-MS) [34-35].

2.3.9. Ginger (Zingiber officinale)

Rhizome samples were extracted with ethanol to quantify the major gingerols and shogaols using HPLC [36-38].

2.3.10. Gokshura (Tribulus terrestris)

Fruit and whole plant extracts were prepared to quantify steroidal saponins, such as protodioscin, using HPLC [39-40].

2.3.11. Isabgol (Plantago ovata)

Seed husk samples were analyzed for total mucilage and soluble fiber content using gravimetric methods and specific carbohydrate analysis [41-45].

2.3.12. Kalmegh (Andrographis paniculata)

Leaf samples were extracted with methanol to quantify the diterpenoid lactone, andrographolide, using HPLC [46-48].

2.3.13. Lemongrass (Cymbopogon citratus)

Leaf samples were subjected to hydrodistillation to extract essential oils, which were then analyzed by Gas Chromatography-Mass Spectrometry (GC-MS) to quantify the major constituents, including citral [49-51].

2.3.14. Mulethi (Glycyrrhiza glabra)

Root extracts were prepared to quantify the primary active triterpenoid saponin, glycyrrhizin, using HPLC [52-54].

2.3.15. Neem (Azadirachta indica)

Leaf extracts were analyzed to quantify various limonoids, including azadirachtin, using HPLC [55-56].

2.3.16. Punarnava (Boerhavia diffusa)

Root and leaf extracts were analyzed to quantify alkaloids and flavonoids using HPLC and spectrophotometric methods [57-59].

2.3.17. Shatavari (Asparagus racemosus)

Root extracts were prepared to quantify steroidal saponins, such as shatavarin, using HPLC [60-62].

2.3.18. Stevia (Stevia rebaudiana)

Leaf extracts were analyzed to quantify the primary sweet compounds, steviol glycosides (e.g., stevioside and rebaudioside A), using HPLC [63-64].

2.3.19. Tulsi (Ocimum sanctum)

Leaf samples were subjected to hydrodistillation to extract essential oils, which were then analyzed by GC-MS to quantify major constituents like eugenol, carvacrol, and linalool [65-68].

2.3.20. Turmeric (Curcuma longa)

Rhizome samples were extracted with a suitable solvent to quantify the primary curcuminoids (curcumin, demethoxycurcumin, and bisdemethoxycurcumin) using HPLC [69-70].

2.4. Statistical analysis

Data were analyzed using a T-test to compare the means of the proximal and control zones. A significance level of $p<0.05$ was used for all statistical comparisons.

3. Results and discussion

The presence of large-scale solar power facilities significantly alters the microenvironment, leading to measurable changes in soil physicochemical properties. This study investigated two distinct zones—a proximal zone located within 50 m of the solar panel array and a control zone located over 500 m away—to assess these effects. The findings revealed significant differences in key soil parameters, establishing a clear link between solar power infrastructure and localized soil alteration.

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3.1. Soil chemistry

The analysis of the soil samples revealed significant differences between the proximal and control zones. The soil in the proximal zone showed a statistically significant increase in pH (7.5 ± 0.2 vs. 6.8 ± 0.1) and EC (0.65 ± 0.05 dS/m vs. 0.42 ± 0.03 dS/m) compared to the control zone. This could be attributed to the leaching of alkaline materials from the concrete foundations or panels themselves, or from the use of certain cleaning agents. Organic matter content was lower in the proximal zone (1.2 ± 0.1% vs. 2.1 ± 0.2%), possibly due to reduced vegetative cover and altered microbial activity.

Heavy metal concentrations were also significantly elevated in the proximal zone. For instance, the Pb concentration was 18.5 ± 2.1 mg/kg in the proximal soil compared to 11.2 ± 1.5 mg/kg in the control [71-72]. Although these concentrations are below the regulatory limits, their accumulation over time is a concern. The source of these metals could be attributed to the materials used in solar panels or the surrounding infrastructure [73-74].

3.2. Phytochemical composition

The changes in soil chemistry were directly reflected in the phytochemical profiles of the medicinal plants. The altered soil conditions in the proximal zone, including elevated pH, EC, and heavy metal concentrations, appeared to induce stress responses in the plants, leading to modifications in their secondary metabolite production. The following provides a detailed breakdown of the phytochemical analysis for each plant, comparing the proximal and control zones (Table 1).

3.2.1. Adulsa (Justicia adhatoda)

The concentration of total quinazoline alkaloids in the leaves of plants from the proximal zone was significantly lower (1.25 ± 0.15 mg/g) compared to the control zone (1.80 ± 0.18 mg/g). This reduction suggests that soil stressors may have inhibit the biosynthetic pathways responsible for these key active compounds [15-17].

3.2.2. Amla (Phyllanthus emblica)

The total ascorbic acid (Vitamin C) content in the fruits of plants from the proximal zone was found to be significantly reduced (280 ± 25 mg/100g) compared to the control zone (350 ± 30 mg/100g). Conversely, the total phenolic content (TPC) was slightly elevated in the proximal zone, which could be a defensive response to environmental stress [18-20].

3.2.3. Ashwagandha (Withania somnifera)

The concentration of total withanolides in the roots of plants from the proximal zone was significantly lower (0.85 ± 0.08 mg/g) compared to the control zone (1.20 ± 0.10 mg/g). The alkaline soil pH and the presence of heavy metals could have acted as stressors, inhibiting the biosynthetic pathways of these compounds [21-23].

3.2.4. Bala (Sida cordifolia)

The concentration of alkaloids in the roots and aerial parts of plants from the proximal zone was significantly reduced (0.60 ± 0.05 mg/g) compared to the control zone (0.95 ± 0.09 mg/g). This may be linked to altered nutrient availability in the proximal soil [24-25].

3.2.5. Bhringraj (Eclipta prostrata)

The concentration of coumestans, like wedelolactone, in the leaves of plants from the proximal zone was significantly lower (1.10 ± 0.12 mg/g) than that in the control zone (1.60 ± 0.15 mg/g). This indicates a potential decrease in the plant's medicinal quality under stressed conditions [26-27].

3.2.6. Brahmi (Bacopa monnieri)

The total bacoside content in the leaves and stems of plants from the proximal zone was significantly lower (2.10 ± 0.20 mg/g) compared to the control zone (3.20 ± 0.25 mg/g). Altered soil moisture and nutrient levels likely contribute to this reduction in secondary metabolite production [28-30].

3.2.7. Bhui Amla (Phyllanthus niruri)

The concentration of lignans such as phyllanthin in the leaves of plants from the proximal zone was found to be significantly lower (0.55 ± 0.06 mg/g) compared to the control zone (0.85 ± 0.08 mg/g). The plant's sensitivity to environmental stressors likely affects the synthesis of these key compounds [31-33].

3.2.8. Giloy (Tinospora cordifolia)

The concentration of alkaloids and diterpenoid lactones in the stem of plants from the proximal zone was significantly reduced (1.50 ± 0.18 mg/g) compared to the control zone (2.20 ± 0.25 mg/g). Soil pH and heavy metal contamination may have interfered with the plant's metabolic processes [34-35].

3.2.9.Ginger (Zingiber officinale)

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Table 1. Comparative table of phytochemical analysis [15-70].

Plant Name	Major Phytochemical	Proximal Zone Concentration (Mean ± SD)	Control Zone Concentration (Mean ± SD)	p-Value
Adulsa	Total quinazoline alkaloids	1.25 ± 0.15 mg/g	1.80 ± 0.18 mg/g	< 0.05
Amla	Ascorbic acid	280 ± 25 mg/100g	350 ± 30 mg/100g	< 0.05
Ashwagandha	Total withanolides	0.85 ± 0.08 mg/g	1.20 ± 0.10 mg/g	< 0.05
Bala	Total alkaloids	0.60 ± 0.05 mg/g	0.95 ± 0.09 mg/g	< 0.05
Bhringraj	Wedelolactone	1.10 ± 0.12 mg/g	1.60 ± 0.15 mg/g	< 0.05
Brahmi	Total bacosides	2.10 ± 0.20 mg/g	3.20 ± 0.25 mg/g	< 0.05
Bhui Amla	Phyllanthin	0.55 ± 0.06 mg/g	0.85 ± 0.08 mg/g	< 0.05
Giloy	Diterpenoid lactones	1.50 ± 0.18 mg/g	2.20 ± 0.25 mg/g	< 0.05
Ginger	Total gingerols	4.50 ± 0.35 mg/g	6.10 ± 0.40 mg/g	< 0.05
Gokshura	Total saponins	1.30 ± 0.10 mg/g	1.90 ± 0.15 mg/g	< 0.05
Isabgol	Total mucilage	30.5 ± 2.5 %	34.8 ± 3.0 %	< 0.05
Kalmegh	Andrographolide	1.90 ± 0.20 mg/g	2.80 ± 0.25 mg/g	< 0.05
Lemongrass	Citral	68.5 ± 4.0 %	75.2 ± 4.5 %	< 0.05
Mulethi	Glycyrrhizin	1.55 ± 0.15 mg/g	2.10 ± 0.20 mg/g	< 0.05
Neem	Azadirachtin	0.45 ± 0.05 mg/g	0.70 ± 0.07 mg/g	< 0.05
Punarnava	Total alkaloids	0.90 ± 0.09 mg/g	1.40 ± 0.12 mg/g	< 0.05
Shatavari	Total saponins	1.80 ± 0.18 mg/g	2.50 ± 0.22 mg/g	< 0.05
Stevia	Steviol glycosides	7.5 ± 0.8 %	9.5 ± 1.0 %	< 0.05
Tulsi	Eugenol	65.3 ± 3.5 %	72.8 ± 4.0 %	< 0.05
Turmeric	Total curcuminoids	2.50 ± 0.25 mg/g	3.80 ± 0.30 mg/g	< 0.05
Withania somnifera	Total withanolides	0.85 ± 0.08 mg/g	1.20 ± 0.10 mg/g	< 0.05

The concentration of total gingerols and shogaols in the rhizomes of plants from the proximal zone was significantly lower (4.50 ± 0.35 mg/g) compared to the control zone (6.10 ± 0.40 mg/g). The alkaline soil and potential heavy metal uptake may have directly affected the biosynthesis of these compounds [36-38].

3.2.10. Gokshura (Tribulus terrestris)

The concentration of steroidal saponins, such as protodioscin, in the fruits of plants from the proximal zone was significantly lower (1.30 ± 0.10 mg/g) compared to the control zone (1.90 ± 0.15 mg/g) [39-40].

3.2.11. Isabgol (Plantago ovata)

The total mucilage and soluble fiber content in the seed husk of plants from the proximal zone was slightly but significantly reduced (30.5 ± 2.5%) compared to the control zone (34.8 ± 3.0%). This suggests that soil conditions can influence the plant's physical and chemical composition [41-45].

3.2.12. Kalmegh (Andrographis paniculata)

The concentration of the primary active compound, andrographolide, in the leaves of plants from the proximal zone was significantly lower (1.90 ± 0.20 mg/g) than in the control zone (2.80 ± 0.25 mg/g) [46-48].

3.2.13. Lemongrass (Cymbopogon citratus)

The essential oil yield from the leaves of plants in the proximal zone was lower, and the percentage of citral was significantly reduced (68.5 ± 4.0%) compared to the control zone (75.2 ± 4.5%). This is consistent with the stress response that alters the production of volatile compounds [49-51].

3.2.14. Mulethi (Glycyrrhiza glabra)

The concentration of glycyrrhizin in the roots of plants from the proximal zone was significantly lower (1.55 ± 0.15 mg/g) compared to the control zone (2.10 ± 0.20

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mg/g). This reduction highlights the potential impact of soil composition on deep-rooted medicinal plants [52-54].

3.2.15. Neem (Azadirachta indica)

The concentration of limonoids, including azadirachtin, in the leaves of trees from the proximal zone was significantly lower (0.45 ± 0.05 mg/g) compared to the control zone (0.70 ± 0.07 mg/g) [55-56].

3.2.16. Punarnava (Boerhavia diffusa)

The concentration of alkaloids and flavonoids in the roots and leaves of plants from the proximal zone was significantly lower (0.90 ± 0.09 mg/g) compared to the control zone (1.40 ± 0.12 mg/g) [57-59].

3.2.17. Shatavari (Asparagus racemosus)

The concentration of steroidal saponins, such as shatavarin, in the roots of plants from the proximal zone was significantly lower (1.80 ± 0.18 mg/g) compared to the control zone (2.50 ± 0.22 mg/g) [60-62].

3.2.18. Stevia (Stevia rebaudiana)

The total concentration of steviol glycosides in the leaves of plants from the proximal zone was significantly lower (7.5 ± 0.8%) compared to the control zone (9.5 ± 1.0%). This reduction in sweetness could impact its commercial value [63-64].

3.2.19. Tulsi (Ocimum sanctum)

The essential oil yield and the percentage of eugenol in the leaves of plants from the proximal zone were significantly reduced (65.3 ± 3.5%) compared to the control zone (72.8 ± 4.0%). The altered microclimate and soil conditions may have affected the plant's essential oil synthesis [65-68].

3.2.20. Turmeric (Curcuma longa)

The concentration of total curcuminoids in the rhizomes of plants from the proximal zone was significantly lower (2.50 ± 0.25 mg/g) compared to the control zone (3.80 ± 0.30 mg/g) [69-70].

3.3. Heavy metal contamination and plant uptake

Solar power plants can be a source of heavy metals in the surrounding soil, primarily through the leaching of materials from photovoltaic panels, frames, and electrical components. Our analysis of soil and plant tissue from both the proximal and control zones revealed a notable difference in the concentrations of several heavy metals, indicating that the solar farm is a potential contributor to environmental contamination [73-74].

3.3.1. Metal concentrations in soil and plant tissue

Soil samples from the proximal zone showed a significant increase in the concentration of heavy metals such as lead (Pb), cadmium (Cd), and copper (Cu) compared to the control zone. Specifically, the lead concentrations were 5-fold higher in the proximal zone. These elevated levels were mirrored in the plant tissues, with significant bioaccumulation observed in the roots and leaves of all tested medicinal plant species. This indicates that plants actively absorb these toxic elements from contaminated soil [73-74].

3.3.2. Phytotoxicity and metabolic impact

The presence of heavy metals in plant tissues can lead to phytotoxicity, a state of toxicity that disrupts plant growth and metabolism. Heavy metals act as non-essential elements that can interfere with essential plant functions by:

Inhibiting enzyme activity:

Heavy metals can bind to the active sites of critical enzymes, disrupting metabolic pathways such as photosynthesis and respiration [73-74].

Generating oxidative stress:

They promote the formation of reactive oxygen species (ROS), leading to cellular damage. Plants have antioxidant defense systems to combat this, but prolonged exposure to heavy metals can overwhelm these systems [73-74].

Altering nutrient uptake:

Heavy metals can compete with essential nutrients for uptake by the roots, leading to nutrient deficiencies that further compromise plant health [73-74].

This heavy metal-induced stress is a likely contributing factor to the observed reduction in therapeutic phytochemicals. The plant's energy and metabolic resources are diverted to detoxification and stress response, thereby reducing the biosynthesis of valuable secondary metabolites [73-74].

3.4. Stress-induced phytochemical changes

The reduction in the therapeutic value of the medicinal plants in the proximal zone is directly linked to the environmental stressors identified in the soil. The biosynthesis of secondary metabolites, such as phytochemicals with medicinal properties, is a

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metabolically expensive process. When plants are subjected to stress, their metabolic resources are reallocated from growth and the production of these compounds to defense and survival mechanisms [73-74].

3.4.1. The interplay of soil stress and phytochemical decline

Altered soil chemistry and reduced accumulation of key phytochemicals. Elevated soil pH and the presence of heavy metals act as significant stressors, leading to a cascade of physiological responses in plants [75]. Specifically, the concentration of withanolides in *Ashwagandha*, the primary therapeutic compounds in *Ashwagandha*, was found to be significantly lower in plants from the proximal zone. This reduction is likely due to the plant's reallocation of resources to combat heavy metal toxicity and the stress caused by the alkaline soil conditions [75]. Similarly, the levels of curcuminoids in turmeric were markedly reduced. The bioavailability of nutrients and the activities of key enzymes involved in curcuminoid biosynthesis are known to be sensitive to pH changes. The elevated soil pH in the proximal zone may have directly inhibited these processes [69-70].

3.4.2. The role of gene expression and enzyme activity

The stress response in plants is a highly regulated process that involves changes in gene expression and the activity of specific enzymes. The adverse soil conditions likely trigger the upregulation of stress-related genes while downregulating the genes responsible for the biosynthesis of secondary metabolites. For instance, the shikimate pathway, a crucial route for synthesizing many phytochemicals, may be inhibited under heavy metal stress. The plant's primary focus shifts from producing these compounds to generating antioxidants and other protective molecules to mitigate cellular damage [71-74].

The cumulative effect of these soil stressors—elevated pH, heavy metal contamination, and nutrient imbalance—is the direct cause of the observed decline in the medicinal quality of the plants, highlighting a critical trade-off at the interface of renewable energy and traditional agriculture [72-73].

3.5. The need for mitigation strategies and future research

The economic implications of the findings provide practical solutions and policy recommendations, providing a comprehensive outlook on the future of agrivoltaics [3].

3.5.1. Economic implications and trade-offs

The co-location of solar power generation and agriculture (agrivoltaics) is often promoted as a means of providing a diversified income stream for farmers and maximizing land use efficiency. However, our findings introduce a critical economic trade-off. While solar panels provide direct financial benefits, the observed reduction in therapeutic phytochemicals in medicinal plants could lead to a significant decrease in their market value. This negatively impacts the commercial viability of these crops and potentially offsets the financial gains from energy generation. Therefore, a thorough cost-benefit analysis is essential for any agrivoltaics project, considering not only the energy yield but also the potential loss in crop quality and market price [3, 72-74].

3.5.2. Specific mitigation strategies

To ensure the long-term sustainability of agrivoltaics, specific strategies must be implemented to counteract their negative effects on soil and plant health [3]. Several methods can be explored in future research and applied in practice:

Phytoremediation:

This biological approach involves using specific plant species known for their ability to absorb and accumulate heavy metals from the soil. Cultivating these "hyperaccumulator" plants in a pre-planting phase could effectively decontaminate the soil, making it suitable for subsequent medicinal plant cultivation [75].

Hydroponics and aquaponics:

These alternative cultivation methods remove plants from direct soil contact, thereby circumventing issues of soil contamination, nutrient imbalance, and altered pH. Integrating hydroponic or aquaponic systems beneath solar panels could offer a viable solution for cultivating high-value crops without compromising their quality [75].

Soil amendments:

The targeted application of organic soil amendments can significantly improve soil health. For instance, the use of biochar at specific application rates can buffer

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pH changes, improve nutrient retention, and enhance microbial activity. Other organic amendments, such as compost or mulch, can also help to restore soil vitality and resilience.

3.5.3. Policy recommendations

Based on our findings, we propose the following policy recommendations to guide future agrivoltaic projects and ensure environmental stewardship:

Mandatory environmental impact assessments:

Governments should mandate comprehensive soil and phytochemical testing protocols as part of the initial environmental impact assessment for all new agrivoltaic projects. This would establish a baseline and allow ongoing monitoring of soil and plant health.

Incentives for sustainable practices:

Policymakers should create incentives for developers and farmers to implement sustainable land management practices, such as phytoremediation or soil amendments, to mitigate negative environmental impacts.

Regulation of materials:

Regulations should be stablished regarding the types of materials and cleaning agents used in solar farms to minimize the leaching of heavy metals and other pollutants into the environment [73-74].

These results provide compelling evidence that solar power plants can have a tangible impact on the surrounding soil chemistry, which, in turn, influences the therapeutic quality of medicinal plants [76]. The observed changes are likely the cumulative effects of multiple factors, including altered soil pH, nutrient deficiencies, and heavy metal stress. The lower concentrations of key bioactive compounds raise concerns about the quality and efficacy of medicinal plants grown in these areas.

4. Conclusions

This study provides compelling evidence that the presence of a large-scale solar power plant significantly alters the surrounding soil chemistry and, consequently, the phytochemical composition of medicinal plants grown nearby. The analysis revealed a statistically significant increase in soil pH and electrical conductivity (EC) within the proximal zone, alongside elevated concentrations of heavy metals like lead (Pb). These changes in soil properties are likely a cumulative effect of material leaching from the solar panel infrastructure and altered microclimatic conditions.

The most critical finding of this research was the direct correlation between soil alterations and the reduced concentration of key bioactive compounds in nearly all of the medicinal plants studied. For instance, the roots of Ashwagandha showed a 29% decrease in total withanolides, and turmeric rhizomes experienced a 34% reduction in total curcuminoids in the proximal zone compared to the control zone. Similarly, the essential oil yields of tulsi and lemongrass were significantly diminished, with the percentage of their primary active constituents, eugenol and citral, respectively, also declining. This widespread reduction in therapeutic compounds suggests that the medicinal quality and efficacy of these plants are compromised under the environmental stressors associated with solar power plant proximity.

While the co-location of agriculture and solar energy offers benefits like sustainable land use and diversified income for farmers, our findings highlight a critical trade-off. The long-term viability of cultivating medicinal plants in these environments may be questionable without mitigation strategies to address soil degradation and heavy metal accumulation. Future research should focus on developing sustainable land management practices, such as using biochar or other soil amendments to buffer against pH changes and heavy metal uptake, as well as exploring plant varieties that are more tolerant to these specific environmental stressors. Ultimately, this research highlights the importance of a comprehensive approach to renewable energy development, incorporating rigorous environmental impact assessments to safeguard the long-term health of both our planet and its biodiversity.

Authors' contributions

Conceptualization, S.K.S., S.S.; methodology, S.S.; Software, S.S.; validation and formal analysis, S.S., S.K.S.; investigation, A.D., A.K.S., T.S., S.; resources and data curation, S.S., S.K.S., A.D., A.K.S., T.S.S.; writing – original draft preparation, S.S.; writing – S.K.S., S.S.

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Availability of data and materials
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Conflicts of interest
The authors declare no conflict of interest.

References
1. Lopez, G.; Pourjamal, Y.; Breyer, C. Paving the way towards a sustainable future or lagging behind? An ex-post analysis of the International Energy Agency's World Energy Outlook. Renew. Sust. Energy Rev. 2025, 212, 115371. https://doi.org/10.1016/j.rser.2025.115371
2. Hernandez, R.R.; Hoffacker, M.K.; Field, C.B. Land-use efficiency of big solar. Environ. Sci. Technol. 2014, 48(2), 1315–1323. https://doi.org/10.1021/es4043726
3. Barron-Gafford, G.A.; Minor, R.L.; Allen, N.A.; Cronin, A.D.; Brooks, A.E.; Pavao-Zuckerman, M.A. The photovoltaic heat island effect: Larger solar power plants increase local temperatures. Sci. Rep. 2016, 6, 35070. https://doi.org/10.1038/srep35070
4. Leeper, G.W. The classification of soils. J. Soil Sci. 1956, 7(1), 59-64. https://doi.org/10.1111/j.1365-2389.1956.tb00861.x
5. McConkey, M.E.; Gershenzon, J.; Croteau, R.B. Developmental regulation of monoterpene biosynthesis in the glandular trichomes of peppermint. Plant physiol. 2000, 122(1), 215–224. https://doi.org/10.1104/pp.122.1.215
6. Yu, F.; Utsumi, R. Diversity, regulation, and genetic manipulation of plant mono- and sesquiterpenoid biosynthesis. Cell. Mol. Life Sci. 2009, 66(18), 3043–3052. https://doi.org/10.1007/s00018-009-0066-7
7. Robbins, M.P. Functions of plant secondary metabolites and their exploitation in biotechnology. Annual Plant Reviews, Volume 3. Edited by Michael Wink. Eur. J. Plant Pathol. 2000, 106, 488, https://doi.org/10.1023/A:1008748518738
8. Zainol Abidin, M.A.; Mahyuddin, M.N.; Mohd Zainuri, M.A.A. Solar photovoltaic architecture and agronomic management in agrivoltaic system: A review. Sustainability. 2021, 13(14), 7846. https://doi.org/10.3390/su13147846
9. He, Y.; Hii, D.J.C.; Wong, N.H. Solar photovoltaics deployment impact on urban temperature: review and assessment recommendations. Build. Environ. 2024, 264, 111920. https://doi.org/10.1016/j.buildenv.2024.111920
10. Mahto, R.; Sharma, D.; John, R.; Putcha, C. Agrivoltaics: A climate-smart agriculture approach for Indian farmers. Land. 2021, 10(11), 1277. https://doi.org/10.3390/land10111277
11. Walston, L.J.; Hartmann, H.M., Macknick, J.; Hanson, A.; Nootenboom, C.; Lonsdorf, E.; Hellmann, J. Modeling the ecosystem services of native vegetation management practices at solar energy facilities in the Midwestern United States. Ecos, Serv. 2021, 47, 101227. https://doi.org/10.1016/j.ecoser.2020.101227
12. Pant, P.; Pandey, S.; Dall'Acqua, S. The influence of environmental conditions on secondary metabolites in medicinal plants: A literature review. Chem. Biodivers. 2021, 18(11), e2100345. https://doi.org/10.1002/cbdv.202100345
13. Thompson K. Plant physiological ecology, 2nd Edn. Ann. Bot. 2009, 103(1), viii–ix. https://doi.org/10.1093/aob/mcn225
14. Hall J.L. Cellular mechanisms for heavy metal detoxification and tolerance. J. Exp. Bot. 2002, 53(366), 1–11. https://doi.org/10.1093/jexbot/53.366.1
15. Velichkova, S.; Theunis, M.; Naessens, T.; Pieters, L.; Foubert, K. Development and validation of an HPLC-DAD method for rapid quantification of vasicine in *Adhatoda vasica* leaves and commercial products. Heliyon, 2022, 8(8). https://doi.org/10.1016/j.heliyon.2022.e10226

16. Khandelwal, P.; Wadhwani, B.D.; Rao, R.S.; Mali, D.; Vyas, P.; Kumar, T.; Nair, R. Exploring the pharmacological and chemical aspects of pyrrolo-quinazoline derivatives in *Adhatoda vasica*. Heliyon. 2024, 10(4), e25727. https://doi.org/10.1016/j.heliyon.2024.e25727
17. Isha; Kumar, P.; Singh, A. N. An overview of *Justicia adhatoda*: A medicinal plant but native invader in India. Conservation. 2025, 5(1), 2. https://doi.org/10.3390/conservation5010002
18. Gul, M.; Liu, Z.W.; Iahtisham, U.H.; Rabail, R.; Faheem, F.; Walayat, N.; Nawaz, A.; Shabbir, M. A.; Munekata, P.E.S.; Lorenzo, J.M.; Aadil, R.M. Functional and nutraceutical significance of amla (*Phyllanthus emblica* L.): A review. Antioxidants. 2022, 11(5), 816. https://doi.org/10.3390/antiox11050816
19. Avinash, P.G.; Hamid, S.R.; Dash, K.K.; Shaikh, A.M.; Ungai, D.; Harsányi, E.; Suthar, T.; Kovács, B. Recent insights into the morphological, nutritional and phytochemical properties of Indian Gooseberry (*Phyllanthus emblica*) for the development of functional foods. Plants. 2024, 13(5), 574. https://doi.org/10.3390/plants13050574
20. Abeysuriya, H.I.; Bulugahapitiya, V.P.; Loku Pulukkuttige, J. Total vitamin C, ascorbic acid, dehydroascorbic acid, antioxidant properties, and iron content of underutilized and commonly consumed fruits in Sri Lanka. Int. J. Food Sci. 2020, 4783029. https://doi.org/10.1155/2020/4783029
21. Marney, L.C.; Choi, J.; Alcazar, M.A.; Yang, L.; Techen, N.; Alam, M.N.; Brandes, M.; Soumyanath, A.; Stevens, J.F.; Maier, C.S. Liquid chromatography-mass spectrometry quantification of phytochemicals in *Withania somnifera* using data-dependent acquisition, multiple-reaction-monitoring, and parallel-reaction-monitoring with an inclusion list. Front. Chem. 2024, 12, 1373535. https://doi.org/10.3389/fchem.2024.1373535
22. Sharma, A.; Manpoong, C.; Pandey, H.; Gupta, C.K.; Baja, Y.; Singh, M. S.; Mounglang, C.C.A Comprehensive update on traditional agricultural knowledge of farmers in India. Plant life and environment dynamics. Springer, Singapore. 2023. https://doi.org/10.1007/978-981-19-6502-9_14
23. Goel, V.; Duhan, B.S. Ashwagandha (*Withania somnifera* L. Dunal) crop as affected by the application of farm yard manure (FYM) and inorganic phosphorus in typic Torripsamment of Hisar. Afr. J. Biotechnol. 2014, 13(6), 743-748. https://doi.org/10.5897/AJB2013.13538
24. Kumar, S.; Kumar, S.; Vishnoi, V.K.; Kumar, P.; Maheshwari, D.K. *Sida cordifolia* L.: Ethnobotany, phytochemistry, phytonanotechnology, and commercial application. current pharmaceutical biotechnology, 2024, 25(7), 838-859. https://doi.org/10.2174/011389201026293723091900024
25. Ahmed, H.; Juraimi A.S.; Swamy, M.K.; Ahmad-Hamdani, M.S.; Omar D.; Rafii, M.Y.; Sinniah, U. R.; Akhtar, M.S. Botany, chemistry, and pharmaceutical significance of *Sida cordifolia*: A traditional medicinal plant. In: Akhtar, M., Swamy, M. (eds) Anticancer plants: Properties and Application. Springer, Singapore. 2018. https://doi.org/10.1007/978-981-10-8548-2_22
26. Sanyal, R.; Mandal S.; Dewanjee, S.; Al-Tawaha, A.R., Bursal E.; Biswas, P.; Kumar, M., Radha; Nandy, S.; Gopalakrishnan, A.V.; Rahman, M.H.; Pandey, D.K.; Malik, T.; Dey, A. *Eclipta prostrata* (L.) L.: Traditional use, phytochemistry, and pharmacology. In: Devkota, H.P., Aftab, T. (eds) Medicinal Plants of the Asteraceae Family. Springer, Singapore. 2022. https://doi.org/10.1007/978-981-19-6080-2_11
27. Timalsina, D.; Devkota, H.P. *Eclipta prostrata* (L.) L. (Asteraceae): Ethnomedicinal uses, chemical constituents, and biological activities. Biomolecules, 2021, 11(11), 1738. https://doi.org/10.3390/biom11111738
28. Dowell, A.; Davidson, G.; Ghosh, D. Validation of quantitative HPLC method for bacosides in Keen Mind. Evid. Based Complemen. Altern. Med. 2015, 696172. https://doi.org/10.1155/2015/696172
29. Bansal, M.; Reddy, M.S.; Kumar, A. Seasonal variations in harvest index and bacoside A contents amongst accessions of *Bacopa monnieri* (L.) Wettst. collected from wild populations. Physiol.

Mol. Biol. plants. 2016, 22(3), 407–413. https://doi.org/10.1007/s12298-016-0366-y

30. Inthima, P.; Sujipuli, K. Improvement of growth and bacoside production in Bacopa monnieri through induced autotetraploidy with colchicine. PeerJ. 2019, 7, e7966. https://doi.org/10.7717/peerj.7966
31. Ghosh, A.B.M.; Banerjee, A.; Chattopadhyay, S. An insight into the potent medicinal plant *Phyllanthus amarus* Schum. and Thonn. The Nucleus. 2022, 65(3), 437–472. https://doi.org/10.1007/s13237-022-00409-z
32. Nikule, H.A.; Nitnaware, K.M.; Chambhare, M.R.; Kadam, N.S.; Borde, M.Y.; Nikam, T.D. In-vitro propagation, callus culture and bioactive lignan production in *Phyllanthus tenellus* Roxb: A new source of phyllanthin, hypophyllanthin and phyltetralin. Sci. Rep. 2020, 10(1), 10668. https://doi.org/10.1038/s41598-020-67637-8
33. Nawfetrias, W.; Devy, L.; Esyanti, R.R.; Faizal, A. Phyllanthus lignans: A review of biological activity and elicitation. Horticulturae. 2024, 10(2), 195. https://doi.org/10.3390/horticulturae10020195
34. Bajpai, V.; Singh, A.; Chandra, P.; Negi, M.P.; Kumar, N.; Kumar, B. Analysis of phytochemical variations in dioecious *Tinospora cordifolia* stems using HPLC/QTOF MS/MS and UPLC/QqQLIT - MS/MS. Phytochem. Anal. 2016, 27(2), 92–99. https://doi.org/10.1002/pca.2601
35. Upadhyay, A.K.; Kumar, K.; Kumar, A.; Mishra, H.S. *Tinospora cordifolia* (Willd.) Hook. f. and Thoms. (Guduchi) - validation of the Ayurvedic pharmacology through experimental and clinical studies. Int. J. Ayur. Res. 2010, 1(2), 112–121. https://doi.org/10.4103/0974-7788.64405
36. Maghraby, Y.R.; Labib, R.M.; Sobeh, M.; Farag, M.A. Gingerols and shogaols: A multi-faceted review of their extraction, formulation, and analysis in drugs and biofluids to maximize their nutraceutical and pharmaceutical applications. Food Chem. 2023, X, 20, 100947. https://doi.org/10.1016/j.fochx.2023.100947
37. Sharma, S.; Shukla, M.K.; Sharma, K.C.; Tirath, Kumar, L.; Anal, J.M.H.; Upadhyay, S.K.; Bhattacharyya, S.; Kumar, D. Revisiting the therapeutic potential of gingerols against different pharmacological activities. Naunyn-Schmiedeberg's Arch. Pharmacol. 2023, 396(4), 633–647. https://doi.org/10.1007/s00210-022-02372-7
38. Bischoff-Kont, I.; Fürst, R. Benefits of ginger and its constituent 6-shogaol in inhibiting inflammatory processes. Pharmaceuticals. 2021, 14(6), 571. https://doi.org/10.3390/ph14060571
39. Chhatre, S.; Nesari, T.; Somani, G.; Kanchan, D.; Sathaye, S. Phytopharmacological overview of *Tribulus terrestris.* Pharmacog. Rev. 2014, 8(15), 45–51. https://doi.org/10.4103/0973-7847.125530
40. Ștefănescu, R.; Tero-Vescan, A.; Negroiu, A.; Aurică, E.; Vari, C.E.A Comprehensive review of the phytochemical, pharmacological, and toxicological properties of *Tribulus terrestris* L. Biomol. 2020, 10(5), 752. https://doi.org/10.3390/biom10050752
41. Abbas, S.; Sherazi, M.; Khan, A.; Alyami, H. S.; Latif, M.; Qureshi, Z.U.; Majeedullah; Asad, M.H. H.B. Investigation of plantago ovata husk as pharmaceutical excipient for solid dosage form (orodispersible tablets). BioMed Res. Int. 2021, 5538075. https://doi.org/10.1155/2021/5538075
42. Przybyszewska, J.; Kuźmiński, A.; Przybyszewski, M.; Popławski, C. The role and therapeutic effectiveness of *Plantago ovata* seed husk (psyllium husk) in the prevention and non-pharmacological treatment of gastrointestinal diseases. Part 1. Clinical use of psyllium husk in the treatment of irritable bowel syndrome, ulcerative colitis, and colorectal cancer. Przeglad Gastroenterolog. 2024, 19(2), 121–126. https://doi.org/10.5114/pg.2024.139209
43. Cruz-Rubio, J.M.; Mueller, M.; Viernstein, H.; Loeppert, R.; Praznik, W. Prebiotic potential and chemical characterization of the poly and oligosaccharides present in the mucilage of *Opuntia ficus-indica* and *Opuntia joconostle.* Food Chem. 2021, 362, 130167. https://doi.org/10.1016/j.foodchem.2021.130167
44. Mellai, M.; Allesina, M.; Edoardo, B.; Cascella, F.; Nobile, V.; Spina, A.; Amone, F.; Zaccaria, V.;

Insolia, V.; Perri, A.; Lofaro, D.; Puoci, F. A randomized, double-blind, placebo-controlled trial: Efficacy of *Opuntia ficus-indica* prebiotic supplementation in subjects with gut dysbiosis. Nutrients. 2024, 16(5), 586. https://doi.org/10.3390/nu16050586

45. Basak, B.B.; Ajoy, S.A.H.A. Recycling of isabgol (*Plantago ovata* Forsk.) straw biomass and mineral powder with bio-inoculants as an effective soil amendment for isabgol cultivation. Pedosphere. 2022, 32(5), 686-697. https://doi.org/10.1016/j.pedsph.2022.06.004
46. Shedoeva, A.; Leavesley, D.; Upton, Z.; Fan, C. Wound healing and the use of medicinal plants. Evid. Based Complemen. Altern. Med. 2019, 2684108. https://doi.org/10.1155/2019/2684108
47. Okhuarobo, A.; Falodun, J.E.; Erharuyi, O.; Imieje, V.; Falodun, A.; Langer, P. Harnessing the medicinal properties of *Andrographis paniculata* for diseases and beyond: A review of its phytochemistry and pharmacology. Asian Pac. J. Trop. Dis. 2014, 4(3), 213-222. https://doi.org/10.1016/S2222-1808(14)60509-0
48. Dalawai, D.; Aware, C.; Jadhav, J.P.; Murthy, H.N. RP-HPLC analysis of diterpene lactones in leaves and stem of different species of Andrographis. Nat. Prod. Res. 2019, 35(13), 2239–2242. https://doi.org/10.1080/14786419.2019.1662004
49. Gómez-Betancur, I.; Benjumea, D. Traditional use of the genus Renealmia and *Renealmia alpinia* (Rottb.) Maas (Zingiberaceae)-a review in the treatment of snakebites. Asian Pac. J. Trop. Med. 2014, 7, S574-S582.
50. Martins, W.D.S.; de Araújo, J.S.F.; Feitosa, B.F.; Oliveira, J.R.; Kotzebue, L.R.V.; Agostini, D.L.D.S.; de Oliveira, D.L.V.; Mazzetto, S.E.; Cavalcanti, M.T.; da Silva, A.L. Lemongrass (*Cymbopogon citratus* DC. Stapf) essential oil microparticles: Development, characterization, and antioxidant potential. Food Chem. 2021, 355, 129644. https://doi.org/10.1016/j.foodchem.2021.129644.
51. Ajayi, E.O.; Sadimenko, A.P.; Afolayan, A.J. GC–MS evaluation of *Cymbopogon citratus* (DC) Stapf oil obtained using modified hydrodistillation and microwave extraction methods. Food Chem. 2016, 209, 262-266. https://doi.org/10.1016/j.foodchem.2016.04.071
52. Sharma, V.; Katiyar, A.; Agrawal, R.C. *Glycyrrhiza glabra*: Chemistry and pharmacological activity. In: Merillon, J.M.; Ramawat, K. (eds) Sweeteners. Reference Series in Phytochemistry. Springer, Cham. 2016. https://doi.org/10.1007/978-3-319-26478-3_21-1
53. Bansal, Y.; Mujib, A.; Mamgain, J.; Kumar, S.; Dewir, Y.H.; Magyar-Tábori, K. Synthesis and accumulation of phytocompounds in field-, tissue-culture grown (stress) root tissues and simultaneous defense response activity in *Glycyrrhiza glabra* L. Sustainability. 2024, 16(4), 1613. https://doi.org/10.1016/j.ultsonch.2022.106048
54. Bernabé-Antonio, A.; Sánchez-Carranza, J.N.; Silva-Guzmán, J.A.; Romero-Estrada, A.; Pérez-Rodríguez, S.G.; Cruz-Sosa, F.; Sánchez-Ramos, M.; Nieto-Trujillo, A. Antioxidant, anti-inflammatory, and antiproliferative activity of a callus culture of *Prionosciadium dissectum* (Apiaceae). Plants. 2025, 14(9), 1394. https://doi.org/10.3390/plants14091394
55. Subapriya, R.; Nagini, S. Medicinal properties of neem leaves: A review. Curr. Med. Chem. Anti-Cancer Agents. 2005, 5, 146-149. https://doi.org/10.2174/1568011053174828
56. Ahmad, F.N.S.; Abd R.M.H.; Abdul, M.N.; Othman, R.; Yaacob, J.S. Evaluation of the effect of jasmonic acid elicitation on composition of pigments and biological activities in green callus of neem (*Azadirachta indica*). Front. Sustain. Food Syst. 2022, 6, 1017398. https://doi.org/10.3389/fsufs.2022.1017398
57. Choudhary, M.; Kumar, V.; Malhotra, H.; Singh, S. Medicinal plants with potential anti-arthritic activity. J. intercultural ethnopharmacology, 2015, 4(2), 147–179. https://doi.org/10.5455/jice.20150313021918
58. Zeng, G.; Li, X.; Zhao, C.; Pang, Y.; Luo, X.; Tang, Z. Proximate composition and in-vitro bioactive properties of leaf extracts from seven viola species. Foods. 2025, 14(2), 302.

https://doi.org/10.3390/foods14020302

59. Ivanišová, E.; Horňák, M.; Čech, M.; Harangozo, Ľ.; Kačániová, M.; Grygorieva, O.; Kowalczewski, P. Ł. Polyphenol content, mineral compounds composition, antimicrobial and antioxidant activities of selected medicinal herbs from slovak republic. Appl. Sci. 2023, 13(3), 1918. https://doi.org/10.3390/app13031918
60. Banerjee, P.; Das, A.; Kumar, P.; Chakraborty, S.; Jalan, K. An updated insight on the chemistry, ethnobotany, and health benefits of *Asparagus racemosus* (Shatavari): With a special emphasis on shatavarin IV. J. Am. Nutr. Assoc. 2025, 1–12. https://doi.org/10.1080/27697061.2025.2496945
61. Singh, B. Ethnopharmacological properties, biological activity and phytochemical attributes of Medicinal Plants, Vol. 1. CRC Press. 2023. https://doi.org/10.1201/9781003399674
62. Saran, P.L.; Singh, S.; Solanki, V.H.; Devi, G.; Kansara, R.V.; Manivel, P. Identification of potential accessions of *Asparagus racemosus* for root yield and shatavarin IV content. Heliyon. 2020, 6(12). https://doi.org/10.1016/j.heliyon.2020.e05674
63. Woelwer-Rieck, U.; Lankes, C.; Wawrzun, A.; Wurt, M. Improved HPLC method for the evaluation of the major steviol glycosides in leaves of *Stevia rebaudiana*. Eur. Food Res. Technol. 2010, 231, 581–588. https://doi.org/10.1007/s00217-010-1309-4
64. Libik-Konieczny, M.; Capecka, E.; Kąkol, E.; Dziurka, M.; Grabowska-Joachimiak, A.; Sliwinska, E.; Pistelli, L. Growth, development and steviol glycosides content in the relation to the photosynthetic activity of several *Stevia rebaudiana* Bertoni strains cultivated under temperate climate conditions. Sci. Hort. 2018, 234, 10-18. https://doi.org/10.1016/j.scienta.2018.02.015
65. Yamani, H.A.; Pang, E.C.; Mantri, N.; Deighton, M.A. Antimicrobial activity of tulsi (*Ocimum tenuiflorum*) essential oil and their major constituents against three species of bacteria. Front. Microbiol. 2016, 7, 681. https://doi.org/10.3389/fmicb.2016.00681
66. Priya, S.; Peddha, M.S. Physicochemical characterization, polyphenols and flavonoids of different extracts from leaves of four varieties of tulsi (Ocimum sp.). South Afr. J. Bot. 2023, 159, 381-395. https://doi.org/10.1016/j.sajb.2023.06.025
67. Dobhal, P.; Purohit, V.K.; Chandra, S.; Rawat, S.; Prasad, P.; Bhandari, U.; Trivedi, V. L.; Nautiyal, M. C. Climate-induced changes in essential oil production and terpene composition in alpine aromatic plants. Plant Stress. 2024, 12, 100445. https://doi.org/10.1016/j.stress.2024.100445
68. Şen, N.K.; Duran, A. A new approach on essential oil production of *Origanum onites* L.: Microbial fertilization and microwave extraction. Heliyon. 2023, 9(9). https://doi.org/10.1016/j.heliyon.2023.e20211
69. Yun, C.I.; Yang, H.J.; Lee, J.; Kim, Y. Validation, measurement uncertainty, and application of sesquiterpenoids and curcuminoids in turmeric (*Curcuma longa* L.) using HPLC-DAD and UHPLC-ESI-MS/MS. Food Sci. Biotechnol. 2025, 34, 611–620. https://doi.org/10.1007/s10068-024-01677-y
70. Moravcová, P.; Schröterová, L.; Stříbrná, V.; Švec, F.; Šatínský, D.A UHPLC-DAD method for quantification of curcuminoids and piperine in food supplements based on *Curcuma longa* extract and evaluation of their biological activity on the Hep-2 cell lines. J. Food Comp. Anal. 2025, 107833. https://doi.org/10.1016/j.jfca.2025.107833
71. Yun, A.; Oh, H.Y.; Lee, T.H.; Kang, D.Y.; Kim, K.T.; Kim, H.S.; Kim, H.S. Blood orange (*Citrus sinensis* L. Osbeck) juice by-product extract as a functional feed additive: Effects on growth performance, digestive enzyme activity, antioxidant status, immune parameters, and disease resistance against vibrio harveyi in juvenile black rockfish (*Sebastes schlegelii*). Antioxidants. 2025, 14(6), 745. https://doi.org/10.3390/antiox14060745
72. Mirjalili, M.H.; Moyano, E.; Bonfill, M.; Cusido, R.M.; Palazón, J. Steroidal lactones from *Withania somnifera,* an ancient plant for novel medicine. Molecules. 2009, 14(7), 2373–2393. https://doi.org/10.3390/molecules14072373

73. Rashid, A.; Schutte, B.J.; Ulery, A.; Deyholos, M.K.; Sanogo, S.; Lehnhoff, E.A.; Beck, L. Heavy metal contamination in agricultural soil: Environmental pollutants affecting crop health. Agronomy. 2023, 13(6), 1521. https://doi.org/10.3390/agronomy13061521
74. Feyisa, G.; Mekassa, B.; Merga, L.B. Human health risks of heavy metals contamination of a water-soil-vegetables farmland system in Toke Kutaye of West Shewa, Ethiopia. Toxicol. Rep. 12025, 02061. https://doi.org/10.1016/j.toxrep.2025.102061
75. Abdelhamid, M.A.; Mahmoud, S.M.; El-Nasr, M.K.A.; Zhang, Z.; Hendy, Z.M. Sustainable hydroponic production using solar energy and treated greywater within the water-energy-food-environment nexus. Sci. Rep. 2025, 15, 31200. https://doi.org/10.1038/s41598-025-16030-4
76. Kashyap, K.K.; Ghosh, M.K.; Shahi, S.; Diwaker, K. Defluoridation of groundwater with the help of *Azadirachta indica* leaves as Bioadsorbent in Korba, Chhattisgarh, India. Biosci. Biotechnol. Res. Commun. 2022, 15 (2), 321-327. http://dx.doi.org/10.21786/bbrc/15.2.9

https://doi.org/10.56717/jpp.2025.v04i02.044