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Air Pollution and Skin Aging

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Aim of the study:
The aim of this article was to review the impact of air pollution on skin aging, with a focus on its mechanisms, such as oxidative stress, inflammation, and microbiome disruption, as well as potential therapeutic strategies.

Materials and Methods:
A literature review was conducted using the "PubMed", Google Scholar, and Medline databases, with keywords including "air pollution", "skin aging", and "oxidative stress".

Results and conclusions:

Air pollution accelerates skin aging through oxidative stress and inflammation, contributing to wrinkles, hyperpigmentation, and skin barrier disruption. Antioxidants, moisturizers, and UV protection can help mitigate some effects, but further research is needed to explore long-term strategies and personalized approaches to prevent pollution-related skin damage.

ABSTRACT

Air pollution is a leading environmental health risk worldwide, with detrimental effects not only on human health but also on skin aging. This review explores the link between air pollution and skin aging, focusing on the harmful effects of particulate matter (PM) and other pollutants such as polycyclic aromatic hydrocarbons (PAHs), nitrogen oxides (NO2), and ozone (O3). These pollutants penetrate the skin, inducing oxidative stress and inflammation, which accelerates the degradation of collagen and elastin in the extracellular matrix. This contributes to premature aging, wrinkles, hyperpigmentation, and inflammatory skin conditions. The smallest fractions of PM, particularly PM2.5, are the most harmful, causing significant cellular damage. Long-term exposure to these pollutants also disrupts the skin's microbiome, leading to dysbiosis and further weakening the skin's protective barrier. Current therapeutic strategies focus on protecting the skin using antioxidants, such as Vitamin C and Vitamin E, as well as probiotics and moisturizers that support the skin's natural defenses. Sunscreens also play a vital role in protecting the skin from UV-induced oxidative stress, further mitigating pollution-related damage. This review highlights the importance of developing comprehensive skincare regimens that target both pollution-induced oxidative stress and the maintenance of a healthy skin barrier. It also emphasizes the need for further research into personalized approaches to counteract the aging effects of air pollution on the skin.

Keywords: air pollution; skin aging; particulate matter (PM); oxidative stress; inflammation; antioxidants; UV radiation

INTRODUCTION

Air pollution is recognized as the largest environmental health risk worldwide, significantly harming human health. Declining air quality is largely driven by rapid urbanization and population growth, with developing countries being the hardest hit [1]. Atmospheric contamination, a key factor in the global rise of non-communicable diseases, is largely driven by particulate matter (PM). These microscopic particles, containing a blend of harmful chemicals and biological elements, can seriously impact human health [2]. PM induces inflammation through its absorption by tissue-resident immune cells, triggering proinflammatory pathways across different cells and organs. This results in the release of cytokines, which can affect the function of organs even at distant sites [3].

As the largest organ, the skin provides crucial protection against external elements that may disrupt bodily functions. Together with the respiratory and oral pathways, it acts as a key route for chemical entry into the body [4]. The skin serves as the body's foremost defense against environmental hazards such as air pollution and UV radiation. Airborne pollutants primarily affect the uppermost layer of the epidermis, making it one of the first areas to be affected by damage [5]. Airborne pollutants may result in a range of skin-related conditions, such as premature aging, disturbances in the skin's microbiome, heightened inflammatory responses (such as allergies, acne, atopic dermatitis, and eczema), and potentially even cancer [6]. Skin aging is affected by various environmental toxins, including pollutants in the air and water, exposure to LED light, electromagnetic fields, fungi, parasites, mold, and heavy metalS. Standard skincare products alone are inadequate for shielding the skin and body from these daily stressors [7].

The purpose of this review is to examine the link between air pollution and skin aging, outlining potential underlying mechanisms and exploring emerging therapeutic strategies based on this connection.

SKIN AGING

Skin aging can result from natural aging (intrinsic) and prolonged exposure to external factors (extrinsic). Aging occurs due to changes in the structure and composition of dermal extracellular matrix proteins [8]. As skin ages, it exhibits fine wrinkles, tissue atrophy, and a noticeable reduction in elasticity [9].

Multiple environmental factors contribute to extrinsic skin damage, such as ionizing radiation, prolonged psychological and physical stress, high alcohol consumption, poor dietary habits, overeating, pollution, and UV radiation exposure. Among these, UV radiation is estimated to account for up to 80% of the damage [10]. Harmful UV radiation accelerates the production of reactive oxygen species (ROS) and heightens the risk of skin cancer. It also causes the breakdown of key extracellular matrix components, including collagen type I, fibronectin, elastin, and proteoglycans. The degradation of these proteins is influenced by the upregulation of the mitogen-activated protein kinase (MAPK) signaling pathway [11]. Photoaging results in structural changes in the skin, including compromised stratum corneum integrity, altered skin thickness, reduced hydration, and decreased lipid levels. These changes contribute to the development of wrinkles and sagging skin [12].

Intrinsic aging, also known as chronological aging, is shaped by factors such as cell senescence, oxidative damage, and the involvement of specific metalloproteinases (MMPs) [13]. In the human dermis, intrinsic aging presents through several changes: collagen depletion, which causes dermal thinning; weakening of the elastic fiber network; and decreased moisture content in the skin [14]. Oxidative stress is a significant factor in the skin, contributing to both intrinsic and extrinsic aging processes [15]. Degradation of the extracellular matrix (ECM) occurs due to changes in senescent cells and ROS, which lead to higher levels of matrix MMps that break down collagen [16].

AIR POLLUTION

Air pollution consists of a diverse blend of gasses and particles, which come from both stationary and mobile sources. These pollutants may either be released directly (primary emissions) or develop in the atmosphere (secondary emissions) [17].

Particulate matter (PM) is composed of diverse components originating from various sources such as traffic, biomass combustion, waste incineration, industrial processes, long-range air pollution, road wear, resuspension of dust, car brake debris, and soil erosion [18]. The harmful effects of particulate matter are likely linked to certain substances it contains, such as polycyclic aromatic hydrocarbons (PAHs), gases like nitrogen oxides, sulfur oxides, ozone, heavy metals including chromium, arsenic, lead, manganese, mercury, as well as microorganisms [19]. Air particles are classified as fine (PM2.5) and coarse (PM10). Fine particles often result from combustion, while coarse particles are generated by mechanical processes that release dust. The smallest PM fractions, especially those below PM10, are the most toxic, with higher levels of extractable organic matter and greater radical-generating potential. These smaller fractions also show stronger correlations between their chemical composition and toxicity [20]. Under specific atmospheric conditions, secondary pollutants like ozone and peroxyacetyl nitrates (PANs) can form through photochemical reactions involving primary pollutants, heat, and solar ultraviolet (UV) radiation [21].

AIR POLLUTION AS A FACTOR IN SKIN AGING

One study discovered that pollutants can reach the skin either through direct accumulation on its surface or via the bloodstream following inhalation or ingestion. PAHs have been detected in the air, as well as in human bodily fluids and hair, serving as valuable indicators for assessing the impact of airborne pollution on skin health and diseases [22]. Skin aging is linked to oxidative stress, inflammation, and damage to both the cutaneous barrier and the extracellular matrix, all of which are caused by pollution [23]. Research showed that dust particles stimulated the production of cytokines IL-6, IL-8, and GM-CSF, which play important roles in inflammation and immune response. Additionally, caspase 14 expression was notably elevated in human epidermal keratinocytes cells, indicating that dust particles may directly impact keratinocyte differentiation [24].

Epidemiological research has revealed that PM plays a crucial role in both the development and worsening of skin diseases. By stimulating the production of ROS, PM induces oxidative stress and triggers the release of pro-inflammatory cytokines, including TNF-α, IL-1α, and IL-8 [25]. Particles in PM are thought to cause lipid oxidation, likely due to the presence of metals, leading to elevated levels of cyclooxygenase 2 and cytochrome P450, both of which play a role in initiating the inflammatory response triggered by PM [26]. Extended exposure to air pollutants can negatively impact skin health by generating free radicals, triggering inflammation, and compromising the skin's natural barrier. For example, continuous contact with ozone (O3) leads to oxidative stress in the skin's outer layer, resulting in the production of free radicals [27]. O3 exposure reduces antioxidant levels and affects oxidation markers in the outer skin layer, while also initiating stress responses in deeper skin cells [28]. Exposure to air pollutants also depletes key skin antioxidants such as Vitamin E and Squalene, reduces ATP levels, and increases oxidized proteins. These changes contribute to keratinocyte hyperproliferation and stimulate the release of inflammatory cytokines [29].

Furthermore, epidemiological studies have revealed a clear connection between exposure to traffic-related air pollution and the appearance of clinical symptoms of skin hyperpigmentation [30]. In one study, increased contact with soot was linked to more pronounced pigment spots and wrinkles. Researchers suggest that PAHs are the primary contributors to skin aging, as their lipophilic nature allows them to pass through the skin barrier with ease. PAHs also activate the aryl hydrocarbon receptor (AhR), which is known to promote both pigment formation and wrinkle development [31]. Dioxins and ozone are also activators of AhR, contributing to the mediation of the biochemical and toxic effects of air pollutants, impacting cellular processes like development and cell specialization [32]. PM and NO2 showed the strongest connections to external skin aging through the formation of pigment spots, with a less noticeable link to wrinkles. On the other hand, exposure to elevated ozone (O3) levels was linked to the appearance of coarse facial wrinkles, but no association was observed with pigment spots [33]. Additionally, ozone (O3) showed a strong positive association with increased texture irregularities and enlarged pore size [34]. In individuals exposed to heavily polluted environments or smokers, the acceleration of photoaging is undeniably exacerbated by particulate matter and PAHs [35].

Long-term exposure to air pollutants can lead to significant changes, including an increase in both the diversity and abundance of the facial bacterial microbiome, as well as alterations in metabolic pathways [36]. In one study, the quantification of PAHs indicated a significant reduction in the prevalence of skin commensal microorganisms, alongside an increase in oral bacteria populations [37]. This shift in microbial composition may suggest an impact of PAH exposure on the skin microbiome, potentially leading to dysbiosis and affecting overall skin health.

THERAPEUTIC STRATEGIES FOR AGING SKIN BARRIER

The drive to sustain healthy and resilient skin as it ages has prompted growing interest in cutting-edge therapeutic approaches. Among these, a noteworthy focus is the combination of appropriate moisturizers, antioxidants, probiotics, prebiotics, postbiotics, and strong UV protection. This innovative strategy holds potential in fortifying the skin's barrier against the effects of aging [38].

To protect the skin from pollution, it's important to use a gentle cleanser to remove particulate matter, apply antioxidants to prevent or reverse toxic effects, and restore the skin's barrier function with a moisturizing cream [39]. A twice-daily regimen is recommended: the morning cleanse helps build a protective shield, while the evening cleanse focuses on deeply removing pollutants and should be more thorough [40].

Anti-aging creams formulated for the face, eyes, and lips are specifically designed to minimize the appearance of fine lines and deeper wrinkles [41]. Moisturizing creams that affect the skin's barrier can focus on several key areas. One of these is the intercellular lipid bilayers, where alterations in lipid composition or organization may shift the balance of lipids in the fluid phase. Another area of focus could be the size of the corneocytes or the thickness of the stratum corneum, both of which can influence the skin's ability to retain moisture and maintain its protective barrier [42]. The proper use of a moisturizer aims to enhance the skin's natural barrier, providing protection against both internal and external irritants, thereby promoting overall skin health [43]. Moisturizers play a key role by providing humectants, which pull moisture into the skin from the environment and deeper layers, as well as occlusives, which form a barrier to prevent water loss. Most formulations combine humectants, like hyaluronic acid, urea, and allantoin, with occlusives such as petrolatum, mineral oil, and lanolin. Traditional moisturizers, often used to treat dry, photoaged skin, include ingredients like glycerin, propylene glycol, urea, lactic acid, hyaluronic acid, panthenol, and proteins from sources like wheat, rice, and soy [44].

Avoiding sun exposure remains the most effective and controllable measure to minimize the generation of ROS and prevent photo-aging [45]. The study showed notable improvements in skin texture, clarity, and pigmentation after using a broad-spectrum, photostable sunscreen, with all participants benefiting. Regular use of such sunscreen can prevent future damage and reduce existing photodamage [46].

The use of antioxidant-rich formulations can help mitigate oxidative stress in the epidermis by decreasing ROS production and supporting the skin's natural antioxidant defenses, which are often weakened under stress [47]. Supplementing the skin with antioxidants has been shown to enhance protection from sun damage, slow aging, reduce inflammation, and improve skin appearance [48]. By promoting the synthesis of extracellular matrix and basement membrane proteins, Vitamin C has the potential to improve the morphogenesis of the dermal-epidermal junction [49]. Many skincare products incorporate topical vitamin C to address skin aging by protecting against free radical damage, promoting collagen production, and reducing the appearance of hyperpigmentation [50].Vitamin C offers protection against UV damage, visibly reducing erythema and sunburn. It works through various mechanisms, primarily by neutralizing free radicals generated by UV exposure and pollution, thanks to its antioxidant properties [51]. The subsequent active substance glutathione safeguards the intracellular environment, while vitamin E and ubiquinol help preserve the integrity of cellular membranes [52]. Vitamin E protects against UV damage by neutralizing lipid free radicals and its anti-inflammatory effects enhance photoprotection while reducing post-inflammatory hyperpigmentation [53]. Applying vitamin E topically has been demonstrated to reduce the appearance of fine lines and wrinkles, resulting in smoother skin [54]. Topical zinc, in the form of divalent ions, is believed to offer antioxidant protection through two key mechanisms. It can either substitute reactive metals such as iron and copper in proteins and cell membranes, or trigger the production of metallothionein, a protein that helps neutralize free radicals [55]. Polyphenols in green tea act as a photoprotective antioxidant and could help prevent photoaging and skin cancers. Both topical application and oral intake of these polyphenols have been shown to inhibit skin cancer development caused by UV radiation or chemical carcinogens [56]. Ferulic acid, another powerful antioxidant found in plant cell wall membranes, protects against lipid peroxidation while also providing mild UVB protection as a weak sunscreen [57].

Maintaining the stability and integrity of the skin's microbial community is crucial, as it helps regulate the skin's biophysical and biochemical properties. Enhancing the balance of this microbial community could be an effective approach for promoting skin health [58]. Probiotics and prebiotics support the skin's microbiota by optimizing, maintaining, and restoring its balance. Topical probiotic applications strengthen the skin's defense barriers directly at the application site. Both probiotics and the skin's natural bacteria can produce antimicrobial peptides that enhance immune responses and fight off pathogens [59]. Probiotics also enhance antioxidant defenses [60]. Applied topically, probiotics, prebiotics, and postbiotics can improve skin appearance by diminishing fine lines and enhancing skin hydration [61]. Oral and topical probiotics are effective in shielding the skin from UV damage and may offer a promising solution for photoaging. They work by improving gut-skin interactions, decreasing oxidative stress, reducing inflammation, maintaining immune balance, and preventing changes to the extracellular matrix [62]. As we learn more about the microbiome, personalized skincare regimens can be developed to boost beneficial bacteria, enhancing UV protection and suppressing harmful microbes [63].

CONCLUSIONS

While it is clear that air pollution significantly accelerates skin aging through mechanisms like oxidative stress, inflammation, and microbiome disruption, there is still much to learn about the full extent of its impact. PM, PAHs, NO2, O3 have been shown to contribute to skin damage, but many aspects of how different pollutants interact with skin cells and tissues over time remain underexplored.

Current therapeutic strategies such as the use of antioxidants, moisturizers, and UV protection offer promising avenues to mitigate some of the damage caused by pollutants. However, the long-term effectiveness of these interventions, especially in highly polluted environments, is still not fully understood. Further research is needed to delve deeper into the molecular pathways triggered by air pollution, to explore how different pollutants contribute to aging in diverse skin types, and to develop personalized and targeted skincare solutions.

Moreover, more studies are required to investigate the cumulative effects of air pollution in conjunction with other environmental stressors, such as UV radiation, to fully understand the multifaceted nature of extrinsic skin aging.

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