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Natural Aldehydes on Health Effects

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ABSTRACT

This study explores aldehydes, a class of organic compounds widely distributed in nature and naturally occurring in various organisms, including plants and animals. These compounds are prevalent in essential oils, spices, fruits, and certain animal secretions, where they contribute to characteristic aromas and flavors, and play vital roles in interspecies communication and ecological interactions. Natural aldehydes have attracted substantial scientific interest due to their broad spectrum of biological activities, including antioxidant, antibacterial, antifungal, anti-inflammatory, and neuroprotective effects. These properties underpin their use in traditional medicine as well as in modern food, cosmetic, and pharmaceutical industries. However, their natural origin does not ensure safety; at high doses or with improper use, natural aldehydes may cause adverse health effects such as skin irritation and respiratory distress. Consequently, cautious application is recommended, particularly among vulnerable populations such as pregnant and breastfeeding women, children, and individuals with allergies. The primary objective of this study is to investigate the biological properties, natural sources, and health-related applications of natural aldehydes, while also addressing safety concerns. Furthermore, their potential for industrial application and their role in human health are critically evaluated.

Keywords: Natural aldehydes, Biological activities, Safe use.

INTRODUCTION

Aldehydes

Aldehydes are a class of organic compounds characterized by a carbon atom bonded to a hydrogen atom and a double bond with an oxygen atom, forming a carbonyl group. This carbonyl group is a defining structural feature that significantly influences their chemical reactivity and physical properties (Book, 2014).

Most aldehydes are liquid at room temperature, with the notable exception of formaldehyde-the simplest aldehyde-which exists as a gas under standard conditions. Their physical characteristics, such as odor and solubility, are largely determined by molecular weight. Low-molecular-weight aldehydes often have sharp, irritating odors, whereas higher-molecular-weight aldehydes tend to have more pleasant, aromatic scents. Short-chain aldehydes are generally water-soluble, but solubility decreases as the chain length increases. Nonetheless, aldehydes of all molecular sizes display good solubility in organic solvents (Paulus, 2005).

What is a Natural Aldehyde

Natural aldehydes are organic compounds naturally occurring in a wide range of living organisms, from plants to animals. These compounds are key contributors to the distinct smell and taste of many plants and are present in essential oils, fruits, spices, and certain animal secretions. Natural aldehydes facilitate inter-organism communication, enhance survival, and mediate interactions with the environment (Al-Maghrabey *et al.,* 2022).

Importance of Natural Aldehydes

In natural ecosystems, aldehydes play crucial roles in various biological processes. They attract pollinators, act as plant defense agents against pests, and serve as communication signals among animals (Akhoundi *et al.,* 2023). For humans, these compounds are essential in multiple sectors, including food, cosmetics, and pharmaceuticals. Their versatile applications, pleasant aroma, and generally safe profile contribute to their importance for health and well-being. Additionally, their antioxidant and antibacterial properties enhance their value in both traditional and modern medicinal practices (Aljaafari *et al.,* 2022).

Sources of Natural Aldehydes

Natural aldehydes are predominantly found in essential oils derived from plants, spices, and aromatic herbs, which serve as rich and diverse sources (Sinharoy *et al.,* 2019). They are particularly abundant in botanicals such as lavender, mint, cinnamon, and cloves, contributing significantly to the distinctive aromas of these plants (Kim *et al.,* 2022). Beyond aromatic herbs, natural aldehydes are also present in various fruits, dairy products, and certain mushroom species. In animals, aldehydes are typically generated through the oxidative metabolism of fatty acids. Owing to their chemical versatility and bioactivity, natural aldehydes are extensively utilized across the cosmetic, food, and pharmaceutical industries (Catalano *et al.,* 2024).

Mechanisms of Action of Natural Aldehydes

Natural aldehydes exert their biological effects through multiple cellular mechanisms. These compounds may inhibit enzymatic activity by interacting with catalytic sites, modulate signal transduction pathways by binding to specific membrane receptors, or function as antioxidants by scavenging reactive oxygen species (O'Brien *et al.,* 2005). Such diverse modes of action contribute to their therapeutic potential in various biological systems.

Biological Activities of Natural Aldehydes

Natural aldehydes exhibit a wide array of biological activities, including antioxidant, antibacterial, antifungal, antitumor, anti-inflammatory, neuroprotective, and antispasmodic effects. These diverse properties have established their long-standing role in traditional medicine and their growing relevance in modern pharmacology. Their mechanisms of action include neutralization of free radicals, enzyme inhibition, and receptor modulation at the cellular membrane, thereby influencing key biochemical and physiological processes (Catalano *et al.,* 2024).

Uses of Natural Aldehydes

Natural aldehydes are widely utilized across multiple industries due to their diverse bioactivities and aromatic properties. In the food sector, they serve as flavoring agents and preservatives, while in the cosmetics industry, they are incorporated into perfumes and skincare products (Olatunde *et al.,* 2022). In the pharmaceutical field, certain aldehydes act as active pharmaceutical ingredients. Additionally, these compounds are commonly found in cleaning agents, pesticides, and complementary medicine practices such as aromatherapy. Their pronounced antibacterial, antifungal, and anti-inflammatory activities underscore their value in both traditional therapies and contemporary industrial applications (Sinharoy *et al.,* 2019).

Reliability of Natural Aldehydes

Despite their natural origin, aldehydes are not inherently safe. When applied in high concentrations or used improperly, they may pose significant health risks, including dermal irritation and respiratory complications. Particular caution is warranted for vulnerable populations such as pregnant and lactating individuals, children, and those with known hypersensitivities or allergic predispositions, as they may be more susceptible to the adverse effects of these compounds (O'Brien *et al.,* 2005).

Some Natural Aldehydes

Benzaldehyde

Benzaldehyde (Fig. 1) is a naturally occurring aromatic aldehyde found in plants such as Camellia sinensis (tea), Humulus lupulus (hops), Prunus dulcis (almond), and apricot kernels (Adams *et al.,* 2005). It is a clear, colorless to pale yellow liquid characterized by a distinctive bitter almond aroma. Upon exposure, it is readily absorbed through the skin and lungs, distributed systemically, and rapidly metabolized to benzoic acid. The resulting metabolites are subsequently excreted via the urine, primarily as conjugates with glucuronic acid or glycine (Catalano *et al.,* 2024).

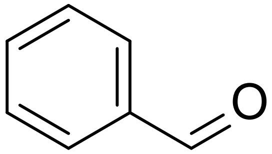

Fig. 1. Benzaldehyde

In industry, benzaldehyde is employed as a solvent and plasticizer in chemical manufacturing and as a fragrance and flavoring agent in cosmetics and food products. It also serves as an intermediate in the synthesis of pharmaceutical compounds such as chloramphenicol, ephedrine, ampicillin, and diphenylhydantoin (Kim *et al.,* 2022). Preliminary studies suggest that benzaldehyde may exhibit antitumor potential, though further research is required. Its antimicrobial efficacy against various bacteria and fungi has also been documented (Catalano *et al.,* 2024).

Although inhalation may cause irritation of the respiratory tract and skin contact may result in dermatitis or urticaria, benzaldehyde is not considered carcinogenic when used at typical concentrations found in cosmetic formulations (Kim *et al.,* 2022)

Cinnamaldehyde

Cinnamaldehyde (Fig. 2) is the principal compound responsible for the distinctive flavor and aroma of cinnamon. It is primarily found in the bark of *Cinnamomum* species and appears as a clear, yellowish, oily liquid (Doyle & Stephens, 2019). Once introduced into the body, cinnamaldehyde is efficiently absorbed through the skin and gastrointestinal tract. It is subsequently oxidized to cinnamic acid and ultimately excreted via the urine as benzoic acid and hippuric acid metabolites (Kim *et al.,* 2022).

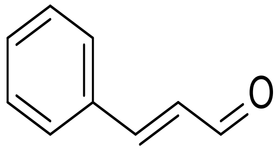

Figure 2. Cinnamaldehyde

This compound is utilized extensively across various sectors: as a flavoring agent in the food industry, a fragrance in perfumery, a polishing agent in electroplating processes, and an insect repellent. It has also demonstrated potential utility in dental care, particularly in the treatment of caries (Catalano *et al.,* 2024). Cinnamaldehyde is widely used in India for its antidiabetic properties and has been shown to significantly reduce plasma glucose levels (Subash Babu *et al.,* 2007).

From a pharmacological perspective, cinnamaldehyde exhibits hypoglycemic, vasodilatory, antifungal, antioxidant, and antimicrobial effects. The trans-isomer, in particular, has demonstrated activity against fungal and bacterial biofilms and is under investigation for its potential to combat bacterial resistance (Catalano *et al.,* 2024). Recent studies have also explored its capacity to modulate intracellular signaling pathways involved in cancer progression, highlighting its promise as an anticancer agent (Peng *et al.,* 2024).

Although cinnamaldehyde may cause skin irritation upon direct contact at high concentrations, current evidence does not suggest carcinogenicity or significant long-term health risks when used appropriately (Kim *et al.,* 2022).

Vanillin

Vanillin (Fig. 3) is one of the most widely used aromatic aldehydes globally, recognized for its characteristic sweet, creamy, and vanilla-like scent. It naturally occurs in the beans or pods of the tropical vanilla orchid *(Vanilla planifolia)* and can also be detected in trace amounts in other plants such as tobacco *(Nicotiana tabacum)* (Catalano *et al.,* 2024). It typically appears as white to slightly yellow crystalline needles or powder (Kim *et al.,* 2022).

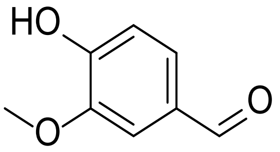

Fig. 3. Vanillin

Upon ingestion or absorption, vanillin undergoes phase I and II metabolism, converting into several metabolites including vanillyl alcohol, vanillic acid, catechol, guaiacol, and their methylated derivatives. Most of these metabolites are eliminated via urine within 24 h (Kim *et al.,* 2022).

Vanillin is extensively used as a flavoring agent in foods and beverages, and as a fragrance in perfumery. In pharmaceutical formulations, it serves as a masking agent and is also employed in the synthesis of certain drugs, such as methyldopa. It has additional applications in galvanotechnics as a brightening agent (Walton *et al.,* 2003; Olatunde *et al.,* 2022).

Pharmacologically, vanillin displays a wide range of bioactivities, including antioxidant, antimicrobial, anti-inflammatory, cardioprotective, diuretic, antidiabetic, and anticancer effects. Its clinical relevance is further highlighted by its application in the treatment of sickle cell anemia (Olatunde *et al.,* 2022). Nevertheless, vanillin may cause adverse skin reactions, such as contact dermatitis, in sensitized individuals (Kim *et al.,* 2022).

Anisaldehyde

Anisaldehyde (Fig. 4) is an aromatic aldehyde characterized by a colorless to pale yellow oily appearance and a pronounced sweet, floral fragrance. It is primarily obtained from the essential oil of *Pimpinella anisum* (anise), but is also found in various plants and foods, including vanilla, acacia, fennel, star anise, cranberries, black currant, cinnamon, and basil (Falcon, 2020; Kim *et al.,* 2022).

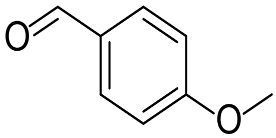

Fig. 4. Anisaldehyde

Structurally, anisaldehyde undergoes mild oxidation of its aldehyde group to form anisic acid, which is considered its main metabolite. Due to its fragrance profile and chemical reactivity, it is commonly used as a flavor and fragrance compound in the food and cosmetic industries, as well as an intermediate in organic synthesis. It is also employed in the development of chemical attractants for pests such as cockroaches (Kim *et al.,* 2022).

From a pharmacological perspective, anisaldehyde exhibits notable antibacterial and antifungal activities. It has demonstrated inhibitory effects against *Pseudomonas aeruginosa*, *Candida spp.*, and *Aspergillus flavus* (Shreaz *et al.,* 2011). Additional roles include functioning as a plant and bacterial metabolite, as well as an insect repellent. Importantly, current evidence suggests that anisaldehyde does not trigger sensitization or allergic reactions in humans when used in conventional concentrations (Kim *et al.,* 2022).

Cuminaldehyde

Cuminaldehyde (Fig. 5) is an aromatic aldehyde with a colorless to pale yellow appearance and a strong, pungent, spicy odor. It occurs naturally in essential oils derived from *Cuminum cyminum* (cumin), myrrh, and eucalyptus species (Kim *et al.,* 2022).

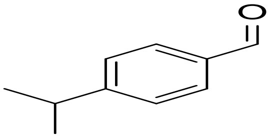

Fig. 5. Cuminaldehyde

Following oral or dermal absorption, cuminaldehyde is distributed via the bloodstream and undergoes biotransformation primarily in the liver. This metabolism is catalyzed by microsomal enzymes, particularly cytochrome P450 isoenzymes. The resulting polar metabolites are excreted through the urine or bile following phase II conjugation reactions (Catalano *et al.,* 2024). Cuminaldehyde has demonstrated several pharmacologically relevant activities. It exhibits antihyperglycemic effects by promoting insulin secretion and protecting pancreatic β-cells. Furthermore, it has shown cytotoxic activity in cancer models, especially against human lung cancer cells, through the induction of apoptosis (Ebada, 2017). Its neuroprotective potential has also been investigated, with evidence suggesting a protective role against neurodegenerative diseases such as Parkinson's disease (Morshedi *et al.,* 2015).

Additionally, cuminaldehyde possesses

anti-inflammatory activity by suppressingpro-inflammatory cytokines and enzymes. It also exhibits antifungal effects, particularly against *Candida albicans*, supporting its role as a multifunctional bioactive compound (Catalano *et al.,* 2024).

Citral

Citral (Fig. 6) is a monoterpene aldehyde characterized by a clear yellow appearance and a distinctive lemon-like aroma. It is abundantly present in various essential oils, particularly those obtained from lemongrass *(Cymbopogon citratus)*, lemon, verbena, and orange (Kim *et al.,* 2022).

Citral is extensively utilized as a flavoring and fragrance agent in the food, cosmetic, and household product industries. In industrial chemistry, it serves as a key intermediate in the synthesis of vitamin A, ionone, and other related compounds (Ganjewala *et al.,* 2012).

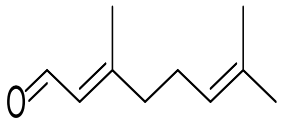

Fig. 6. Citral

Pharmacologically, citral has been shown to exhibit a range of bioactivities, including antimicrobial, antioxidant, anti-inflammatory, antipyretic, and insect-repellent effects. It has demonstrated potent antifungal properties against *Candida* species and has shown antibacterial activity against a variety of pathogens (Onawunmi, 1989; Kim *et al.,* 2022). Moreover, citral supports cardiovascular health due to its radical-scavenging capacity (Kim *et al.,* 2022).

In pain models, citral has displayed significant antinociceptive activity, both in acute and chronic conditions such as postoperative and neuropathic pain. Notably, it provides gastric protection against NSAID-induced ulcers, suggesting additional therapeutic potential (Nishijima *et al.,* 2014). Citral has also emerged as a candidate compound for the prevention and treatment of certain cancers, including breast tumors, through modulation of specific signaling pathways (Emílio-Silva *et al.,* 2017).

Despite its beneficial effects, citral can exhibit cytotoxicity at elevated concentrations, as evidenced by dose-dependent toxic responses in HepG2 liver cells (Souza *et al.,* 2020). Therefore, regulated use is essential to ensure safety in therapeutic or consumer applications.

Salicyaldehyde

Salicylaldehyde (Fig. 7) is an aromatic aldehyde appearing as a colorless to deep red oily liquid with a strong, sharp odor reminiscent of benzaldehyde. It occurs naturally in various food products, including buckwheat grains, grapes, tomatoes, milk, coffee, and tea (Kim *et al.,* 2022).

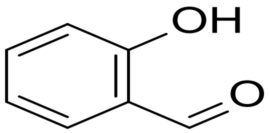

Fig. 7. Salicylaldehyde

This compound has versatile applications across multiple sectors. In the food and fragrance industries, it is used as a sweetening and scenting agent-particularly in the formulation of violet-like perfumes. In chemical synthesis, it serves as a precursor to coumarins and is also utilized as an additive in gasoline formulations (Kim *et al.,* 2022). Furthermore, salicylaldehyde has been identified as a potential eco-friendly pesticide, functioning as both an herbicide and fungicide in sustainable agriculture (Kim & Chan, 2022). Salicylaldehyde exhibits several biological effects, most notably its antimicrobial and anti-allergic properties. It has been shown to inhibit immunoglobulin E (IgE)-mediated mast cell degranulation and cytokine production, thereby reducing symptoms associated with systemic and cutaneous anaphylaxis (Ashikari *et al.,* 2022). These effects position it as a candidate for therapeutic interventions in allergic and inflammatory conditions. However, salicylaldehyde can act as an odor allergen and may induce allergic contact dermatitis in sensitive individuals. Documented symptoms include eczema, skin irritation, and inflammation following dermal exposure, particularly in occupational settings (Kim *et al.,* 2022).

Hexanal

Hexanal (Fig. 8) is a volatile, plant-derived aliphatic aldehyde that appears as a colorless, oily liquid with a pungent odor. It is a major contributor to the characteristic fresh and green aroma of many fruits, often described as citrusy or grassy with woody undertones (Catalano *et al.,* 2024).

Biochemically, hexanal is metabolized

primarily by aldehyde dehydrogenase enzymes in hepatic tissues. It is either converted into hexanoic acid, which may enter the Krebs cycle for further energy metabolism, or eliminated from the body in the form of water-soluble salts (Kim *et al.,* 2022).

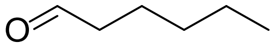

Fig. 8. Hexanal

In industry, hexanal is used as a flavoring agent in fruit-based products and as a preservative to prolong the shelf life of fresh produce by delaying ripening and spoilage. It is also utilized in the manufacture of plasticizers, rubber additives, synthetic resins, paints, and pesticides (Catalano *et al.,* 2024).

Clinically, elevated levels of hexanal have been associated with certain pathological conditions. It has been identified as a uremic toxin that accumulates in individuals with renal impairment, contributing to oxidative stress and disrupting mineral and vitamin D metabolism. Moreover, its elevated presence in exhaled breath has been proposed as a potential non-invasive biomarker for lung cancer diagnosis (Kim *et al.,* 2022).

Despite its functional benefits, exposure to high concentrations of hexanal may cause mucosal irritation, including eye and nasal discomfort, headaches, and solvent-like odors. Caution is advised in occupational settings or applications involving aerosolized formulations (Kim *et al.,* 2022).

Furfural

Furfural (Fig. 9) is an aromatic aldehyde derived from agricultural biomass, typically appearing as a colorless to amber oily liquid with a distinct almond-like odor. It is naturally present in materials such as oats, wheat bran, and corn cobs. Upon exposure to air and light, furfural may undergo oxidative changes, resulting in a reddish-brown discoloration (Kim *et al.,* 2024).

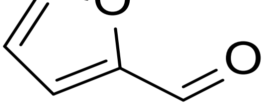

Fig. 9. Furfural

The compound can be absorbed through inhalation of vapors or via dermal contact. Once in the body, furfural is rapidly metabolized in the liver and has a reported biological half-life of approximately 2 to 2.5 hours. Its primary metabolite in humans is furoylglycine, with 2-furanacrylic acid as a secondary product, both of which are excreted via urine (Flek & Sedivěc, 1978).

Industrially, furfural is considered a high-value chemical due to its versatility in chemical synthesis and processing. It is widely employed in the production of resins, plastics, bioplastics, pesticides, fuel additives, pharmaceuticals, and food flavoring agents. Additionally, it is a prominent solvent in the petroleum refining industry and serves as an intermediate in the synthesis of various furan derivatives (Eseyin *et al.,* 2015; Hayes, 1996). Despite its industrial relevance, furfural exhibits notable toxicological properties. Acute exposure may lead to symptoms such as dizziness, nausea, and headache, while chronic exposure has been associated with hepatotoxicity, nephrotoxicity, and neurotoxicity. Genotoxic studies have demonstrated furfural's potential to cause DNA damage and induce genetic mutations. At high doses, it can also affect the central nervous system, resulting in drowsiness, irritability, and motor dysfunction (Hoydonckx *et al.,* 2000).

Citronellal

Citronellal (Fig. 10) is a naturally occurring monoterpenoid aldehyde, typically appearing as a colorless to slightly yellow liquid with a potent, citrus-like floral aroma. It is predominantly found in essential oils derived from *Cymbopogon nardus* (citronella) and *Cymbopogon citratus* (lemongrass) (Kim *et al.,* 2024).

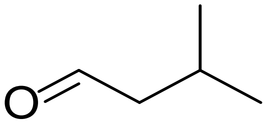

Fig. 10. Citronellal

Citronellal exerts various pharmacological effects, including anti-inflammatory and redox-modulating properties. These effects are largely attributed to its ability to inhibit enzymes in the arachidonic acid cascade, reduce the generation of reactive oxygen species, and suppress leukotriene-mediated cellular migration and edema formation (Kim *et al.,* 2024). Due to its pleasant fragrance and therapeutic activities, citronellal is widely incorporated into commercial products such as perfumes, deodorants, air fresheners, floor polishes, moisturizers, and cleaning agents (Rokonuzzman *et al.,* 2024). Biologically, it has been reported to possess insecticidal, acaricidal, antiviral, anesthetic, antihypertensive, cardioprotective, antidiabetic, anti-inflammatory, and anticancer properties. It also shows promise in the treatment of neurological and cardiovascular disorders (Venancio *et al.,* 2024). Although generally considered safe at low concentrations, exposure to high doses or prolonged contact may lead to adverse effects such as skin irritation, allergic reactions, headaches, dizziness, and respiratory symptoms. Citronellal can also cause eye irritation upon direct contact. Furthermore, high doses have been linked to genotoxic effects, though evidence regarding its carcinogenic potential remains inconclusive (Sinha *et al.,* 2014).

Heptanal

Heptanal (Fig. 11) is an aliphatic aldehyde characterized by a colorless, oily appearance and a strong fruity, citrus-like aroma. It is naturally found in essential oils of certain plants such as *Bupleurum longiradiatum, Kundmannia syriaca*, and *Aristolochia delavayi*, as well as in extracts from green algae and cyanobacteria. It is also a major volatile compound detected in post-harvest cereals and grains (Catalano *et al.,* 2024).

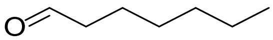

Fig. 11. Heptanal

Once absorbed, heptanal is primarily metabolized in the liver by alcohol and aldehyde dehydrogenase enzymes, yielding heptanoic acid. This metabolite is then conjugated with glucuronic acid or sulfate to form water-soluble derivatives, which are excreted through the kidneys (Kim *et al.,* 2024). Industrially, heptanal is used as a flavoring agent and a synthetic intermediate in the production of fragrances and other organic compounds. It has recently gained attention as a potential biomarker for respiratory diseases, including COVID-19 and lung cancer, due to its detection in breath analysis studies (Zhu & Luo, 2022; Catalano *et al.,* 2024). Additionally, it has demonstrated antifungal activity against *Aspergillus flavus*, suggesting possible applications in agricultural pathogen control (Catalano *et al.,* 2024). Despite its beneficial applications, heptanal may exert toxicological effects at elevated concentrations. It functions as a uremic toxin in patients with kidney dysfunction, where it accumulates and increases oxidative stress by activating NADPH oxidase and reactive oxygen species (ROS) production. These processes may contribute to disturbances in mineral metabolism, vitamin D regulation, and age-related physiological decline (Kim *et al.,* 2024).

Octanal

Octanal (Fig. 12) is a saturated aliphatic aldehyde that appears as a colorless to light yellow-orange oily liquid with a strong fruity aroma. It is naturally present in various plant-derived substances, including *Camellia sinensis* (green tea), *Humulus lupulus* (hops), and essential oils extracted from citrus fruits such as oranges and lemons (Kim *et al.,* 2024).

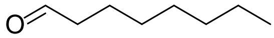

Fig. 12. Octanal

This compound is widely used in the fragrance and flavor industries, particularly in the synthesis of artificial citrus oils and as a precursor to compounds such as alpha-hexylcinnamaldehyde. At low concentrations, it contributes to the aroma profiles of perfumes, colognes, and other cosmetic products (Catalano *et al.,* 2024). Octanal exhibits multiple biological effects, including antioxidant, anti-inflammatory, and antiviral activities. It has demonstrated strong antifungal properties against postharvest pathogens such as *Penicillium digitatum* and *Geotrichum citri-aurantii*, making it a promising candidate for use as a natural fungicide in citrus fruit preservation (Tao *et al.,* 2014). Additionally, octanal modulates the expression of key cytokines and chemokines such as IL-6 and IL-8 in human lung epithelial cells (A549), indicating its role in inflammation and respiratory pathology (Song *et al.,* 2014).

However, excessive exposure to octanal can lead to irritation of the skin, eyes, and mucous membranes, along with systemic symptoms such as dizziness, nausea, and headaches. Ingestion or inhalation at high doses may also cause gastric discomfort and contribute to lung tissue inflammation (Kim *et al.,* 2024).

Nonanal

Nonanal (Fig. 13) is a long-chain aliphatic aldehyde that presents as a clear, brownish liquid characterized by a distinct rose-like and citrus fragrance. It occurs naturally in a variety of essential oils, including rose, citrus (such as orange and lemon), and pine oils, and is also found in *Camellia sinensis* (green tea) and *Humulus lupulus* (hops) (Kim *et al.,* 2024).

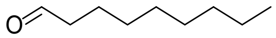

Fig. 13. Nonanal

Biochemically, nonanal is a saturated fatty aldehyde formed through the reduction of nonanoic acid and is involved in both plant metabolism and human cellular processes. In oncology research, it has been identified as a metabolic byproduct associated with cancer cell metabolism, and elevated levels have been detected in airway fluids following ozone exposure (Frampton *et al.,* 1999). Nonanal plays a dual role in food and fragrance industries as a flavor enhancer and aromatic compound. However, toxicological studies have shown that nonanal can induce hemolysis in human erythrocytes and negatively impact DNA synthesis in hepatocytes, especially when combined with oxidative stress agents such as hydrogen peroxide (Frampton *et al.,* 1999). Importantly, nonanal has been classified among uremic toxins-compounds that accumulate in the body during renal insufficiency. These toxins can interact with NADPH oxidase enzymes, leading to elevated levels of reactive oxygen species (ROS). This oxidative imbalance may accelerate aging processes and disrupt mineral and vitamin D metabolism. Accumulation of nonanal has been associated with the onset of uremic syndrome, manifesting with systemic symptoms such as fatigue, anorexia, mental confusion, abnormal bleeding, and fluid retention (Kim *et al.,* 2024).

Decanal

Decanal (Fig. 14) is a saturated aliphatic aldehyde that appears as a colorless to pale yellow liquid with a pleasant floral-citrus aroma. It occurs naturally in essential oils extracted from various citrus fruits, particularly orange and lemon peels, as well as in coriander *(Coriandrum sativum)* and other herbs (Kim *et al.,* 2024; Catalano *et al.,* 2024).

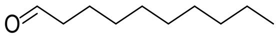

Fig. 14. Decanal

Owing to its desirable fragrance, decanal is widely utilized in the perfume and flavor industries. It also functions as a skin-conditioning agent in cosmetic formulations, contributing both to scent and product texture (Kim *et al.,* 2024). In addition to its sensory applications, decanal exhibits several pharmacological properties. It has been shown to possess significant antifungal activity against pathogens such as *Penicillium italicum* and *Geotrichum citri-aurantii*, both of which affect postharvest citrus fruits (Tao *et al.,* 2014). Furthermore, decanal demonstrates antioxidant and antimicrobial effects, helping to maintain tissue integrity and reduce microbial load on epithelial surfaces (Catalano *et al.,* 2024). Recent *in vivo* studies suggest that decanal may exert protective effects on lung tissue by modulating the inflammatory response and reducing leukocyte infiltration. It has shown potential in the management of inflammatory airway conditions due to its ability to downregulate pro-inflammatory mediators (Kim *et al.,* 2024). While generally recognized as safe at standard usage concentrations, high-dose exposure to decanal may result in mild irritation of the skin, eyes, or respiratory tract. However, no evidence currently indicates mutagenic or carcinogenic risks associated with its conventional use (Catalano *et al.,* 2024).

Phenylacetaldehyde

Phenylacetaldehyde (Fig. 15) is a colorless to slightly yellow, oily liquid with a floral odor. (Kim *et al.,* 2024). It is found in buckwheat, cocoa and coffee beans. (Zhu *et al.,* 2011). A member of the aldehyde class, this compound is derived from acetaldehyde, which carries methyl substitution. Human metabolite, *Saccharomyces cerevisiae* and *Escherichia coli* It plays a role as a metabolite of its metabolite. In addition *Camellia sinensis* and *Tricholoma inamoenum*. It can also be found in organisms such as. (Kim *et al.,* 2024).

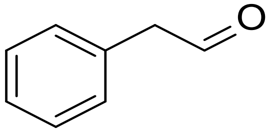

Fig. 15. Phenylacetaldehyde

Phenylacetaldehyde is widely used in the perfume and cosmetics industry. In the food industry, it is used to give taste and smell in confectionery and beverages. It is also involved as an intermediate in chemical synthesis and in the production of some pharmaceutical products. It is also allowed to be used as an inert ingredient in non-food pesticide products. (Kim *et al.,* 2024). It is used as a preservative in cigarette additives and soaps. In biology, it is of interest because of its antimicrobial properties. (Zhu *et al.,* 2011). The attractiveness of phenylacetaldehyde on cabbage caterpillar moths has been previously established, but large variation in attractiveness for female moths has been observed in recent tests. When pheromone is added to traps, it has also been shown to increase the total amount of prey. (Creighton *et al.,* 1973).

Phenylacetaldehyde can cause skin sensitivity and lead to allergic reactions, leading to contact dermatitis. (Kim *et al.,* 2024).

Hydrocinnamaldehyde

Hydrocinnamaldehyde (Fig. 16) is found in cinnamon bark and is the principal component of cinnamon's characteristic odor. It is a colorless or light yellow liquid and has a strong, pungent floral odor. *Cinnamomum sieboldii*, *Syzygium jambos* and *Cinnamomum verum*. It is found in plants such as. (Kim *et al.,* 2024). It can also occur during fermentation in winemaking. It can also be found in low amounts in fruits such as apples, grapes, and some vegetables such as carrots. Fragrance in the perfume industry; It is used as a flavoring agent in the food industry. (Bayaz 2014).

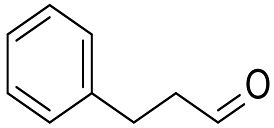

Fig. 16. Hydrocinnamaldehyde

During its metabolism, hydrocinnamaldehyde forms hydrocinnamic acid by oxidation. This transformation takes place through dehydrogenase enzymes. In addition, some organisms can excrete hydrocinnamaldehyde by converting it into different compounds for detoxification purposes. These metabolic processes can help organisms adapt to environmental stresses and strengthen plants' defenses. In the human body, research is being conducted on the antioxidant properties and health benefits of this compound. (Kim *et al.,* 2024).

Hydrocinnamaldehyde may exhibit toxic properties at low to moderate levels. In high concentrations, it can cause irritation of human skin, irritation of the eyes, and respiratory tract irritation. Low doses do not show serious effects, but high doses can lead to systemic problems such as headaches and nausea. Toxic effects can also occur on animals and microorganisms, but these usually become more pronounced at high doses or with long-term exposure. (Lee *et al.,* 2008).

Perillaldehyde

Perillaldehyde (Fig. 17) is a pale yellowish oily liquid with an oily, spicy, and herbaceous odor. It is a natural compound that is abundant in the bark of the annual perilla plant and citrus fruits. *Tetradenia riparia, Perilla frutescens* and some other organisms. (Kim *et al.,* 2024).

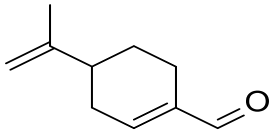

Fig. 17. Perillaldehyde

Perillaldehyde is usually processed in the body by phase I and phase II metabolism reactions. At the first stage, perilate acid is formed. Then this intermediate can undergo phase II reactions and be conjugated with glucuronic acid, sulfate, or glutathione, making them water-soluble. It is excreted from the body through urine or bile. (Ishida *et al.,* 1989).

Perillaldehyde has been shown to have healing effects on diabetic cardiomyopathy and cardiotoxicity associated with cardiovascular diseases. (Yu *et al.,* 2023). Antifungal effects, especially *Aspergillus niger, Aspergillus flavus* and *Ceratocystis fimbriata.* It is effective against foodborne fungi such as. (Kim *et al.,* 2024). *P. frutescens* Its leaf and extracts offer anti-inflammatory and antiallergic properties, suppressing the activity of tumor necrosis factor. For this reason, it is used in the treatment of conditions such as inflammatory bowel disease and indigestion and exerts calming effects. (Uemura *et al.,* 2018).

In addition, Perillaldehyde is included in food additives, perfume ingredients and traditional medicine mixtures. Biological analyses have revealed that perilaldehyde has good antioxidant activity and can be used as an organic fruit and food preservative. Animal studies show that perillaldehyde has potent anticancer, antidepressant, and anti-inflammatory effects. (Erhunmwunsee *et al.,* 2022)

Perillaldehyde can cause irritation to the respiratory tract, skin and eyes. In addition, central nervous system effects such as dizziness, headache and nausea can also be seen. Long-term exposure to high doses can lead to liver and kidney damage. (Kim *et al.,* 2024).

Formaldehyde

Formaldehyde (Fig. 18) is a colorless, flammable, pungent and highly reactive chemical that occurs naturally in small amounts in the human body. (Kim *et al.,* 2024). Humans can be exposed to environmental formaldehyde from a variety of sources, including engine exhaust, tobacco smoke, natural gas, and waste incineration. (Gerberich *et al.,* 2000). When ingested into the body, it oxidizes in the liver and other organs and distributes to different regions. This process helps reduce the harmful effects of free formaldehyde. (Reingruber & Pontel 2018).

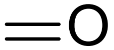

Fig. 18. Formaldehyde

It has a wide range of uses, from industrial production to the medical field. It is involved in various applications in the medical field, from wart treatment to skin disinfection. It is involved in the production of wood materials, plastics, textiles and building materials, in the production of some medicines and vaccines due to its protective and sterilizing properties. Formaldehyde is also found in some household products. For example, it is used as a preservative in antiseptics, medicines, cosmetics and some foods. (Catalano *et al.,* 2024).

It is also widely used in pesticide production and plant protection in agriculture. However, short-term exposure can lead to symptoms such as burning in the nose, eyes and throat, coughing, wheezing, nausea and skin irritation, while long-term exposure can increase the risk of cancer. The World Health Organization (WHO) and the International Agency for Research on Cancer (IARC) have classified formaldehyde as a carcinogen. Formaldehyde has been linked to nasopharyngeal cancer and leukemia and can also lead to respiratory conditions such as asthma and allergic reactions. (Protano *et al.,* 2021).

Verataldehyde

Veratraldehyde (Fig. 19) is found in vanilla plants and a variety of flowers. It appears as light peach powder with needles or coarse-grained, with a vanilla bean smell. It is also found in mint, ginger, raspberries and other fruits. *Wisteria floribunda* and *Zingiber montanum* It has been reported to be detected in organisms such as. (Kim *et al.,* 2024).

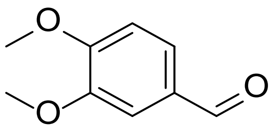

Fig. 19. Verataldehyde

It has antifungal properties. (Kim *et al.,* 2024). Veratraldehyde has high repellent activity against mosquitoes and ticks and has been confirmed to have similar effects to the widely used synthetic DEET compound. (Kim *et al.,* 2021).

Veratraldehyde is also harmful if it comes into contact with the skin, ingested or inhaled. It can lead to signs of inflammation such as redness, watering and itching in the eye. However, there is currently no information available about its long-term effects such as carcinogenicity, mutagenicity, teratogenicity and developmental toxicity. (Kim *et al.,* 2024).

Isovaleraldehyde

Isovaleraldehyde (Fig. 20) is a colorless liquid with a pungent and suffocating odor like an apple and produces an irritating vapor. It is found in olives as a volatile ingredient and is a flavoring agent, plant metabolite, essential oil component, and *Saccharomyces cerevisiae*. It plays a role as a metabolite. *Francisella tularensis*, *Eucalyptus pulverulenta* and has also been detected in some other organisms. (Kim *et al.,* 2024).

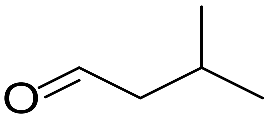

Fig. 20. Isovaleraldehyde

When ingested into the body, ısovaleraldehyde is converted to isovaleryl alcohol by aldehyde reductase enzymes. Isovaleric acid is oxidized in the liver by the enzymes alcohol dehydrogenase and aldehyde dehydrogenase and converted into isovaleric acid. Isovaleric acid can be used for energy production, and these metabolites are converted into carbon dioxide and water, which are usually excreted through urine. (Roberts *et al.,* 1991).

Isovaleraldehyde is used to make flavors, fragrances, medicines, and resins, and is also used as a pesticide, solvent, and emollient. The isovaleraldehyde contained in cocoa bean extract increases mRNA levels without causing toxic effects in cells. It also promotes KREB phosphorylation by the cAMP-coupled protein kinase mechanism. (Shimada *et al.,* 2024).

Isovaleraldehyde is a toxic compound that can cause skin and eye irritation, respiratory problems, and adverse effects on the central nervous system. Contact with the skin can cause redness, and contact with eyes can cause watering and irritation. It is thought that long-term exposure can lead to carcinogenic effects and organ damage. (Kim *et al.,* 2024).

Safranal

Safranal (Fig. 21) is a monoterpene aldehyde and the principal aromatic component of saffron *(Crocus sativus L.)*, contributing to its distinctive warm and sweet fragrance. It is a volatile yellow oily liquid formed through the enzymatic or thermal degradation of picrocrocin, a glycoside precursor found in saffron stigmas. Due to its chemical structure, safranal is highly sensitive to environmental factors such as heat, light, and oxygen, leading to rapid degradation under improper storage conditions (Yildiz & Çelik, 2024).

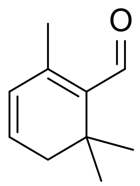

Fig. 21. Safranal

Safranal is widely employed in the food industry as a flavoring and coloring agent and is also used in the formulation of perfumes and cosmetics due to its unique scent profile. Beyond its aromatic qualities, safranal exhibits a broad spectrum of pharmacological properties. It has demonstrated potent antioxidant activity by scavenging free radicals and reducing lipid peroxidation, thereby offering cellular protection against oxidative damage (Esmaealzadeh *et al.,* 2021).

In terms of therapeutic potential, safranal shows promise in managing diabetes by enhancing insulin sensitivity and reducing blood glucose levels (Picheta *et al.,* 2015). It has also been studied for its anticancer activity, primarily through the induction of apoptosis and inhibition of tumor proliferation. Furthermore, safranal displays anti-inflammatory, antinociceptive, and antidepressant properties, largely by modulating neurotransmitters such as dopamine, serotonin, and norepinephrine (Maeda *et al.,* 2014).

Safranal's neuroprotective effects have been documented in models of neurodegenerative diseases, including Alzheimer's and Parkinson's disease. These benefits are attributed to its ability to reduce oxidative stress and neuroinflammation while preserving neuronal structure and function (Esmaealzadeh *et al.,* 2021).

However, despite its promising biological effects, safranal may exhibit cytotoxic and genotoxic effects at high doses or with prolonged exposure. Therefore, dose regulation is essential in therapeutic applications to minimize potential adverse effects (Esmaealzadeh *et al.,* 2021).

CONCLUSION

Aldehydes are essential organic compounds naturally occurring in a wide range of living organisms, from plants to animals. Their notable biological properties-particularly antioxidant, antibacterial, antifungal, and anti-inflammatory activities-have enabled their widespread application in the food, cosmetics, and pharmaceutical industries. Additionally, they are employed in alternative medicine practices and cleaning product formulations.

However, despite their natural origin, aldehydes may pose health risks when used at high concentrations or under inappropriate conditions, potentially leading to skin irritation, respiratory issues, or allergic reactions. Therefore, their safe and controlled use is of paramount importance.

To maximize the therapeutic and industrial potential of natural aldehydes, further scientific investigations are required. In particular, more in-depth studies are needed to clarify their mechanisms of action and biological effects.

Establishing clear regulatory standards and dosage limits is crucial, especially for industrial and consumer use. Furthermore, increased attention should be directed toward vulnerable populations such as pregnant and lactating individuals, children, and those with allergic sensitivities.

Expanding the exploration of novel natural sources of aldehydes may offer new opportunities for commercial development. Lastly, promoting the use of eco-friendly aldehyde-based compounds in areas such as green cleaning products and sustainable agriculture could broaden their accessibility and contribute to public health and environmental safety.

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