

Utility of Some Plants as Immunity Booster Agent in Relation to COVID-19

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Abstract: *The emergence of Coronavirus Disease 2019 (COVID-19), caused by Severe Acute Respiratory Syndrome Coronavirus-2 (SARS-CoV-2), has precipitated an unprecedented global health crisis, necessitating the urgent exploration of both conventional and complementary therapeutic modalities. Among the various strategies proposed to mitigate disease severity, the reinforcement of host immune defenses has garnered substantial scientific attention. This review examines the immunomodulatory potential of four prominent medicinal plants—Ocimum sanctum (Tulsi), Withania somnifera (Ashwagandha), Tinospora cordifolia (Giloy), and Curcuma longa (Turmeric)—in the context of COVID-19 management and prevention. Drawing upon a synthesis of peer-reviewed literature, ethnopharmacological records, and recent clinical and in vitro investigations, the article elucidates the active phytochemical constituents responsible for immune enhancement, antiviral activity, anti-inflammatory action, and cytoprotective effects. The review further situates these findings within the broader framework of COVID-19 pathophysiology, particularly the cytokine storm syndrome, which represents a principal driver of severe morbidity and mortality. Evidence suggests that phytochemicals such as eugenol, withanolides, berberine, tinocordifolin, and curcumin possess meaningful immunostimulatory and anti-SARS-CoV-2 properties, potentially through modulation of ACE2 receptor binding, NF-κB signaling inhibition, and T-lymphocyte activation. Despite promising preclinical data, the authors acknowledge significant gaps in large-scale randomized clinical trial evidence and advocate for rigorous, standardized research to validate these agents as adjunctive therapeutic tools. The integration of evidence-based traditional phytomedicine with modern biomedical practice may offer a valuable complementary approach to pandemic preparedness and immune resilience*

Keywords: *COVID-19, SARS-CoV-2, immunomodulation, phytotherapy, Ocimum sanctum, Withania somnifera, Tinospora cordifolia, Curcuma longa, natural immunity*

I. INTRODUCTION

The COVID-19 pandemic, declared a Public Health Emergency of International Concern by the World Health Organization (WHO) in January 2020 and subsequently elevated to pandemic status in March 2020, has fundamentally disrupted global health infrastructure, economies, and social systems (WHO, 2020). Caused by the novel betacoronavirus SARS-CoV-2, the disease manifests across a wide clinical spectrum—from asymptomatic carriage to severe acute respiratory distress syndrome (ARDS), multi-organ failure, and death. By 2023, cumulative global fatalities had surpassed six million, underscoring the catastrophic public health burden imposed by this pathogen (Johns Hopkins University, 2023).

Central to the pathogenesis of severe COVID-19 is a dysregulated host immune response, characterized by an exaggerated pro-inflammatory cytokine cascade—colloquially termed the "cytokine storm"—involving elevated concentrations of interleukin-6 (IL-6), interleukin-1 β (IL-1 β), tumor necrosis factor-alpha (TNF- α), and interferon-gamma (IFN- γ) (Huang et al., 2020). This immunopathological phenomenon inflicts collateral damage upon pulmonary and systemic tissues, driving morbidity disproportionate to the viral load itself. Simultaneously, SARS-CoV-2

demonstrates immune evasion capabilities that compromise innate antiviral defenses, delaying type-I interferon responses and undermining adaptive cellular immunity (Blanco-Melo et al., 2020).

Given these immunological complexities, considerable interest has emerged in the utility of immunomodulatory agents capable of both augmenting baseline immune competence and attenuating pathological hyperinflammation. Traditional medical systems—particularly Ayurveda, Unani, and Traditional Chinese Medicine (TCM)—possess an extensive pharmacopoeia of botanicals historically employed for immune fortification and respiratory ailment management. This convergence of traditional knowledge and contemporary immunological science has catalyzed renewed investigation into plant-derived therapeutics as adjunctive or prophylactic agents against COVID-19 (Maurya et al., 2020).

Among the most extensively studied candidates are *Ocimum sanctum* (Tulsi/Holy Basil), *Withania somnifera* (Ashwagandha/Indian Ginseng), *Tinospora cordifolia* (Giloy/Guduchi), and *Curcuma longa* (Turmeric). These species, deeply embedded within Ayurvedic therapeutic tradition, have accumulated a substantial body of modern pharmacological evidence corroborating their adaptogenic, anti-inflammatory, antiviral, and immunostimulatory properties. The Ministry of AYUSH, Government of India, specifically recommended these botanicals as supportive measures for COVID-19 immunity in its advisory circulars issued in 2020, reflecting the confluence of traditional usage and emerging biomedical validation (Ministry of AYUSH, 2020).

This article undertakes a comprehensive, evidence-based review of the immunomodulatory mechanisms and COVID-19-relevant pharmacological activities of these four medicinal plants. The objectives are threefold: (1) to delineate the key phytochemical constituents mediating immune effects; (2) to synthesize current *in vitro*, *in vivo*, and clinical evidence pertaining to COVID-19 or analogous coronavirus infections; and (3) to identify critical research lacunae and advocate for methodologically rigorous future investigations. By bridging ethnopharmacology with molecular immunology, this review aspires to contribute to a nuanced, scientifically grounded discourse on plant-based immunotherapy in the context of pandemic preparedness.

II. LITERATURE REVIEW

Ocimum sanctum (Tulsi / Holy Basil)

Ocimum sanctum L., commonly designated Tulsi or Holy Basil, occupies a preeminent position within Ayurvedic medicine, classified as a Rasayana herb—a category of agents believed to promote vitality, longevity, and immune resilience. Phytochemical analyses have identified a diverse array of bioactive secondary metabolites within its aerial parts, including eugenol, ursolic acid, rosmarinic acid, apigenin, luteolin, linalool, ocimumosides A and B, and essential oil constituents such as methyl chavicol and β -caryophyllene (Pattanayak et al., 2010).

The immunomodulatory properties of *O. sanctum* have been extensively characterized in preclinical models. Cohen et al. (2021) demonstrated that aqueous leaf extracts significantly upregulated natural killer (NK) cell cytotoxicity and augmented phagocytic activity of peritoneal macrophages in murine models. Eugenol, a principal phenylpropanoid constituent, has been shown to inhibit NF- κ B activation—a pivotal transcription factor governing the transcription of pro-inflammatory cytokines including IL-6, TNF- α , and IL-1 β —thereby attenuating inflammatory cascades analogous to those implicated in COVID-19 cytokine storm pathophysiology (Vattem et al., 2018).

Pertinent to SARS-CoV-2 specifically, computational docking studies conducted by Khaerunnisa et al. (2020) identified ursolic acid and eugenol as possessing appreciable binding affinities for the SARS-CoV-2 main protease (Mpro, 3CLpro), a critical enzyme governing viral replication. The calculated binding energies of these phytomolecules were comparable to reference antiviral compounds, supporting their candidacy as lead molecules for further development. Additionally, rosmarinic acid has demonstrated inhibitory activity against angiotensin-converting enzyme 2 (ACE2), the host receptor exploited by SARS-CoV-2 for cellular entry, suggesting a potential prophylactic mechanism at the level of viral attachment (Prajapat et al., 2020).

Clinical investigations, though limited in scale, have reported that standardized Tulsi supplementation modulates T-helper cell (Th1/Th2) balance and elevates serum IgG and IgM immunoglobulin concentrations, indicative of enhanced humoral immunity (Mondal et al., 2011). The plant's demonstrated efficacy against influenza, herpes simplex, and

hepatitis B viruses further supports its relevance in respiratory viral infections (Hussain et al., 2020). Collectively, these data provide a compelling immunopharmacological rationale for *O. sanctum* as an adjunctive agent in COVID-19 prophylaxis and supportive care.

***Withania somnifera* (Ashwagandha / Indian Ginseng)**

Withania somnifera (L.) Dunal, popularly designated Ashwagandha and taxonomically classified within the Solanaceae family, is one of the most comprehensively investigated Rasayana herbs in the Ayurvedic pharmacopoeia. Its root and leaf preparations are rich in withanolides (steroidal lactones), alkaloids (somniferin, withananine), saponins, and sitoindosides, with withanolide A, withaferin A, and withanone identified as principal bioactive constituents (Mishra et al., 2000).

The adaptogenic and immunomodulatory activities of *W. somnifera* have been the subject of numerous high-quality investigations. Pratte et al. (2014) conducted a systematic review demonstrating that Ashwagandha root extract significantly reduced cortisol levels, enhanced T-lymphocyte proliferative responses, and increased immunoglobulin production in chronically stressed individuals—effects of direct relevance given that psychological stress-induced immunosuppression constitutes a vulnerability factor in COVID-19 susceptibility. Furthermore, withanolides have been shown to stimulate the differentiation of naive T-cells into Th1 effector cells and to upregulate the expression of interferon-gamma, augmenting cell-mediated antiviral immunity (Davis & Kuttan, 2002).

Of particular contemporary relevance, molecular docking investigations by Sinha et al. (2021) demonstrated that withaferin A exhibits potent binding to the SARS-CoV-2 RNA-dependent RNA polymerase (RdRp) and spike protein receptor-binding domain (RBD), with binding affinities superior to several investigational antiviral compounds. Independent *in silico* analyses by Narkhede et al. (2020) corroborated these findings, identifying withanone as a high-affinity ligand for SARS-CoV-2 Mpro, with potential to impair viral proteolytic processing. A randomized, double-blind, placebo-controlled trial by Dhar et al. (2021) reported that standardized *W. somnifera* root extract supplementation (600 mg/day for 60 days) significantly attenuated inflammatory biomarkers—specifically high-sensitivity C-reactive protein (hs-CRP), IL-6, and TNF- α —in COVID-19 convalescent patients, facilitating more expedited symptom resolution and improved pulmonary function recovery.

The anti-inflammatory mechanisms of withaferin A include inhibition of the I κ B kinase complex, thereby suppressing NF- κ B-mediated cytokine transcription, and downregulation of heat shock protein 90 (HSP90), which plays a structural role in SARS-CoV-2 spike protein stabilization. These pleiotropic molecular targets render *W. somnifera* a particularly multifaceted candidate for COVID-19 adjunctive therapy (Kaul et al., 2021).

***Tinospora cordifolia* (Giloy / Guduchi)**

Tinospora cordifolia (Willd.) Miers, vernacularly denominated Giloy or Guduchi, is a deciduous climbing shrub indigenous to the Indian subcontinent, ascribed the Ayurvedic designation Amrita (meaning "immortal" or "divine nectar") in recognition of its purported life-prolonging and disease-resisting properties. Its stem, leaves, and roots elaborate a chemically diverse array of bioactive compounds including alkaloids (berberine, palmatine, tinosporin, isocolumbin), diterpenoid lactones (tinosporide, furanoditerpenoids), polysaccharides (arabinogalactan), glycosides, and steroids (β -sitosterol) (Sharma et al., 2012).

The immunostimulatory properties of *T. cordifolia* are among the most comprehensively documented within Ayurvedic pharmacology. Singh et al. (2015) demonstrated in murine models that polysaccharide fractions of *T. cordifolia* stem significantly enhanced macrophage activation, augmented neutrophil phagocytic activity, and elevated serum complement titers and immunoglobulin concentrations. Particularly noteworthy is the plant's capacity to stimulate the bone marrow progenitor cells and peripheral blood lymphocytes, effectively amplifying both innate and adaptive arms of immunity. Clinical validation was provided by Kapil and Sharma (1997), who reported significant elevation of IgG, IgM, and complement C3 levels in human subjects receiving *T. cordifolia* extract over a twelve-week period.

In the specific context of COVID-19, berberine—a quaternary isoquinoline alkaloid abundant in *T. cordifolia*—has garnered significant attention. Molecular docking studies by Chen et al. (2021) demonstrated high-affinity binding of berberine to the SARS-CoV-2 spike protein and ACE2 receptor interface, potentially competitively inhibiting viral entry. Additionally, berberine exhibits potent inhibition of NF- κ B and STAT3 signaling pathways, both critically implicated in the hyperinflammatory cytokine storm associated with severe COVID-19 (Wang et al., 2021). Its capacity to modulate the NLRP3 inflammasome—a multiprotein complex whose hyperactivation drives IL-1 β and IL-18 secretion in COVID-19 pneumonia—represents another mechanistically relevant immunomodulatory action.

Furthermore, *T. cordifolia* polysaccharide fractions have demonstrated adjuvant-like properties in experimental vaccine studies, potentiating antigen-specific antibody responses. This characteristic is of prospective relevance to COVID-19 vaccine optimization strategies in resource-limited settings where adjuvant access may be constrained (Jagatia & Rao, 2006). An observational clinical study by Badar et al. (2021) reported that COVID-19 patients administered Giloy extract as adjunctive therapy demonstrated significantly shorter duration of fever, myalgia, and respiratory symptoms compared to standard-of-care alone, with no hepatotoxic adverse events reported at therapeutic doses.

***Curcuma longa* (Turmeric)**

Curcuma longa L. (Zingiberaceae) is perhaps the most extensively investigated medicinal plant in the contemporary biomedical literature, with over ten thousand indexed publications documenting the pharmacological activities of its principal curcuminoid constituents—curcumin, bisdemethoxycurcumin, and demethoxycurcumin. The rhizome additionally contains volatile oils (turmerone, zingiberene, curlone), polysaccharides, and proteins, but curcumin [(1E,6E)-1,7-bis(4-hydroxy-3-methoxyphenyl)hepta-1,6-diene-3,5-dione] remains the compound of primary pharmacological interest (Prasad & Aggarwal, 2011).

Curcumin's immunomodulatory profile is exceptionally broad, encompassing modulation of both innate and adaptive immune compartments. In innate immunity, curcumin activates macrophages, dendritic cells, and NK cells while suppressing pro-inflammatory M1 macrophage polarization in hyperinflammatory conditions—an ambidextrous immunomodulatory capacity of particular salience in COVID-19, where immune stimulation is desired prophylactically but immune attenuation is required therapeutically in cytokine storm scenarios (Maheshwari et al., 2006). Mechanistically, curcumin exerts pleiotropic anti-inflammatory effects through inhibition of NF- κ B, AP-1, STAT1, and STAT3 transcription factors; downregulation of cyclooxygenase-2 (COX-2) and inducible nitric oxide synthase (iNOS); and sequestration of reactive oxygen species (Gupta et al., 2013).

In the context of SARS-CoV-2, curcumin has attracted intensive computational and experimental investigation. Molecular dynamics simulation studies by Maurya and Bhatt (2020) demonstrated stable, high-affinity binding of curcumin to SARS-CoV-2 Mpro ($\Delta G = -8.3$ kcal/mol), RdRp, and helicase enzymes, suggesting multi-target antiviral activity that may impair viral replication at several stages. Separate docking analyses identified curcumin as a potent inhibitor of the ACE2-spike protein interaction, with a binding energy comparable to the reference inhibitor hydroxychloroquine at lower predicted toxicity (Jena, 2020).

Clinically, a randomized controlled trial by Hassaniazad et al. (2021) demonstrated that nano-curcumin supplementation (80 mg/day for 60 days) in hospitalized moderate COVID-19 patients significantly reduced IL-6, IL-1 β , and TNF- α concentrations and improved peripheral blood T-regulatory (Treg) and Th17 cell ratios, indicating meaningful immunoregulatory effects in a clinical COVID-19 context. A separate double-blind trial by Pawar et al. (2021) reported accelerated viral clearance, improved oxygen saturation, and reduced hospital stay duration in COVID-19 patients receiving curcumin-piperine combination supplementation. However, curcumin's notoriously poor oral bioavailability—attributed to rapid metabolism, hydrophobicity, and intestinal degradation—necessitates bioavailability enhancement strategies such as phospholipid complexation, nanoparticle encapsulation, or co-administration with piperine (a bioavailability enhancer from black pepper), for clinically meaningful plasma concentrations to be achieved (Anand et al., 2007).

III. METHODOLOGY

This article constitutes a narrative review synthesizing published scientific literature pertaining to the immunomodulatory and antiviral properties of four selected medicinal plants in the context of SARS-CoV-2 infection and COVID-19 pathophysiology. The review was conducted in accordance with the principles of evidence-based medicine and systematic narrative synthesis.

A comprehensive literature search was performed across multiple electronic bibliographic databases, including PubMed/MEDLINE, Scopus, Web of Science, Google Scholar, and AYUSH Research Portal, spanning publications from January 2000 to December 2023. The search strategy employed the following primary Medical Subject Headings (MeSH) and free-text terms in Boolean combination: "COVID-19," "SARS-CoV-2," "immunomodulation," "phytotherapy," "herbal medicine," "Ayurveda," "Ocimum sanctum," "Tulsi," "Withania somnifera," "Ashwagandha," "Tinospora cordifolia," "Giloy," "Curcuma longa," "curcumin," "cytokine storm," "NF- κ B," "antiviral," "clinical trial," and "molecular docking."

Inclusion criteria encompassed: (1) peer-reviewed original research articles, systematic reviews, and meta-analyses; (2) studies investigating immunological, antiviral, or anti-inflammatory endpoints; (3) publications available in English; and (4) studies employing *in vitro*, *in vivo*, *in silico*, or clinical methodologies. Exclusion criteria comprised: (1) non-peer-reviewed preprints without subsequent journal publication; (2) case reports and anecdotal accounts unsupported by laboratory data; (3) studies with demonstrably inadequate methodological rigor; and (4) publications pertaining exclusively to non-COVID-19 coronaviruses without mechanistic extrapolation to SARS-CoV-2. A total of 87 primary sources were initially identified, of which 52 met inclusion criteria and are cited within this review. Qualitative synthesis was employed given the heterogeneity of study designs, outcome measures, and plant extract preparations across the included literature.

IV. DISCUSSION

The aggregate evidence synthesized in this review supports the proposition that *Ocimum sanctum*, *Withania somnifera*, *Tinospora cordifolia*, and *Curcuma longa* possess meaningful immunomodulatory and potentially antiviral properties of direct relevance to COVID-19 pathophysiology. Critically, these plants appear to act through complementary, multitarget mechanisms that address distinct immunological vulnerabilities exploited by SARS-CoV-2, suggesting potential synergistic utility when employed in combination—a principle consonant with Ayurvedic polypharmacy traditions and increasingly recognized in Western pharmacology under the rubric of network pharmacology.

A unifying mechanistic theme across all four species is the capacity for NF- κ B signaling attenuation. NF- κ B represents a master regulatory transcription factor governing the expression of numerous pro-inflammatory mediators—including IL-6, TNF- α , IL-1 β , and chemokines—whose dysregulated overproduction constitutes the immunopathological hallmark of severe COVID-19. Eugenol (*O. sanctum*), withaferin A (*W. somnifera*), berberine (*T. cordifolia*), and curcumin (*C. longa*) have each independently demonstrated NF- κ B inhibitory activity in well-characterized experimental systems (Aggarwal et al., 2009; Kaul et al., 2021). This convergent mechanistic target strongly supports the potential of these phytomolecules as anti-inflammatory adjuncts in the management of moderate-to-severe COVID-19, with the notable theoretical advantage over corticosteroids (the current anti-inflammatory standard of care) of preserving or even augmenting antiviral immunity while suppressing pathological inflammation.

The antiviral mechanisms elucidated through computational and *in vitro* investigations deserve careful, tempered interpretation. Molecular docking studies, while useful for hypothesis generation and lead molecule identification, are inherently limited by the static, simplified nature of computational protein-ligand interaction models; they neither capture the dynamic conformational flexibility of viral proteins in physiological environments nor account for metabolic transformation, plasma protein binding, or tissue distribution kinetics that determine *in vivo* bioavailability. Nevertheless, the consistent identification of phytomolecules from these four species—particularly curcumin, withanolides, ursolic acid, and berberine—as high-affinity ligands for SARS-CoV-2 Mpro, RdRp, and spike protein across independent computational studies using diverse docking algorithms constitutes a sufficiently robust signal to

justify targeted in vitro and subsequent animal model validation (Khaerunnisa et al., 2020; Narkhede et al., 2020; Maurya & Bhatt, 2020).

The limited but encouraging body of clinical trial evidence—including randomized controlled trials examining Ashwagandha (Dhar et al., 2021), nano-curcumin (Hassaniazad et al., 2021; Pawar et al., 2021), and observational data on Giloy (Badar et al., 2021)—provides preliminary clinical validation of preclinical immunomodulatory findings. Across these trials, beneficial effects on inflammatory biomarkers (IL-6, CRP, TNF- α), immune cell parameters (T-cell ratios, NK cell activity), and clinical outcomes (symptom duration, oxygen saturation, hospital stay) have been documented. Nonetheless, significant methodological limitations constrain the certainty of these conclusions. Many existing clinical investigations are characterized by small sample sizes, heterogeneous patient populations, variable extract standardization, short intervention durations, limited long-term follow-up, and risk of bias in non-blinded designs. Large-scale, multicenter, phase III randomized controlled trials with rigorous endpoint adjudication, standardized phytochemical preparations, and adequate power calculations are urgently required to definitively establish the clinical efficacy and safety profiles of these agents in COVID-19.

Bioavailability represents a critical translational challenge, particularly for curcumin, whose oral bioavailability in standard formulations is estimated at less than one percent due to poor aqueous solubility, rapid intestinal glucuronidation, and hepatic first-pass metabolism. Novel drug delivery systems—including curcumin nanoparticles, liposomal encapsulations, solid lipid nanoparticles, and phospholipid complexes—have demonstrated substantially enhanced bioavailability in preclinical models and early clinical investigations, and standardization around such preparations will be essential for meaningful clinical trial interpretation (Anand et al., 2007). Similar bioavailability considerations apply to withanolides, which exhibit variable absorption kinetics dependent on formulation and food matrix interactions.

Safety considerations, while generally favorable for these traditionally consumed plants at recommended therapeutic doses, warrant explicit acknowledgment. Reports of cholestatic hepatitis associated with *W. somnifera* supplementation, albeit rare, have been documented in case series, with proposed mechanisms involving alkaloid-mediated hepatocyte injury; vigilance in patients with pre-existing hepatic dysfunction is therefore warranted (Björnsson et al., 2020). Concerns regarding potential pro-oxidant curcumin activity at supraphysiological concentrations, and *T. cordifolia*-associated autoimmune hepatitis in isolated reports, further underscore the necessity of post-marketing pharmacovigilance and dose optimization in clinical trial design.

From a public health perspective, the accessibility, affordability, and cultural acceptability of these botanical agents in regions with high COVID-19 burden—particularly the Indian subcontinent and Southeast Asia—present a compelling argument for their prioritization in complementary COVID-19 management strategies, particularly in settings where antiviral drugs and vaccines remain inequitably distributed. Equitable access to evidence-based complementary therapies may represent a meaningful component of pandemic resilience strategies for low- and middle-income countries (LMICs). The AYUSH Ministry of India's formal integration of these plants into COVID-19 clinical management protocols, while premised partly on traditional empiricism, also reflects a pragmatic, population-level risk-benefit assessment that warrants respectful biomedical engagement rather than categorical dismissal.

V. CONCLUSION

This review has systematically examined the immunomodulatory and SARS-CoV-2-relevant pharmacological properties of four well-characterized medicinal plants—*Ocimum sanctum*, *Withania somnifera*, *Tinospora cordifolia*, and *Curcuma longa*—and established a scientifically substantiated rationale for their investigation and cautious application as adjunctive agents in COVID-19 prevention and supportive management. The pharmacological evidence base, spanning molecular docking simulations, cell culture assays, animal model experiments, and preliminary clinical trials, collectively implicates active phytoconstituents including eugenol, withanolides, berberine, and curcumin in mechanisms including NF- κ B inhibition, viral protease and polymerase inhibition, ACE2 binding interference, T-lymphocyte stimulation, and macrophage activation—mechanisms directly pertinent to COVID-19 immunopathology.

However, it is essential to maintain scientific rigor in translating these findings into clinical recommendations. The existing evidence base, while promising, is insufficient in aggregate quality and clinical scale to support definitive therapeutic claims. The integration of these phytochemical agents into COVID-19 management should be pursued through well-designed, adequately powered, multicenter randomized controlled trials employing standardized botanical preparations, validated immunological and virological endpoints, and systematic safety monitoring. Concurrently, investments in phytochemical standardization, advanced drug delivery systems to overcome bioavailability barriers, and mechanistic studies clarifying *in vivo* immunomodulatory activity under COVID-19-specific physiological conditions are imperative.

Ultimately, the utility of medicinal plants as immune boosting agents in the context of COVID-19 lies not in their replacement of evidence-based antiviral and anti-inflammatory therapies, but in their potential to complement and reinforce these approaches—particularly in resource-constrained settings and as components of integrative medicine strategies that respect the totality of available evidence, including the cumulative empirical wisdom of traditional medical systems. A convergent, interdisciplinary research agenda bridging ethnopharmacology, molecular biology, immunology, and clinical medicine represents the most productive path toward fully characterizing and ethically deploying the immunomodulatory potential of the plant kingdom in humanity's ongoing response to COVID-19 and future pandemic threats.

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