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Review

The Beneficial Elements in Forest Environment Based on Human Health and Well-Being Perspective

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Abstract: Illness is a significant global societal issue in the 21st century. Forest, as an important part of terrestrial ecosystem, holds substantial health and well-being benefits. People can gain health benefits from interacting with forests, even for short periods. Unfortunately, there is a lack of systematic concern regarding the beneficial elements that forest provides to humans. In this study, a systematic review and meta-analysis were conducted following established guidelines, comprehensively evaluating the beneficial elements of the forest environment. The results indicated that the beneficial forest elements relevant to human health include beneficial substances (clean air, high-quality freshwater, CO_2/O_2 balance, negative air ions, and phytoncides) and beneficial factors (moderate thermal environment and biodiversity). These beneficial forest elements are products of plant's physiological processes. While their production pathways are relatively well understood, the mechanisms by which these elements impact health are unclear. This review provided the foundational data and theoretical insights for future research on the health benefits of forest elements.

Keywords: forest elements; forest therapy; urban forest; urban green space; human health and well-being; mental health; health mechanism

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1. Introduction

Significant global health challenges exist in the 21st century [1]. Illnesses such as obesity, cardiovascular disease, insomnia, mood disorders, and cognitive disorders are major societal problems worldwide. The world urbanization prospects: the 2018 revision: highlights showed that 55% of the world's population lived in urban areas in 2018; in 1950, 30% of the population was urban, and by 2050, 68% of the world's population is predicted to be urban [2]. These data showed that urbanization was accelerating and that health challenges would become more severe in the future. Diseases in cities are caused by a variety of factors. Previous research has confirmed a strong correlation between these health issues, the absence of natural elements in urban environments, and the reduction in people's daily exposure to nature [3,4].

As an important part of the terrestrial ecosystem, forests are rich in material resources and form a good ecological environment, which provides the basic survival guarantee for the entire global terrestrial life [5]. In recent years, the health-promoting function of forest environments has received people's attention. Studies have confirmed consistent negative associations between forest environments and human mortality, as well as violent behavior and positive associations with attention, mood, sleep quality, and physical activity [6–10]. Furthermore, current research generally agrees that people gain health and well-being benefits from forests in various forms (such as nature exposure, nature connectedness, and guided forest activities), even for short periods [11–13]. With the support of a number of studies, many countries around the world have carried out alternative therapy activities that benefit human health in forest environments. These activities are generally referred to as forest therapy [14,15]. Forest therapy has currently played an important role in improving human health, especially mental health. Moreover, it is noteworthy that the forest ecosystem also faces some environmental problems, such as pollution, land use change, natural disasters, etc. [16–18]. Obviously, the existence of these problems will damage forests and then impact human health. A variety of research results have been obtained in this field. The beneficial elements in forests have a more direct effect on human health and well-being. Unfortunately, in the past, the attention in this field has primarily focused on the function of forest ecosystems, and there has been an overlooking of the elements themselves. There is a lack of awareness and systematic summary regarding the beneficial elements that forest provides to human health. Although the function is a critical aspect and evaluation basis of elements [5,19], a specific ecological function of forests is frequently determined by particular elements or a combination of multiple elements. From the perspective of forestry managers, clarifying the beneficial forest elements is essential for better managing non-timber forest systems that provide ecological services.

Therefore, this study focuses on the forest elements that directly impact human health and excludes the functions produced by these elements. First, the elements were identified, and the available evidence was systematically reviewed. Moreover, the ways in which these forest elements produce health effects were discussed, and their mechanism of action was then explored. This review can provide the foundational data and theoretical insights for future research on the health benefits of forest elements.

2. Materials and Methods

In this study, the beneficial forest elements were defined as the capacity of the forest environment to provide ecological services that support life on Earth and contribute directly or indirectly to human health and well-being. Based on the keywords, such as forests, urban forests, urban parks, urban green spaces, health, health and well-being, psychological, physical, health factors, health elements, health components, and health substances, a systematic review and meta-analysis was conducted in March 2024. The searches were restricted to the year between January 1990 and December 2023.

By searching for these terms independently or in combination in PubMed, Web of Science, ScienceDirect, and Scopus databases, 158 articles were identified in the initial database. In order to ensure the accuracy, reliability, and completeness of the literature, we selected potentially relevant papers through the following procedures: (1) screening the title, (2) screening the abstract, and (3) searching and screening the full text when the abstract did not provide sufficient data or was unavailable, leaving 67 papers. In addition, scientific readings were carried out, and the literature that studied only about forests, only about health, or no control condition was excluded. A total of 31 papers were used in this review.

The number of studies was too small to conduct a meta-analysis. After reviewing the literature, the beneficial forest elements relevant to human health were divided into two aspects: beneficial substances (clean air, high-quality freshwater, CO_2/O_2 balance, negative air ions, and phytoncides) and beneficial factors (moderate thermal environment and biodiversity).

3. Results

3.1. Beneficial Substances

The beneficial substances in the forest environment refer to the particular kind of matter that positively affects human health and well-being, which absence or even slight fluctuation can bear on human health. In the review, the beneficial substances include clean air, high-quality freshwater, CO_2/O_2 balance, negative air ions, and phytoncides (Table 1).

Table 1. Beneficial substances bearing on human health and well-being.

Beneficial Substances	Ecological Services	Pathway	Citations
Clean air	Plants in the forest environment play an important role in ameliorating air pollution and improving human health.	(1) Affecting the diffusion of air pollutants; (2) Trapping particulate matter; (3) Absorbing and storing air pollution.	Nowak et al., 2014 [20] Manes et al., 2016 [21] Bagheri et al., 2017 [22] Nowak et al., 2018 [23] Almeida et al., 2020 [24] Azwardi et al., 2021 [25]
High-quality freshwater	Forests are natural water purifiers, providing an important ecological service that improves human health.	(1) Filtering solid pollutants in runoff; (2) Precipitating and degrading organic pollutants; (3) Absorbing nutrient ions.	Cunha et al., 2016 [26] Shah and Nisbet, 2019 [27] Kumarasiri et al., 2021 [28] Piaggio and Siikamki, 2021 [29]
CO_2/O_2 balance	Forest plants regulate the balance between O_2 and CO_2 by absorbing CO_2 and releasing O_2.	(1) Photosynthesis; (2) Respiration.	Fang et al., 2001 [30] Tang et al., 2018 [31] Wen et al., 2018 [32] Green and Keenan, 2022 [33]
Negative air ions	NAIs are known as "air vitamins" and directly benefit human health.	(1) Photosynthesis in forests' canopies; (2) Electrolysis of air from branches and leaves; (3) Air ionization from volatile substances released by plants; (4) Surviving for a long time in the forest environment.	Yan et al., 2015 [34] Miao et al., 2018 [35] Wang et al., 2020 [36]
Phytoncides	Phytoncides are aromatic volatile substances emitted by the organs and tissues of plants.	The release of phytoncides is closely related to the physiological activities of plants.	Yang et al., 2010 [37] Li, 2013 [38] Kim et al., 2020 [39]

3.1.1. Clean Air

Air pollution is a significant global problem affecting human health and well-being. Common air pollutants include carbon monoxide (CO), nitrogen dioxide (NO_2), ozone (O_3), sulfur dioxide (SO_2), and particulate matter less than 2.5 µm ($PM_{2.5}$) and 10 µm (PM_{10}) [23]. In 2005, there were approximately 130,000 deaths related to $PM_{2.5}$ pollution and around 4700 deaths related to O_3 pollution in the United States [40].

Living plants in forest environments play an important role in ameliorating air pollution. While it is true that the pollen of some plants can cause allergies, volatile organic compounds (VOCs) released by some plants may contribute to the formation of other pollutants, such as O_3 and $PM_{2.5}$ [23]. Studies indicate that plants have net benefits for air quality. Trees can alter wind speed and direction, affecting the diffusion of air pollutants while trapping particulate matter on their surfaces [24]. These trapped pollutants are then washed to the ground with precipitation. Plants continuously absorb gaseous air pollution, storing these compounds in their tissues through physiological metabolism. Tree canopies, particularly those with hairy leaves or dense needles, play a crucial role in this process [41].

Much research has focused on the role of urban forests in mitigating air pollution and improving human health. Almeida et al. found that over nine months, PM_{10} concentrations (70.9 ± 10.3 µg m^{-3}) and NO_2 (34.3 ± 5.2 µg m^{-3}) near heavily trafficked urban roads were significantly higher than those in nearby urban forests (37.2 ± 4.2 µg m^{-3} and 18.1 ± 3.1 µg m^{-3}) [24]. Epidemiological surveys indicated that the frequency of respiratory symptoms among children was three times higher in schools near highways or roads than in schools near urban parks. Using simulations based on local environmental data, Nowak et al. estimated that trees and forests in the United States removed 17.4 million tonnes of air pollutants in 2010, saving 6.8 billion U.S. dollars in health costs and preventing more than 850 incidences of human mortality and 670,000 incidences of acute respiratory symptoms.

They also estimated that trees in 86 Canadian cities removed 16,500 tonnes of air pollutants in 2010, saving 227.2 million Canadian dollars in human health costs and preventing 30 deaths and 22,000 incidents of acute respiratory symptoms [20,22]. Manes et al. estimated that in 2003, periurban forests in 10 cities in Italy sequestered 7150 Mg PM_{10} and 30,014 Mg O_3 valued at 47 million USD and 297 million USD, respectively [21].

Other studies have extended beyond simply urban forests to demonstrate the effects of green vegetation on reducing pollution. Bagheri et al. found a significant negative correlation between green patches and air pollution levels, indicating that the reduction of green patches would exacerbate air pollution [22]. Another national-level study analyzed the effect of forest area on air pollution in 33 Indonesian provinces from 2010 to 2017 and found that forests reduced air pollution in all regions, with any increase in forest area leading to improved air quality [25].

3.1.2. High-Quality Fresh Water

Freshwater resources around the world have faced significant pressure in recent decades due to climate change and human activity. A study indicates that only 40% of surface water bodies in Europe are in a good ecological state, including in boreal areas, which hold a large share of the world's freshwater wetlands [42]. Natural causes of water quality decline are primarily attributed to sediment runoff and erosion from disturbances such as high-intensity wildfires [28,43]. In anthropogenic environments, pollutants from industrial wastewater, atmospheric deposition of waste gas, and agricultural chemicals are the main contributors to water quality degradation. Human impacts on water quality are also evident in the forest environment, which has been extensively altered by human activities worldwide.

Artificial water purification often employs chemicals that can sometimes pollute drinking water. In contrast, forests act as natural water purifiers, providing an essential ecological service that enhances human health. Forests improve water quality by reducing soil erosion, filtering solid pollutants in runoff, precipitating and degrading organic pollutants, and absorbing nutrient ions such as nitrogen (N) and phosphorus (P) [29]. Pollutant concentrations in runoff from forests are lower than those from industrial, urban, and agricultural land use types [44]. A study conducted in Sao Paulo, Brazil, showed that the average turbidity in forested watersheds was 5–6 times lower than in industrial/urban and agriculture areas [26]. Kumarasiri et al. found a significant negative correlation between forest cover and nitrate nitrogen level (r^2 = 0.521, p = 0.008) in 12 water basins of the Samanalawewa watershed in Sri Lanka [28]. Piaggio and Siikamki observed that forest cover significantly improved water quality and reduced the amount of chemicals needed to supply drinking water, based on six years of monthly samples from water treatment plants in Costa Rica. They estimated that forests could provide water purification services worth up to 9.50 USD per hectare per year, with the value of this service inversely proportional to the catchment area. Another study found that deforestation increased levels of water phosphate, dissolved organic carbon (DOC), and suspended sediment [27].

3.1.3. CO_2/O_2 Balance

As a crucial product of photosynthesis, oxygen (O_2) is essential for the survival of all aerobic life forms on Earth [45]. Evidence from paleogeological studies indicates that O_2 was a significant driver of the evolution of life on Earth [46]. During the Great Oxidation Event (GOE) between 2.45 and 2.22 billion years ago, aerobic organisms capable of aerobic respiration gradually replaced anaerobic organisms that thrived without O_2, becoming the dominant life forms on Earth [47]. Aerobic respiration produces more energy, significantly accelerating the rate of evolutionary processes [48,49]. A doubling of O_2 levels around 205 million years ago facilitated the evolution of placental mammals [50]. Simultaneously, CO_2 levels in the Earth's atmosphere were low, but CO_2 was also critical for climate regulation, ecological balance, and the evolution of life. Driven by the physiological processes of photosynthesis and respiration, Earth's ecosystem gradually stabilized, forming a relatively balanced state between O_2 and CO_2. This prolonged stability allowed life on Earth to flourish, eventually leading to advanced civilizations, including humans.

Since the Industrial Revolution, the concentration of CO_2 has been gradually increasing. Carbon originally sequestered in fossil fuels has been rapidly released into the atmosphere in the form of CO_2. Meanwhile, the destruction of forests has significantly limited the efficiency of carbon fixation [51]. CO_2 is a greenhouse gas, and rising CO_2 concentrations pose a series of environmental problems, including enhanced greenhouse effect, climate warming, and sea level rise [52]. While it is true that plant growth may increase as a result of higher CO_2 levels due to improved photosynthetic efficiency and potentially increased solar radiation from reduced cloud driven by climate change, this effect is not sufficient to offset the broader negative impacts. Indeed, from 1982 to 1999, net primary production (NPP) worldwide increased by 6% (3.4 Pg C) [53]. However, with the acceleration of global urban expansion, the replacement of natural vegetation with impervious surfaces, and alterations to biogeochemical cycles, it is likely that global land NPP will decline. One study showed that urban sprawl resulted in a net loss of 22.4 Tg C per year between 2000 and 2010 [54].

The disruption of the balance between O_2 and CO_2 can have serious effects on human health and survival. Plants naturally regulate this balance by absorbing CO_2 and releasing O_2 through photosynthesis and respiration [32,33]. A study on changes in forest biomass carbon stocks in China between 1949 and 1998 showed that, since the late 1970s, carbon stocks have increased from 4.38 Tg C to 4.75 Tg C in 1998, with an average annual Carbon accumulation rate of 0.021 Tg C. This increase is mainly due to the national afforestation program initiated in the mid-1970s [30]. Another survey of carbon stocks in China's terrestrial ecosystems from 2011 to 2015 indicated that the total carbon pool in forests, shrublands, grasslands, and croplands was 79.24 ± 2.42 Pg C. It is estimated that 1.9–3.4 Pg C could be sequestered in forest biomass over the next 10–20 years, assuming no removals, primarily due to forest growth [31]. Therefore, it is evident that forests, through their energy flow and material circulation processes, can maintain a balance between O_2 and CO_2 to some extent, buffering human disturbances to biogeochemical processes.

3.1.4. Negative Air Ions (NAIs)

Abundant negative air ions (NAIs) exist in forest environments, especially in places with a lot of splashing, such as waterfalls and mountain streams [34]. NAIs are known as 'air vitamins' because they absorb dust, clean air, and generally improve air quality [55]. NAIs were first discovered independently by Elster and Geitel in Germany and Thomson in England at the end of the 19th century [56]. Over the next century of research, NAIs were reported to trigger a variety of physiological and biochemical responses, including altering the concentration of serotonin and cyclic nucleotides in the cerebral cortex of rats, inhibiting the growth of microorganisms, and preventing the spread of diseases in animal pens [55]. Many studies demonstrated that NAIs are directly beneficial for human health by improving neuropsychological performance, enhancing cardiac autonomic nervous function, and treating mood disorders [57,58]. A controlled trial was conducted at Hollins University in Roanoke, USA, to evaluate the effectiveness of exposure to high-density NAIs for 30 or 60 min a day over 18 days on symptoms of seasonal affective disorder (SAD). The results showed exposure to high-density NAIs was superior to zero-density NAIs in alleviating depression and the atypical symptoms of SAD. Both the short and long daily exposure reduced SAD symptoms within the high-density treatment group [59].

In a forest environment, NAIs are mainly produced by the initial ionization of neutral gas molecules. The energy required for this ionization mainly includes cosmic rays and ultraviolet radiation, electrostatic force, photoemission, photosynthesis, waterfall impact, storms, lighting excitation, and so on [55]. Forests often provide ideal conditions for the production of NAIs due to photosynthesis in the forest canopy, electrolysis of air from branches and leaves, and air ionization from volatile substances released by plants. NAIs can survive for a relatively long time in a forest environment [34]. Conversely, environmental pollutants such as NO_X, SO_2, and $PM_{2.5}$ found in urban environments decrease the concentration of NAIs [34,35]. One study found that NAI concentrations in forests (2871 ions cm^{-3}) were significantly higher than those in open spaces (843 ions cm^{-3}) [36]. It is interesting to note that another study found that NAI concentration differed among forest types. The average NAI concentration in natural forests was 3759 ions cm^{-3}, with a maximum value of 5000 ions cm^{-3}. In contrast, the average NAI concentrations in economic forests and greenbelts were all significantly lower (<1900 ions cm^{-3}) [34].

3.1.5. Phytoncides

Phytoncides are aromatic volatile substances derived from trees, including monoterpenes and sesquiterpenes, such as α- and β-pinene, 3-carene, limonene, and terpinene [60,61]. Phytoncides were first discovered in 1928 by Boris P. Tokin, a Russian biochemist [62]. These compounds not only protect plants from bacteria, fungi, parasites, and herbivores but also have positive effects on human health [63,64]. One study found that tree-derived phytoncides significantly increased natural killer (NK) cell activity and perforin content in humans while significantly decreasing the percentage of T cells. Overall, phytoncides significantly enhance human immune function [60,65]. In addition, α-Pinene, a phytoncide from pine trees, was found to have a sleep-enhancing effect on mice by acting as a positive modulator for the GABAA-BZD receptor [66]. Another phytoncide, 3-carene, exhibited similar efficacy [61].

While the health benefits of phytoncides for humans are well established, the mechanism by which phytoncides improve human health remains unclear. Phytoncides are gaseous organic substances emitted by the organs and tissues of forest plants in their natural state [39]. Most studies on the composition and efficacy of phytoncides have focused on conifers, such as pines and cypress [37]. There are fewer studies on the efficacy of phytoncides from broadleaf trees. Although phytoncides can be extracted from the bark, branches, and leaves of trees, the effects of exposure to extracted phytoncides indoors may differ from those of exposure to natural phytoncides in situ. Admittedly, there is insufficient evidence to support the difference in the health effects of these two methods (exposure to forest or indoor addition of essential oils). In a forest environment, the release of phytoncides is generally believed to be closely related to the physiological activities of plants. Therefore, the concentration of phytoncides will exhibit seasonal variations tracking the growth and dormancy of plants and will be spatially concentrated toward the interior of forests rather than at their edges [38]. In general, further systematic study is needed on the spatio-temporal patterns of phytoncide production in a forest environment and the mechanistic link between phytoncides and human health.

3.2. Beneficial Factors

The beneficial factors in the forest environment refer to non-material components that contribute to human health and well-being, and their absence is equally important to health as the beneficial substances. In this study, the beneficial factors include moderate thermal environments and biodiversity (Table 2).

Table 2. Beneficial factors bearing on human health and well-being.

Beneficial Factors	Ecological Services	Pathway	Citations
Moderate thermal environment	A forest environment dominated by trees has more moderate temperatures.	(1) Shading; (2) Cooling effects from evapotranspiration; (3) Low thermal conductivity of biological materials.	USGCRP, 2017 [67] Dimoudi et al., 2013 [68] Huang et al., 2020 [69] Yuan et al., 2020 [70]
Biodiversity	Biodiversity is critical to the ability of ecosystems to sustain society.	All of these life forms in forests together make up the biodiversity of the Earth.	Marselle et al., 2021 [71] Methorst et al., 2021 [72] Wei et al., 2022 [73]

3.2.1. Moderate Thermal Environment

Heat in the body arises from muscle activity and results from aerobic activity and exercise intensity. Once produced by muscles, excess heat must be transferred from the body to the environment [74]. In overly hot or cold environments, heat transmission is hindered or reversed, causing discomfort for the human body.

Compared to man-made environments, forest environments dominated by trees tend to have more moderate temperatures due to shading and cooling effects from evapotranspiration [75]. The USGCRP reported that daytime air temperatures in American cities were 0.5~4.0 °C higher than those in the nearby rural areas and that nighttime air temperatures were 1.0~2.5 °C higher [67]. An analysis of microclimates in urban street canyons in Northern Greece showed that afternoon and night air temperatures were about 5.0 to 5.5 °C higher than in suburban areas [68]. Another study in Wuhan, China, found that afternoon air temperatures and mean radiant temperatures in streets with high tree canopy cover were 3.3 °C and 13.9 °C lower than in similar streets with no tree shade [69].

Building materials in cities, such as asphalt and concrete, have high thermal conductivity and heat capacity. Combined with an urban configuration that affects shading and airflow, this leads to heat being stored in building materials during the day and slowly released at night [76]. As a consequence, overall temperatures in urban environments remain elevated. The use of indoor cooling equipment also aggravates the heat island phenomenon. Moreover, the high thermal conductivity of non-biological materials causes the urban environment to release more heat, resulting in larger daily and seasonal temperature variations compared to urban green space [68,77]. For instance, one study showed that increasing tree cover to about 80% could achieve an average cooling of 2.1 °C in Singapore [70].

3.2.2. Biodiversity

The diversity of life on Earth is extraordinary, encompassing nearly 9 million species [78]. All of these life forms, including humans, together constitute Earth's biodiversity. The Convention on Biological Diversity (CBD) defines biodiversity as 'the variability among living organisms from all sources including, inter alia, terrestrial, marine, and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species, and of ecosystems' [79]. Many scientists have declared that the loss of biodiversity poses an existential threat to the ability of ecosystems to sustain society. Furthermore, the potential threats of species extinction are difficult to estimate [80,81].

To date, the direct impacts of biodiversity on human health are still being characterized. Marselle et al. argue that biodiversity is a cornerstone of human health and well-being, presenting a conceptual framework linking biodiversity to human health via four pathways: (i) reducing harm, (ii) restoring capacities, (iii) building capacities, and (iv) causing harm [71]. A cross-sectional analysis in Germany found a significant positive relationship between plant and bird species richness and mental health [72]. Wei et al. found that relatively more smiles were elicited in urban parks with diverse shrubs and herbs than in urban parks with lower diversity [73]. These studies highlight the importance of species diversity for mental health and well-being. However, it is worth noting that higher species biodiversity does not necessarily mean greater density. Some studies suggest that dense green spaces in highly urbanized areas by some people are dangerous due to providing cover for criminal activity [82,83].

As mentioned above, forest environments contain multiple elements, and although quantitative studies are somewhat deficient, there is sufficient research evidence to confirm that the existence of the forest elements provides essential health support and even survival. This aligns with traditional knowledge and existing research. The forest is the basis of the terrestrial ecosystem, maintaining the material cycles and energy flows within the entire Earth's ecosystem. The role of forest elements in promoting human health is an aspect of ecological function, and the extent of their health contributions is determined through human evaluation rather than inherent properties. In addition, the various forest elements that benefit human health are often by-products generated by plants to meet their own survival needs or to adapt to stress. In other words, these elements are unintentional gifts of forests. This perspective underscores the interdependence of people and nature, highlighting the organic unity of the entire ecosystem.

4. Conclusions

Beneficial forest elements relevant to human health include beneficial substances (clean air, high-quality freshwater, CO_2/O_2 balance, negative air ions, and phytoncides) and beneficial factors (moderate thermal environment and biodiversity). These beneficial forest elements are products of plant's physiological processes, primarily aimed at their own survival, yet they also play a significant role in human health. Additionally, existing research has elucidated the mechanisms by which these beneficial forest elements are produced. However, the exact processes through which these elements exert their health effects remain unclear, and most studies have not assessed the health effects of combinations of two or more elements. A further in-depth investigation is needed from the following aspects: (1) the mechanism of how beneficial elements promote human health needs to be further studied, (2) the health benefits produced by multiple combinations of different elements need to be comprehensively evaluated, and (3) the dose of beneficial elements to health benefits still needs to be quantified.

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