NEW CONCEPTS AND ADVANCED STUDIES IN AGRICULTURE, FOREST AND WATER ISSUES

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Editor
Prof. Dr. NİGAR YARPUZ BOZDOĞAN

New Concepts and Advanced Studies in Agriculture, Forest and Water Issues
Editor: Prof. Dr. NİGAR YARPUZ BOZDOĞAN

Design: All Sciences Academy Design
Published Date: October 2025
Publisher's Certification Number: 72273
ISBN: 978-625-5794-56-7

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CONTENT

Venison As an Alternative Source of Meat

Ayça MEYDANAÇAR[1]

Özen YURDAKUL[2]

1- aycameydanacar@gmail.com ORCID No: 0009-0001-8668-0726
2- Prof. Dr.; Burdur Mehmet Akif Ersoy Üniversitesi Veteriner Fakültesi Gıda Hijyeni ve Teknolojisi Anabilim Dalı ozenkursun@mehmetakif.edu.tr ORCID No: 0000-0001-7680-015X

ABSTRACT

With the rising levels of human population, food supply needs are expected to increase at a rapid rate. In order to meet these needs the food industry must come up with innovative solutions. Especially considering low- and middle-income countries where protein intake per capita falls below the average of those in developed countries; alternative sources of protein must be researched. Red meat, particularly beef is known to contain high levels of cholesterol and fat and therefore there are some concerns regarding meat consumption about its effects on human health. Venison is a good alternative based on the meat content and meat yield. It is common to consume venison in some countries, but still, it’s not popular globally. The food industry may introduce venison to the conscious consumer as a better option than traditional red meat products as it is less exposed to additives or pharmaceuticals and usually has a pasture-based feeding. As an addition to these facts, venison also meets the nutritional needs of the human diet. The aim of this work is to inform the consumer about the qualities and benefits of venison and suggest its potential as an innovative new source of healthy protein for the worlds growing population.

Venison, deer, red meat, alternative proteins, alternative meat and meat products

INTRODUCTION

As the world population increases, the demand for animal sourced protein is gradually increasing. According to the OECD-FAO Agricultural Outlook 2025-2034 published by OECD/FAO (The Organization for Economic Cooperation and Development/ Food and Agricultural Organization); the daily per capita caloric intake from animal sourced products is expected to increase by 6% globally over the next ten years. For low- and middle-income countries, this increase is expected to be around 25%, with the population and income growth resulting in these urbanising populations to consume relatively more livestock and fish products.

In recent years with the worldwide consumer gaining more consciousness, the demand for healthy and authentic meat is rising. This increase brings with it an increasing interest in meat production from alternative sources. Red meat is an important source of protein for humans but lately it has been seen as a potential health concern. These concerns are due to food safety issues, various diseases of livestock animals and the high fat and cholesterol content of red meat. The “conscious consumers” are now researching and preferring new, alternative sources for meat. Venison can be an innovative solution that stands out as an alternative to red meat from domestic ruminants, to meet the rising demand for meat as an addition to being the more “healthy choice”.

Consumer Perception of Venison

Nowadays, the “conscious consumer” places great importance on animal welfare, additives used in meat production and environmental pollution (Volpelli et al., 2003:555). Generally, venison is known to have low levels of fat content. And because deer are less exposed to pharmaceuticals used for treatment of livestock and usually have a pasture-based feeding, venison is seen as organic and safe for consumption (Kelava et al., 2023:391). Through all these perspectives, venison obtained from free-ranging deer meets all the necessary requirements. On the other hand, some practices that are used in deer farming such as castration of stags, intensive feeding, artificial insemination and vaccinations can be seen as controversial by the consumer. All these practices mentioned in the deer farming industry may cause harm to the general image of venison being safe and organic product (Hoffman and Wiklund, 2006:198; Kelava et al., 2023:391).

In a study conducted in 1998 in Louisiana, a randomly selected sample of 3,180 households was asked which type of meat—sourced from animals considered "exotic" and offered at the same price—they would prefer to purchase. The options included buffalo meat, emu meat, ostrich meat, venison, and "none." Among these, venison was the most preferred choice, selected by 41.4% of respondents. These findings suggest that individuals living in rural areas are less likely to perceive venison as an "exotic" meat compared to those living in urban settings (Schupp et. al.,1998:35-43).

As a result, the following are the likely reasons for the modern consumer’s demand for venison:

- With the increasing mainstream media attention in recent years to issues such as animal welfare, sustainability, and environmental pollution, consumers are becoming more inclined to make environmentally conscious decisions.
- Health-conscious consumers, in search of nutritious food, are turning to alternatives to red meat due to its high fat and cholesterol content and associated health risks. In this context, venison appears as a suitable option due to its low fat and cholesterol levels.
- Consumers’ desire to discover new flavours and their adventurous attitudes may lead them to choose venison.

Meat quality and nutritional properties

The chemical composition of venison can vary due to a lot of endogenous (age, sex, overall health) and exogenous factors (living conditions and the seasons) (Wiklund et.al., 2010a:720-727).

Fat from ruminants is an important source of energy for humans but because they contain a high amount of saturated fatty acids and cholesterol, they are generally not considered highly favourable in the human diet. Characteristics such as low intramuscular fat and cholesterol content, as well as a higher proportion of lean meat, make venison more appealing to consumers (Kudrnáčová et al., 2018:9-27). Furthermore, venison is regarded as a good source of minerals, essential amino acids, and polyunsaturated fatty acids. Notably, venison fat contains significantly high levels of butanoic acid, 2-methylbutanoic acid, 2-ethylhexanoic acid, and octanoic acid in comparison to beef or pork fat (Serrano et al., 2019:227-268).

Most of the fat—especially in older deer—is located subcutaneously and intermuscularly rather than intramuscularly. In the primary cuts of the saddle and hindquarter, approximately 55–65% of the fat is distributed subcutaneously and is easy to trim. However, in the forequarters, neck, and ribs, the trimmable fat constitutes only about 16–30% of the total fat and is more difficult to remove (Pearse, 1990:11).

Compared to meat derived from farm animals, venison is generally considered a more significant source of complete protein (i.e., proteins that contain all essential amino acids). This is because, in addition to myofibrillar proteins, muscle tissues in venison also contain substantial amounts of sarcoplasmic proteins and have a lower proportion of connective tissue (Taylor et al., 2002:321-326; Barnier et al., 1999:13-18).

Venison provides all essential amino acids in balanced proportions according to human nutritional requirements (Lorenzo et al., 2013:77-83). Among the essential amino acids, lysine, leucine, and arginine are the most abundant, together making up approximately 50% of the total essential amino acids, while methionine shows the lowest levels, accounting for about 2.5% of the total essential amino acid content. Regarding non-essential amino acids, glutamic acid, aspartic acid, and arginine together represent approximately 65% of the non-essential amino acids. Serine, glycine, and proline are the least abundant of the non-essential amino acids; combined, they make up approximately a quarter (25%) of that total group (Serrano et al., 2019:227-268).

In terms of mineral content, the ash content in venison represents its overall mineral composition (Dahlan and Norfarizan Hanoon, 2008:498-503). The ash content in venison is approximately 1.1% (Volpelli et al., 2003:555-562; Šnirc et al., 2017:754-761; Daszkiewicz et al., 2015:77-83).

Generally, the most abundant macro-element is potassium, followed by phosphorus and sodium. (Serrano et al., 2019:227-268). Game meat has higher levels of both trace minerals and phosphorus compared to meat from domesticated ruminants like cattle, sheep, and goats. (Zarkadas et al., 1987:520–525). Regarding trace minerals, iron is the dominant element observed in the meat of wild red deer (Lorenzo et al., 2018:1561-1567; Maggiolino et al., 2018: 1938-1945). It is worth noting that the iron content in venison is approximately four times higher than that found in pork and beef (Dannenberger et al., 2007:90–93; Mahecha et al., 2009:365–371).

The mineral composition of venison is influenced by feeding regimes (Kudrnáčová et al., 2018:9–27), and it varies among different muscles depending on the type of physical activity and the composition of muscle fiber types (Serrano et al., 2019:227-268; Hoffman et al., 2007:762–767).

The pH level stands out as one of the most critical physical measures for assessing meat quality. This characteristic is a critical indicator of the meat's processing quality, directly affecting its storage stability, moisture retention, palatability, and visual appearance (color). (Wiklund et al., 2010a: 720–727; Kudrnáčová et al., 2018:9–27). Obtaining pH measurements from hunted animals is challenging, which results in limited data on pH values 45 minutes post-mortem. Available literature indicates that pH in venison is around 6.5 at 45 minutes after slaughter, decreases to 5.4–6.0 after 24 hours, and further drops to 5.3–5.9 between 36- 48 hours post-mortem (Serrano et al., 2019:227-268).

pH is especially influenced by the method of slaughter. Interventions performed prior to or following slaughter are directly linked to the speed and extent of the fall in pH (Hutchison et al., 2014:104-109). Animals subjected to stress during transport to the slaughterhouse exhibit higher pH values compared to animals that are shot directly in the paddock without any handling (Smith and Dobson, 1990:155–158). Therefore, avoiding stress factors prior to slaughter has a significant direct impact on meat quality (Serrano et al., 2019:227-268).

Supplementary feeding using high-quality pastures and grain-based feed mixtures has been shown to increase energy reserves in the muscles of animals, which positively affects the pH values of venison. Furthermore, the pH of wild game meat typically exhibits a lower pH compared to meat sourced from farmed animals. Additionally, the pH value of venison varies depending on factors like species, domestication status, sex, age, and muscle type (Serrano et al., 2019:227-268).

Sensory Properties

Organoleptic properties are pivotal determinants of consumer quality perception and subsequent acceptance of meat products. Specifically, visual characteristics such as colour serve as the initial attractive quality; nevertheless, flavour exerts the most profound influence on product acceptability. (Serrano et al., 2019:227-268).

Various factors have an effect on the sensory qualities, including the feeding and production type, gender, body condition score, low intramuscular fat content, type of suspension during slaughter, muscle type and breed. It is also suggested that feeding methods, by influencing the chemical composition of meat (especially fat and moisture content), can affect the flavour of venison (Franco et al., 2011:292–298; Lorenzo et al., 2013:77–83; Domínguez et al., 2014:223–230; Franco and Lorenzo, 2014:327–334; Dahlan and Norfarizan Hanoon, 2008:498-503).

Colour

Meat colour is a very important criterion for consumers. The typical dark red-brown colour of venison is usually explained by its higher myoglobin content (Young and West, 2001: 39–70), which is necessary because the muscles are subjected to greater physical demands in the wild (Ruiz de Huidobro et al., 2003:1439–1446). According to Hoffman and Wiklund (2006:197-208), the very dark colour of venison is also due to the low amount of light-coloured connective tissue.

Meat's coloration is determined by a range of influences, including the amount of myoglobin, the level of lipid oxidation, the muscle's physical makeup (which relies on pH), intramuscular fat (marbling), bacterial proliferation, the rate of oxygen usage, and factors related to slaughter like blood drainage. (Tateo et al., 2013: 293–302). These factors are affected by genetics, nutrition, slaughter age/weight, pre-slaughter conditions, post-mortem conditions, and preservation methods (Mancini and Hunt, 2005:100–121).

Colour evaluation is performed using spectroscopy according to the CIE Lab system, which measures lightness (L*) and chromaticity (redness a* and yellowness b*). For venison, CIELAB parameters range from 28.4 to 43.5 for L*, 10.7 to 23.2 for a*, 3.4 to 14.4 for b*, and 14.1 to 22.6 for chroma (Serrano et al., 2019:227-268).

Daszkiewicz et al. (2009:428–448) determined the colour of red deer meat using the CIE L*a*b* model, noting differences based on gender. Male roe deer meat was redder than female roe deer meat, with higher a* values and lower b* and L* values. According to measured L* values, female roe deer meat was lighter in colour (Dominik et al., 2012:185-191).

Tenderness

Tenderness is the primary factor affecting eating quality. Venison is generally more tender compared to beef, and certain species such as red deer and fallow deer (Dama dama) do not require aging for more than 1 to 3 days after slaughter (Barnier et al., 1999:13–18; Sims et al., 2004:119).

The rapid tenderization of venison is attributed to increased activity of proteolytic enzymes and smaller muscle fibre diameter (Wiklund et al., 1997: 33–43; Farouk et al., 2007:1023-1039)

When deer carcasses are hung by the pelvic suspension, the meat comes out more tender and juicier compared to hanging by the Achilles tendon This outcome is due to pelvic suspension creating greater extension in various muscle groups compared to Achilles tendon hanging. Crucially, increased muscle stretching during rigor mortis development leads to meat with greater tenderness. However, this effect does not apply to the tenderloin (M. psoas major) (Wiklund et al., 2014:55–61; Sims et al., 2004:119; Wiklund et al., 2004:87–94; Hutchison et al., 2010:311–316).

Regarding toughness, the leg muscles are more chewable in female roe deer, while the fillet is more tender in males (Dominik et al., 2012:185-191).

Water Holding Capacity

Venison contains approximately 75% moisture, and water holding capacity (WHC) is a key measure of meat quality and processability, thus influencing juiciness and tenderness (Okuskhanova et al., 2017:623–629). Due to the low intramuscular fat content of venison, WHC during cooking has a significant impact on meat quality (Wiklund et al., 2014:55–61). Cooking losses range between 21.5% and 37.3%, with lower values reported for farmed female fallow deer (Ludwiczak et al., 2017:1149–1155). Furthermore, hanging the carcasses post-slaughter for up to 6 weeks at +2°C has been shown to improve the water holding capacity of fallow deer meat (Wiklund et al., 2004:87–94).

Aroma and Flavour Intensity

Venison exhibits higher aroma and flavour intensity compared to beef (Rodbotten et al., 2004:137–144; Bureš et al., 2015:2299–2306). These differences primarily stem from heterogeneity in the lipid profile of the muscle, particularly the higher levels of unsaturated fatty acid content and rapidly oxidizable phospholipids. The diet consumed by the animals also influences the flavour profile of the meat (Serrano et al., 2019:227-268). Deer grazing on pasture produce meat rich in polyunsaturated fatty acids and exhibit more “grassy,” “gamey,” and “wild” flavours, whereas grain-fed animals yield meat with significantly lower levels of polyunsaturated fatty acids and a “milder,” “beef-like” taste (Wiklund et al., 2003a: 573–581,2003b:419–424). Additionally, wild fallow deer meat scores higher in terms of flavour, aroma, and juiciness, while farmed fallow deer meat tends to be more tender (Daszkiewicz et al., 2015:77-83).

Hygienic Quality

The shelf life of fresh meat is generally determined by microbial growth. Microbial growth is affected by many factors such as pH, slaughter hygiene, chilling and storage conditions. A critical threshold for assessing microbiological quality is 7 log10 CFU/g of aerobic microorganisms, above which the meat is considered unfit for human consumption (Wiklund et al., 2010b). Microbiological data reported for New Zealand chilled venison cuts stored at -1.5°C showed counts of 2 log10 CFU/g and 4 log10 CFU/g after 3 and 9 weeks, respectively (Wiklund et al., 2010b). In contrast, Swedish reindeer meat stored at +4°C for 3 weeks showed a higher microbial load of 6.8 log10 CFU/g (Wiklund, 2011:297). This difference might be related to different slaughter and processing procedures in these studies. Bacteriological loading of farmed deer carcasses compares favourably to beef, where counts between 500 and 1000/cm² are common (Nottingham and Wyborn, 1975:23-27), while wild venison may exceed 10,000/cm² (Sumner et al., 1977:829-832)

RESULTS AND DISCUSSION

The consumption of animal-derived protein plays a crucial role in maintaining a healthy diet. The use of meat derived from rabbits and deer as an alternative to traditional red meat is increasing day by day. Venison and venison products are becoming increasingly sought-after products due to growing consumer demand in recent years. Consumers prefer these products because of their nutritional properties such as having low calories and especially high iron content. An increase in deer farming and slaughterhouse establishments has been observed, particularly in New Zealand and European countries. Besides deer farming, venison is also marketed as game meat derived from wild deer. As an addition the by-products of deer farming and venison industry such as velvet antlers, deer skin, blood and musk have great economic importance. It is important to promote deer farming and to inform both the producers and the consumers about the benefits and economic value of venison and its by-products.

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The Production and Consumption of Venison Throughout the World

Ayça MEYDANAÇAR[1]
Özen YURDAKUL[2]

1- aycameydanacar@gmail.com ORCID No: 0009-0001-8668-0726
2- Prof. Dr.; Burdur Mehmet Akif Ersoy Üniversitesi Veteriner Fakültesi Gıda Hijyeni ve Teknolojisi Anabilim Dalı ozenkursun@mehmetakif.edu.tr ORCID No: 0000-0001-7680-015X

ABSTRACT

In recent years, production of venison and deer-derived products have gained increasing attention globally due to their nutritional value, economic potential and diverse applications. Deer farming (which is expanding especially in New Zealand, Australia and European countries) has a significant role in international trade and rural development. Venison is seen an attractive alternative to conventional red meat such as beef and pork due to its high protein content and low-fat levels. Beyond meat, deer farming provides valuable by-products like antlers, musk and bristle which are utilized in the cosmetic, pharmaceutical and traditional medicine industries. Recently growing consumer demand for natural, healthy and sustainable food sources has significantly contributed to the increasing popularity of deer products in both niche and mainstream markets. Additionally, deer farming helps maintain ecological balance and offers economic advantages for producers through efficient land use and high value outputs. Overall, deer industry represents a dynamic and rapidly growing sector with significant implications for food security, public health and the global economy which is why it's particularly important to inform and educate both the consumer and the producers about this sector's benefits. This work aims to raise awareness among producers and consumers about the benefits of these products, thereby encouraging both their production and consumption.

Keywords - Venison, deer, deer farming, velvet antler, musk

INTRODUCTION

Commercially, deer serve many purposes, yielding a diverse range of products including meat for the global market, plus valuable materials such as antlers, hides, bristles, musk and teeth. (Maggiolino et al., 2018:1938-1945). Venison is either obtained by farm-raised deer or hunted animals. The number and ratio of the wild and farm-raised deer vary across different regions of the world. Australia and New Zealand are prominent in deer breeding with their well-established deer farm systems. Although the production of antlers was common in Asia for centuries, modern deer farming started in the early 1970s in New Zealand, which was the first country to legalize deer breeding (Janiszewski et al. 2008:337-342; Kudrnáčová et al., 2018:9-27; Kelava et al., 2023:391). Hunting and game meat consumption have long held an important place in Turkish culture. Venison too is known as a red meat product which is important in Turkish culture. Its presence in Seljuk and Ottoman culinary culture, as well as in the pre-Islamic period, has been proven with historical documents (Özer and Özcan, 2023:607-623).

The predominant deer species in Europe, New Zealand and Australia are *Cervus elaphus* and *Dama dama.* In the Nordic countries Russia and

Alaska, reindeer (*Rangifer tarandus)* are raised in semi-domesticated herding systems. In North America and the United States, *Cervus canadensis*, fallow deer, *Cervus nippon* and *Axis axis* are commonly found in farms. Deer breeding is one of the fastest-growing industries in rural areas (Hoffman and Wiklund, 2006:198; Daszkiewicz et al., 2015:77-83; Kudrnáčová et al., 2018:9-27).

From a statistical perspective, there is a considerable lack of information, as data on venison consumption are often aggregated with beef. According to a study conducted in Germany in 1998, the average venison consumption in Europe was reported as 0.37 kg/year and the number of deer hunted in the EU was 300.000. Looking at more recent data, Quality Deer Management Association has stated in their report in 2014 that 5,57 million white-tailed deer has been hunted in the United States. (QDMA,2016)

Meat Yield

Looking at numerous studies on deer carcass quality and meat composition, it is understood that meat yield differs to species. But from a general perspective, deer species exhibit relatively high meat yield, and it has similar values to other ruminant meats (Kudrnáčová et al., 2018:9-27). Since venison is predominantly obtained through hunting, reliable data on carcass yield remain limited, as weighing animals before and after slaughter is rarely possible under hunting conditions. Based on the studies conducted, in general, deer carcass yield can be accepted as 55-60%. But it is known that this yield is influenced by several factors, including genetic background, species, sex, and slaughter age. (Serrano et al., 2019:227-268). Table 1 compares the nutritional composition of red deer and reindeer venison, beef and lamb.

Table 1. Examples of nutritional composition of red deer and reindeer meat, beef and lamb (Wiklund et al., 2014).

Species	Muscle/meat cut	Protein	Fat	Iron	Selenium	Vitamin E	Cholesterol	Total PUFA.
		g/100g	g/100g	mg/100g	µg/100g	mg/100g	mg/100g	g/100g
Red deer	*M. longissimus* (striploin)	22.6	1.2	3.3	9.0	0.8	59.0	0.3
Reindeer	*M. semimembranosus* (inside)	22.6	1.8	3.4	19.7	0.8	69.1	0.4
Beef	*M. longissimus* (striploin)	21.8	3.9	2.2	9.0	0.1	52.0	0.2
Lamb	*M. longissimus* (striploin)	20.0	2.5	1.6	1.4	0.7	78.0	0.2

Carcass weight in deer shows significant variation influenced by species and sex. Reported weights range dramatically, from as low as 17 kg for the European forest roe deer (Janiszewski et al. 2016:169-178) to 30–33 kg for fallow deer (Stanisz et al. 2015:1055-167), and exceeding 70 kg for farmed red deer (Phillip et al. 2007:215-221). Even within a single species, such as wild red deer, carcass weight varies widely by age, ranging from 20.6 kg to 58.5 kg (Maggiolino et al., 2018:1938-1945). Furthermore, female deer consistently yield lower carcass weights than males due to their reduced birth weight and slower growth rate (Landete-Castillejos et al., 2001:1085-1092; Janiszewski et al., 2008:337-342; Wiklund et al., 2008:174-177).

DEER PRODUCTS

There are lots of other products that are derived from deer besides venison. Especially deer skin, velvet antler, blood and musk have high economic value as they can be used in multiple industries ranging from cosmetics and fashion to functional health products.

Deer Skin

Deer skin is a valuable raw material for leather and fur industry. Skins of young animals, especially those up to 3 months old are in high demand (Bakharev et al., 2018:51-55). But the value of the skin can vary depending on species. Red deer skin is a high-quality leather which looks good, is soft and durable (Clark and Webster, 1985:303-306).

Nowadays, Northern people produce clothing and shoes out of deerskin. They also make sleeping bags and blankets. Leather is used to warm the floor in their homes; placed in sleds for warmth and comfort and it is also used to cover the items carried on sleds. Reindeer fur can be used for hats, fur clothing and resistant shoes. Felt boots with leather soles and boots made of reindeer skin are in great demand among the public. Reindeer skin is also used in the making of souvenirs and bags (Bakharev et al., 2018:51-55).

Antlers

Antlers are periodically replaced skull appendages that develop from permanent protrusions of the frontal bones known as pedicles (Kierdorf et al., 2009:535-542). The growth stage of the antlers of male members of the deer family is called velvet antlers (Kawtikwar et al., 2010:245-251). The velvet structure covers the antler during the annual development period to ensure blood circulation and nutrition (Kuba et al., 2015:591). Velvet antler is a valuable deer product that is used in the treatment of a wide variety of human diseases in eastern medicine (Brown, 1992:231).

The main material collected from antlers is called “velvet” because of the fine hairs covering the surface of the antler and this term is used to indicate the growth stage of the antler before calcification or ossification. Naturally, the antlers fall off on their own after they ossify; therefore, velvet cannot be obtained from fallen antlers. It is cut off by veterinarians or specialists under veterinary supervision when the deer is under local anaesthesia, following the Velveting Code of Practice (Kawtikwar et al., 2010:245-251).

Figure 1: Antler bases (ABs) created through velveting of the first set of growing antlers (first cut ABs) at a level 2–3 cm above the junction with the pedicle. (a, b) Red deer; (a) velveting; arrow: cutting line; (b) first cut AB (asterisk) created after velveting. (c, d) Sika deer; (a) two-branch antler; arrow: cutting line; (b) three-branch antler, yet to be velveted (Li, 2021:387)

There are lots of different uses for velvet as it has many different benefits for human health. Here listed are some examples.

- Antlers, in China and some Southeast Asian countries and Russia have been used as a traditional medicine for over 2000 years (Li, 2021; Kong and But, 1985; Batchelder, 1999:40-51). It has been used in the treatment of diseases related to the cardiovascular system, immune system deficiencies and tissue regeneration for many years (Wu et al., 2013:403-415).
- Velvet antler extract is also used as acupuncture injections with special effects on some issues such as sciatic neuritis, impotence, shoulder pain, stiff neck and post-stroke effects. (Brown, 2012:231). Velvet antler has been used for strengthening bones, boosting bone marrow, nourishing the blood, kidney deficiency, cold limbs, limb soreness, dizziness, blurred vision, seminal emission and impotence (Kawtikwar et al., 2010:245-251).
- Use of deer antler gelatine supports the kidney, frees the blood of the thoroughfare vessel, produces blood, and stops excessive uterine bleeding (Kawtikwar et al., 2010:245-251).

- Products containing velvet are also reported to have potential benefits in managing various conditions, including jaundice, mastitis, breast cancer, and infertility in both human and animal subjects. (Chen et al., 1989:9-12; Wu et al., 2013:403-415). Recent studies show that it benefits joints in cases of arthritis and osteoarthritis and improves athletic performance (Kawtikwar et al., 2010:245-251).

Deer Blood

One of the inevitable by-products of the meat industry is blood and it can amount to %4 of the live animal weight and %6 or %7 of the lean meat content of the carcass (Wismer-Pedersen, 1988:31-45). Deer blood is rich in proteins and polypeptides, and these components present a variety of physiological functions. Because of these bioactive components, deer blood has anti-aging and anti-fatigue properties. It also enhances immunity and enriches blood. For many years various products made with deer blood has been in use in Asia. Researchers investigated the effect of fermented deer blood on exercise induced fatigue and found that fermented deer blood can alleviate fatigue by eliminating harmful serum metabolites, reducing oxidative damage and supporting the intestinal barrier (Cui et. Al., 2021:1543).

A recent study showed that deer blood peptides exhibit photoprotective effects and can shield the skin from UV irradiation and has a potential of use in the form of topical gels (Bao et al., 2024).

Musk

Musk is a dried substance harvested from a specialized sac gland found between the abdomen and genitalia of mature male musk deer species. These include the Forest musk deer (Moschus berezovskii), Alpine musk deer (Moschus sifanicus), and Siberian musk deer (Moschus moschiferus), all belonging to the Cervidae family (Liu ve ark., 2021:46). Musk has a strong odour and can be light yellow, dark black or brown in colour (Kavak, 2018:188-229).

Musk is commonly used in the making of high-end cosmetics and perfumes. In addition to this, musk is known to have many pharmacological properties, such as stimulating and inhibiting the central nervous system, treating anti-myocardial ischemia, stimulating the cardiovascular system, enhancing the immune system, stimulating uterine contractions, stimulating the respiratory system, and providing anti-tumour, anti-ulcer, anti-dementia, and anti-bacterial effects, among others (Cao and Zhou, 2007:1662-1665; Feng and Liu, 2015:212, Liu et al. 2021:46).

- In India and Nepal, musk is used in Ayurvedic medicine as a stimulant to treat bronchitis, pneumonia, impotence, typhoid, typhus, and as a sedative to treat asthma, epilepsy, hysteria, and other nervous disorders (Shrestha, 1998:245-250).

- Musk has been used in China since ancient times (Liu et al. 2021:46) especially in the treatment of vascular headaches, stroke, coronary heart disease, angina, coma, neurasthenia, convulsions, ankylosing spondylitis, bedsores, ulcers and facial nerve paralysis (Shrestha, 1998:245-250).
- As an anti-inflammatory agent, musk is a more effective antidote for snake venom than hydrocortisone (Arora et al., 1962:453-457).
- A study by Ayuob and colleagues suggests that inhaling musk can significantly improve several symptoms associated with chronic unpredictable mild stress (a model for depression). Specifically, it helped to restore normal behavior, lower elevated stress hormones (glucocorticoids), and reduce damage to both memory and the structure of brain and salivary gland tissue (Abd El Wahab et al., 2018:221-231; Ayuob et al., 2016:271-284; Ayuob et al., 2019:95-102).

Due to its potential effectiveness, musk is often used in conjunction with other traditional Chinese medicines to treat illnesses. For example, Xihuang Wan, which contains dried bovine gallstones, olibanum oil, myrrha herb, and musk, is a traditional recipe for detoxifying the body, reducing phlegm, promoting blood circulation, and reducing swelling, as well as relieving stasis and help with pain relief. Primarily, it is used to manage and treat conditions like breast cancer, blisters, scrofula and multiple abscesses including those in the lungs and small intestine (Pharmacopoeia of the People's Republic of China, 2020).

RESULTS AND DISCUSSION

Nowadays the modern consumer is more conscious about the effects of food and diet on human health. This awareness especially in the meat industry has caused an increase in venison consumption as it has great nutritional value. The increase in demand for venison has caused deer farming practices to expand and made the price of venison more expensive compared to other meat and meat products. At an international level, New Zealand is recognized as the primary exporter. Venison can be marketed as fresh cuts of meat, frozen, dried or made into meat products like sausages and both venison and venison products are popular especially in European countries. The by-products of deer farming like deer skin, deer blood, bristles, velvet antler and musk all have many different uses in different industries. Use of deer products and venison go back both in eastern and western history. Musk for example is widely used in the production of luxury perfumes and cosmetics but also possesses a broad range of pharmacological and therapeutic properties. It has been shown to influence multiple body systems including stimulating and inhibiting the central nervous system, supporting cardiovascular and respiratory functions, enhancing immune responses, and exhibiting anti-tumour, anti-ulcer, anti-dementia, and anti-bacterial effects. Traditionally, musk has played an important role in Ayurvedic and Chinese medicine, where it has been used to treat conditions such as bronchitis, pneumonia, typhoid, asthma, epilepsy, vascular headaches, stroke, angina, ulcers, and nerve disorders. Another by-product of venison production is blood, and it is usually freeze dried and made into capsules. Deer blood contains elevated levels of iron and protein. Velvet antlers have been used for many years in treating cardiovascular diseases and immunodeficiency. Velvet extract can be used as acupuncture injections. In Chinese medicine, velvet is not only used for treating diseases but also as supplements for preventing diseases and supporting the immune system. The supplements are usually given to children to protect them from flu and similar diseases.

These products have gained a notable position in international trade due to their increasing global demand and economic value. However, their relatively high market price has created some challenges in supply, leading to limited accessibility in certain regions. This situation is further compounded by logistical constraints and seasonal availability which can affect both distribution and market stability. As a result, ensuring a consistent and sustainable supply chain remains a critical issue for producers, traders, and consumers alike.

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Effect of Mole Ratio on Formaldehyde Emission in Particle Board Production

Samet BUYUK[1]

Bulent KAYGIN[2]

Deniz AYDEMIR[3]

Suheyla Esin KOKSAL [4]

Orhan KELLECI[5]

1- Res. Forest Industry Engineer; Bartin University Forestry Faculty Forest Industry Engineering Department. Samet.buyuk@yildizemtegre.com.tr ORCID No: 0009-0008-3520-2557
2- Prof. Dr.; Bartin University forestry Faculty Forest Industry Engineering Department. bkaygin@bartin.edu.tr ORCID No: 0000-0003-3262-8444
3- Prof. Dr.; Bartin University forestry Faculty Forest Industry Engineering Department. denizaydemir@bartin.edu.tr ORCID No: 0000-0002-7484-2126
4- Assist. Prof.; Bolu Abant Izzet Baysal University Mudurnu Sureyya Astarci Vocational School Forestry Department. orhankelleci@ibu.edu.tr ORCID No: 0000-0003-4501-0854
5- Assoc. Prof.; Bolu Abant Izzet Baysal University Mudurnu Sureyya Astarci Vocational School Forestry Department. esinkoksal@ibu.edu.tr ORCID No: 0000-0001-7970-8412

ABSTRACT

This study examines the effects of the formaldehyde/urea (F/U) mole ratio in urea-formaldehyde (UF) resins used in particleboard production on emission levels and board performance. While wood-based panels are widely used in industry for their low cost, high mechanical strength, and aesthetic advantages, they pose environmental and health risks due to formaldehyde release. Formaldehyde can accumulate in indoor environments and cause serious health problems such as respiratory irritation, allergic reactions, and, in the long term, cancer. Therefore, the focus of the study is the development of new formulation designs that will both reduce emissions and maintain structural strength.

The research results show that a low F/U ratio significantly reduces formaldehyde emissions, but board strength decreases due to the weakening of the resin's three-dimensional cross-link structure. Nano-reinforced resins, systems containing lignosulfonate or tannin additives, and alternative bio-based binders are recommended to overcome this problem. Furthermore, the necessity of using international standards such as EN 717-1 in assessing formaldehyde emissions is emphasized.

Consequently, within the framework of sustainable production policies, optimizing the synthesis parameters of UF resins and integrating formaldehyde-scavenging additives are critical for both environmentally friendly production and user health protection. In this context, transitioning to formaldehyde-free adhesive systems will be a strategic goal for the wood panel industry in the future.

Keywords – Formaldehyde emission, Molar ratio (F/U), Sustainable binders, Urea-formaldehyde resin, Particleboard production

INTRODUCTION

Wood composite materials offer many advantages over solid wood. For this reason, their use has increased significantly over the last 50 years. Understanding some of the physical and mechanical properties of wood composites will ensure ease of use and longevity in their intended use. Wood-based composite panels hold a significant place among the economical and sustainable materials widely used in the construction, decoration, furniture, transportation, and building sectors. The advantages of these products, such as low density, aesthetic appearance, ease of processing, and good mechanical performance, have made them highly sought-after materials in both developed and developing countries (Bigin, 2010; Maloney, 1977). However, formaldehyde-containing synthetic adhesives such as urea-formaldehyde (UF), melamine-formaldehyde (MF), or phenol-formaldehyde (PF) are generally used in the production of these panels. These resins release free formaldehyde over time, becoming one of the most significant sources of volatile organic compounds (VOCs) that negatively impact indoor air quality (Roffael, 2006).

Long-term accumulation of formaldehyde in indoor spaces poses serious health risks, especially under poor ventilation conditions. The World Health Organization (WHO) has classified formaldehyde as a human carcinogen. Studies have shown that formaldehyde can cause allergic reactions in the skin, eyes, and respiratory system, weaken the immune system, and, in the case of long-term exposure, cause diseases such as nasopharyngeal cancer and leukemia (Menteşe & Güllü, 2005). Therefore, a primary goal of the wood-based panel industry is to develop next-generation resins that can minimize formaldehyde emissions without compromising mechanical properties. Recent legal restrictions (regarding formaldehyde emissions from wood composite panels), particularly in wood composite panels, have led researchers to develop various formaldehyde scavengers.

Formaldehyde emissions from wood-based panels vary depending on the chemical structure of the resin, production conditions, temperature and relative humidity, and the density of the panel. For example, it is known that emissions increase as the urea/formaldehyde molar ratio increases, while binder performance decreases in resins with lower molar ratios (Que et al., 2007). This creates technical challenges for manufacturers, including increased costs and reduced mechanical properties.

Recent studies have focused on the use of bio-based binders and formaldehyde scavenger additives to reduce emissions. It has been reported that formaldehyde can be prevented from being released by binding compounds such as tannic acid, urea, melamine, ammonia, and propylamine into the resin; some studies have even reported the development of formaldehyde-free adhesive systems using soy protein and natural polymers (Costa et al., 2013; Jang et al., 2011). However, most low-emission adhesives experience reduced bond strength and increased production costs, limiting industrial-scale sustainability (Hematabadi et al., 2012).

Yadav (2021) highlighted the potential of nanotechnology in this field, producing low-formaldehyde-emitting particleboards using inorganic nanoparticles such as nanosilica (SiO_2), nanomontmorillonite (K10), and nanowollastonite ($CaSiO_3$). The study demonstrated that nanomaterials, thanks to their high specific surface area and chemical interaction capacity, facilitate the retention of formaldehyde molecules within the resin and increase crosslink density, improving board strength. This enabled both the reduction of formaldehyde emissions and the preservation of board strength.

Such nano-reinforced resins offer an innovative approach compatible with environmentally friendly and sustainable production, as they can be implemented in existing production lines without requiring major modifications. Unlike previous studies in literature, which generally examine the effects of a single type of nanoparticles (Figure 1), Yadav's (2021) study comparatively examined the physical, mechanical, and chemical effects of multiple nanoparticles, thus filling a knowledge gap in this area and making a significant scientific contribution to reducing formaldehyde emissions.

Figure 1: Silicate nano particle preparing method (Yadav, 2021)

In this context, reducing formaldehyde emissions is not only a technical issue but also a critical requirement for environmental policy and public health. While E0 and E1 emission classes are mandatory in European Union countries, the current lack of legal obligations in Turkey leads to the persistence of substandard production in the sector (İstek et al., 2018). Therefore, awareness must be raised at both the producer and consumer levels; Strategies such as low-formaldehyde resins, alternative bio-based binders, and appropriate storage conditions should be expanded in production processes.

Reducing formaldehyde emissions in wood-based panels is of strategic importance for sustainable material production, indoor air quality, human health, and environmental protection. Research in this area is progressing toward the development of completely formaldehyde-free adhesive systems in the future, and this transformation will strengthen both environmentally friendly production approaches and green building standards.

WOOD COMPOSITE SECTOR

The solid wood panel sector has undergone a significant transformation since the last quarter of the 20th century, driven by technological advances in the woodworking and furniture sectors. Panel products such as MDF, particleboard, and OSB, in particular, have found widespread use thanks to their suitability for mass production, homogeneous structure, and ability to be produced to high-quality standards (Mantanis et al., 2018). These products are preferred in furniture production because they meet the desired aesthetic, durability, and production speed criteria. Furthermore, their low-cost production and readily available raw materials make them widely used in industry (Figure 2).

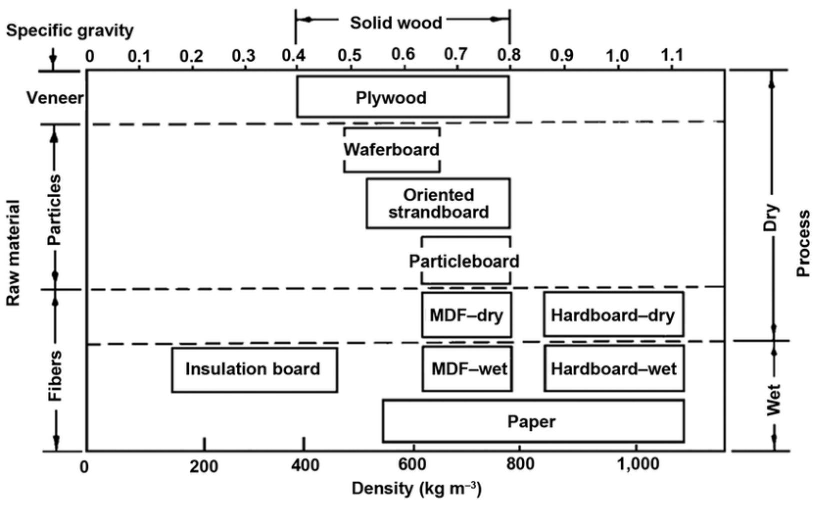

Figure 2: Wood composites classification (de Souza Pinho et al., 2023)

Thanks to developing production technologies, solid wood panels can be produced more efficiently and offer a variety of applications (Nam et al., 2024). Furthermore, the more resistant structure of solid wood panels to internal stresses and their natural fiber texture make them particularly preferred in high-quality interior designs.

The increase in the use of solid wood panels is also noteworthy in terms of environmental sustainability. Studies reveal that solid panel production has lower carbon emissions and energy consumption compared to MDF and particleboard (de Souza Pinho et al., 2023). Furthermore, the recyclability of the natural materials used in the production of solid panels offers a structure compatible with circular economic principles. The choice of wood composite to use is still up to the customer. Customers need assistance in this regard. They should be informed by the vendor about certain properties of the composites. In this case, the vendor must also have extensive knowledge and skills in wood composites (Figure 3).

Figure 3: Some wood composite types

The solid panel sector in Turkey has developed since the 1990s and has become a sector in which more than 30 companies operate. Increasing domestic market demand and export potential are also increasing the economic importance of this sector (Wu et al., 2021). In particular, the increasing preference for natural and healthy products among conscious consumers is contributing to the widespread adoption of solid panel products.

Furniture manufacturers observe that factors such as the durability of solid panels, surface quality, and ease of assembly influence their production preferences (de Souza Pinho et al., 2023).

However, high production costs and the need for technical knowledge are among the main obstacles facing the sector. This necessitates the development of sectoral training programs and technical support infrastructure.

When evaluated from technical, environmental, and economic perspectives, the solid panel sector has strong potential to provide an alternative to traditional panel board products. As the sector evolves towards producing more sustainable, healthy, and high-quality products, the importance of solid panels is increasing. In this context, conducting sectoral analyses at an academic level will ensure more effective use of existing potential. Research such as theses contributes to addressing knowledge gaps in the sector by revealing the structural status of the solid panel industry.

UREA FORMALDEHYDE AND MOLE CONCEPT

Urea-formaldehyde (UF) resins, one of the most widely used binders in wood-based panel production, have found widespread use in the industry due to their low cost and rapid curing. The most commonly used formaldehyde-based adhesives in wood composite panel production are given in Figure 4. However, formaldehyde emissions from these resins have become a significant environmental and legal concern in recent years due to their potential to harm human health and negatively impact indoor air quality (Nuryawan et al., 2017). Regulations aimed at lowering formaldehyde emission limits in many countries, especially the European Union, have necessitated the structural reformulation of these binders.

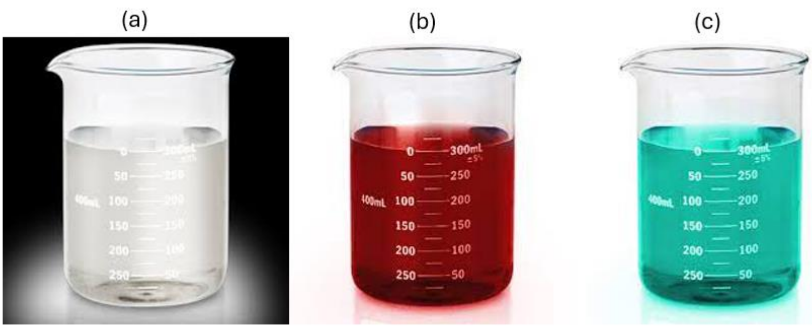

Figure 4: Formaldehyde-based adhesives (resins) are the most commonly used in wood composite panel production, (a) urea formaldehyde, (b) fonol formaldehyde, (c) melamine formaldehyde

One of the most common ways to reduce formaldehyde emissions is to reduce the formaldehyde/urea (F/U) mole ratio used in the production of UF resin (Figure 5). However, research has shown that lowering the F/U ratio can cause significant performance losses in the mechanical and physical properties of panels (Ghafari et al., 2016). This has led manufacturers to seek solutions to develop products that are both durable and have low formaldehyde emissions.

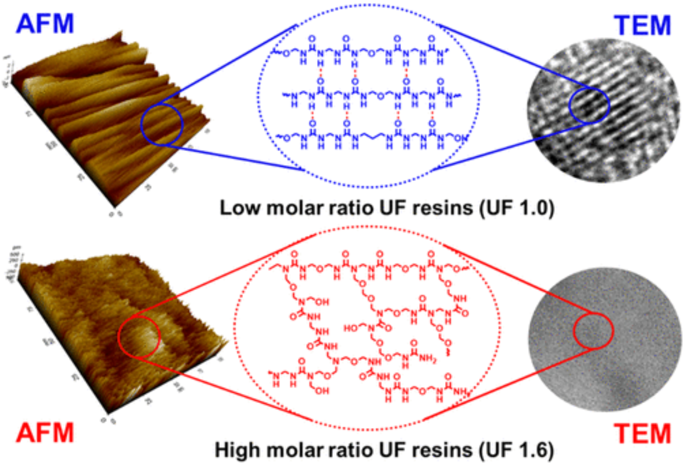

Figure 5: Molecular image of mole ratio change (Wibowo & Park, 2021)

It has been reported that low-molecular-ratio UF resins form crystalline lamellar structures instead of traditional three-dimensional cross-linked structures, thus weakening their adhesion properties (Wibowo & Park, 2021). This physical transformation directly affects both the molecular structure of the resin and the durability of the final product. Among the solutions to this problem in the literature, modifying UF resins with alternative components such as furfural can achieve both internal bond strength (IB) and emission control (Ghafari et al., 2016).

However, in recent years, new synthesis methods have been developed to transform low-mole-ratio crystalline UF resins back into amorphous structures. These methods aim to prevent hydrogen bonding within the resin, allowing the cross-linked structure to re-form, thus improving both adhesion performance and emission values (Wibowo & Park, 2021).

Furthermore, it has been noted that the initial synthesis conditions of UF resins significantly affect final product performance. Studies show that even when the F/U ratio is held constant, the initial mole ratios used affect parameters such as the degree of branching, molecular weight, and adhesion strength of the resin, altering formaldehyde emissions (Lubis & Park, 2020).

Resin formulations that minimize formaldehyde emissions while maintaining the physical and mechanical performance of the panel are needed. Studies in this area in the literature provide a significant knowledge base in line with sustainable production goals and reinforce the scientific basis of the research.

FORMALDEHYDE EMISSION STANDARDS IN THE WOOD PANEL INDUSTRY

Wood-based panels (particleboard, MDF, OSB, etc.) are widely preferred for interior applications. Urea-formaldehyde (UF)-based thermoset resins are generally used in the production of these panels. UF resins offer advantages due to their low cost and rapid curing properties; however, their biggest drawback is formaldehyde emissions, which are harmful to the environment and human health (Artner et al., 2021).

Formaldehyde is classified as a Group 1 carcinogen by the International Agency for Research on Cancer (IARC). Long-term exposure to formaldehyde can lead to health problems such as respiratory irritation, immune suppression, and cancer (Savov & Antov, 2020). Therefore, strict regulations were introduced, particularly in European countries, since the 1980s, and this has evolved into a global standardization over time.

Emission classes (E0, E1, E2) have been developed, requiring manufacturers to comply with specific formaldehyde emission levels (Figure 6). These classes vary depending on production parameters such as the wood species used, the type and ratio of binders, and the pressing temperature (Ghafari et al., 2016).

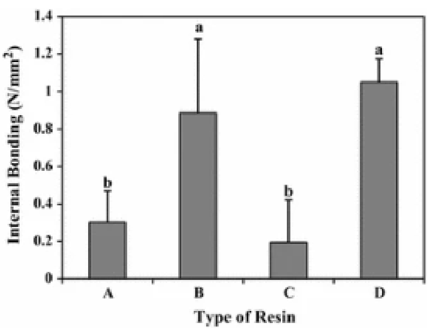

Figure 6: Change in tensile strength perpendicular to the surface according to resin type, (a) Industrial UF, (b) Laboratory UF, (c) urea–formaldehyde furfural resin with 25 % replacing (d) urea–formaldehyde furfural resin with 50 % replacing (Ghafari et al., 2016)

Many strategies have been developed in the literature to reduce formaldehyde emissions. These include UF resins with low F/U (formaldehyde/urea) mole ratios, formaldehyde-scavenging additives (e.g., lignosulfonate, nanoclay, nanocellulose), bio-based resin systems, and alternative adhesives (Antov et al., 2021; Lubis & Park, 2021).

Consequently, standards that limit formaldehyde emissions are of great importance in line with sustainable production goals and to protect human health. The future of the wood panel industry is being shaped in parallel with the development of environmentally friendly resin technologies (Alkan et al., 2025).

UREA FORMALDEHYDE RESINS: SYNTHESIS MECHANISM, EMISSION ISSUES, AND TESTING STANDARDS

Urea formaldehyde (UF) resins have been widely used in wood-based panel production since the 1930s and offer advantages such as strong adhesion, low cost, colorfastness, and heat resistance (Jovanović et al., 2019). However, their biggest drawback is the release of formaldehyde due to hydrolytic decomposition in the presence of moisture and acid.

UF resins are synthesized in three main stages: alkaline methylolation, acidic condensation, and cooling-structure stabilization. During this process, parameters such as the F/U mole ratio (usually 1.8–2.5), pH level, and temperature affect the structure and emission values of the final product (Wibowo & Park, 2021). Low F/U ratios can reduce resin stability and cause resin precipitation.

The pH level is a crucial parameter in emission control. The condensation reaction begins at pH levels of 2–3 and reaches its maximum reaction rate between 5–8. The reaction ceases under high pH conditions, making emission control difficult (Lubis & Park, 2018).

Various test methods based on standards such as ISO, ASTM, and EN are used to measure formaldehyde emissions. The EN 717-1 chamber test is considered the reference method that best simulates real indoor conditions. In the industry, the perforator test is more widely preferred (Wibowo et al., 2022).

Methods developed in the literature to reduce formaldehyde emissions include lowering the F/U mole ratio and adding additives such as lignin, tannin, or nanoclay to the resin. For example, tannin-added resins have better structural rigidity and water resistance (Peng et al., 2022), and nanoclay reinforcement both reduces emissions and improves mechanical properties (Wibowo et al., 2021).

Consequently, optimization of the synthesis parameters of UF resins and application of appropriate testing standards are critical for both environmental sustainability and user health.

CONCLUSION

This study examined in detail the changes in formaldehyde emission values depending on the mole ratio of urea-formaldehyde (UF) resins used in particleboard production. The research findings revealed that low F/U mole ratios are effective in reducing formaldehyde emissions, but this leads to certain deteriorations in the physical and mechanical performance of the panel. Therefore, developing resin formulations that do not cause performance loss while maintaining environmental sustainability in the industry is of critical importance.

Furthermore, the harmful effects of formaldehyde on human health necessitate the strict implementation of internationally recognized standards (e.g., EN 717-1). Variables such as the binder type, pressing temperature, ambient pH, and additives used in panel production processes directly impact formaldehyde release, so these parameters must be optimized. The use of nanotechnology-supported binder systems, bio-based alternative resins, and formaldehyde-scavenging additives are among the promising solutions in this regard.

Consequently, to comply with legal regulations and protect user health, the transition to next-generation formulations in the synthesis of UF resins has become a crucial necessity. In this context, experimental studies provide the scientific basis to support the wood panel industry's shift toward greener, healthier, and more sustainable production methods. The widespread adoption of formaldehyde-free adhesives will be a strategic goal for green building practices and indoor air quality in the future.

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Pansharpening Techniques in Remote Sensing: A Comprehensive Review of Methods, Applications and Advances

Selçuk ALBUT [1]

1- Prof.Dr.; Tekirdağ Namık Kemal Üniversitesi Ziraat Fakültesi Biyosistem Mühendisliği Bölümü. salbut@gmail.com ORCID No: 0000-0002-0055-632X

INTRODUCTION

Pansharpening resolves the enduring trade-off in remote sensing between spatial resolution and spectral fidelity. Contemporary satellites like Landsat-8, Sentinel-2, and WorldView-3 deliver high-quality data, however frequently lack both features concurrently. Over the past two decades, researchers have suggested numerous fusion strategies. Recent advancements indicate substantial enhancements through the utilisation of AI-based models (Ciotola et al., 2022:60; Xu et al., 2023:31; Li et al., 2025:185).

The accessibility of high-resolution imaging facilitates applications in agricultural, urban surveillance, hydrology, forestry, and disaster response. Nonetheless, obstacles persist in refining techniques that enhance performance while maintaining computational economy.

The swift advancement of satellite sensors has led to the extensive utilisation of remote sensing images. Nevertheless, owing to the technical constraints of the sensors and other variables, current remote sensing instruments must engage in a basic trade-off between spatial and spectral resolutions (Fletcher, 2023:1206, Restaino, 2025:16). There are two primary constraints. The radiation energy received by the sensor. The high spatial resolution (HR) panchromatic (PAN) image possesses a greater bandwidth, whereas the low spatial resolution (LR) multispectral (MS) image exhibits a smaller bandwidth. To enhance photon collection and optimise the signal-to-noise ratio (SNR), the dimensions of the MS detector must be increased, resulting in a bigger instantaneous field of view (IFOV) and consequently a reduced spatial resolution. The volume of data gathered by the sensor. The data capacity of the HR MS image is considerably more than that of the combined LR MS and HR PAN images. Consequently, this can surmount the challenge of restricted on-board storage capacity and the data transmission from the platform to the ground. PAN/MS image fusion, commonly known as "pansharpening," integrates the geometric detail of the high-resolution PAN image with the spectral information of the low-resolution MS image to produce a high-resolution MS image, effectively addressing the tradeoff between spatial and spectral resolutions of satellite sensors (Kaur et al., 2021:4961; Shen et al., 2016:7135; Aiazzi et al., 2012:533; Ghassemian, 2016:32; Zhang et al., 2024:943).

In the domains of GIS (Geographic Information Systems) and Remote Sensing, pan-sharpening is a crucial technique employed to enhance the resolution of images captured from satellite or aerial platforms. This technique often involves the integration of multispectral images with low spatial resolution with panchromatic images with high spatial resolution. This amalgamation produces a novel image that encompasses both elevated spatial and spectrum information (Kaur, et al., 2024:980).

The significance of panoramic sharpening, or pan-sharpening, can be summarised as follows.

- Comprehensive Examination: Pan-sharpening enhances the spatial resolution of photographs, facilitating better and more detailed study of terrestrial objects. This is particularly vital in domains such as urban planning, agriculture, and environmental monitoring.
- Conservation of Spectral Data: The pan-sharpening procedure maintains the colour and spectral attributes of multispectral data, yielding spatially enhanced images. This mitigates misinterpretations in applications such as environmental assessments and vegetation surveys.
- Enhanced Efficiency and Precision: Images produced through pan-sharpening facilitate more accurate classification and object detection. This presents a significant advantage, particularly in search and rescue missions as well as military operations.
- Reduced Data Storage and Processing Burden: Images with great spatial resolution are typically huge in size. Pan-sharpening integrates lower-resolution multispectral data with high-resolution panchromatic data to produce detailed information while minimising storage requirements and processing power.
- Enhancing Image Interpretation Skills: It enables the disaggregation of various land types, particularly metropolitan regions, agricultural land, or forest ecosystems. For instance, edifices, thoroughfares, or arable land become more conspicuous.

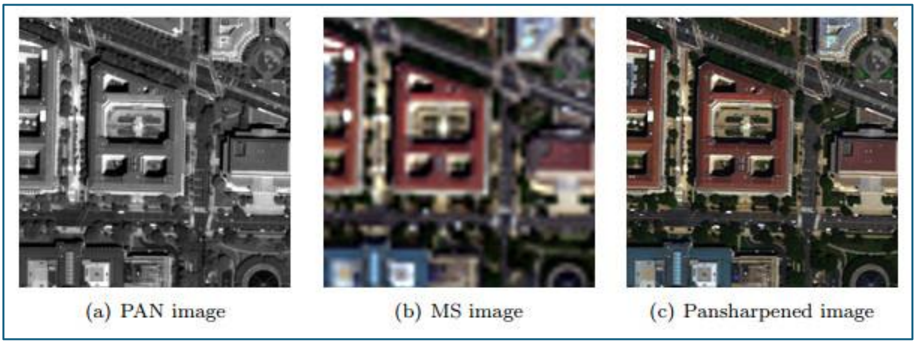

Figure 1: An example of pansharpening (Zhang et al., 2024:943)

Applications of Pansharpening

The pansharpening procedure enhances spectral and spatial detail by integrating high-resolution panchromatic (PAN) images with low-resolution multispectral (MS) images. This procedure is utilised in various domains. Pansharpening enhances both spectral and spatial information by merging high-resolution panchromatic (PAN) images with low-resolution multispectral (MS) images. This procedure is utilised across various domains (Yang et al., 2023:16857; Bandara and Patel, 2022:1767; Wang, 2023:2311; Zhang et al., 2024:943). The primary applications of the pansharpening technique are as follows:

Assessment of Agricultural Zones and Product Monitoring:

- Land Use/Land Cover Mapping (LULC) is employed to identify many categories of land use, including agriculture, forestry, aquatic surfaces, and urban regions.
- Identification of Agricultural Zones and Product Monitoring: Thrace is a significant agricultural region in Turkey. Multispectral pictures are utilised to identify regions of agricultural crops including wheat, sunflower, maize and grapes. Nevertheless, due to the frequently low resolution of these multispectral images, product classification can be enhanced by augmenting the detail using Pan-sharpening.
- The Normalised Difference Vegetation Index (NDVI) can be estimated with greater accuracy using pan-sharpened pictures.
- Agriculture and Vegetation Analysis: This methodology is employed to identify crop varieties in agricultural terrains, monitor crop health, and facilitate precision agriculture initiatives.

Urban Planning and Land Management: High-precision maps can be generated through their application in urbanisation, infrastructure initiatives, and construction assessments. Satellite imagery enables the monitoring of urbanization's progression over time, as well as alterations in agricultural land and forested regions. Pan-sharpening enhances the clarity of features such as new constructions, roadways, and industrial zones.

Natural Resource Management and Environmental Monitoring: It is utilised for the surveillance of forest regions, the analysis of watersheds, and the prolonged observation of environmental alterations. Pan-sharpened satellite imagery enables more precise monitoring of characteristics such as water levels, vegetation alterations, and coastline shifts in critical wetlands. High-resolution photos acquired using pan-sharpening offer significant benefits for monitoring deforestation, assessing post-fire recovery, and identifying illicit logging activities.

Disaster Management and Risk Assessment: Pan-sharpening yields clear images for the analysis of natural disaster impacts, including earthquakes, floods, and fires, facilitating the creation of risk maps.

Examination of Industrial and Environmental Impacts: Industrial facilities are proliferating swiftly in numerous agricultural regions. Comprehensive analysis of images is required to assess aspects such as the proliferation of industrial zones, its effects on agricultural regions, and environmental contamination. Pan-sharpening enhances the detection of items such as industries, waste sites, and sources of smoke or water pollution.

Pansharping Data

Pansharpening is the technique of augmenting the spatial resolution of multispectral images through the integration with a higher-resolution panchromatic image. Table 1 summarises prominent global satellite systems that feature "panchromatic" (PAN) and "multispectral" (MS) bands, facilitating both imaging modalities. (Aiazzi, et al., 2012:533, Fasbender, et al., 2008:1847, Alparone, et al., 2007:3012, Zhou, et.al., 2022:274, Guan, et.al., 2023:6860, NİK System, 2025).

Table 1. Example Satellite Sensors Used in Pansharpening

Satellite	PAN Resolution	MS Resolution	Number of MS Bands	Countries & Organizations Name
DEIMOS-2	1 m	4 m	4	European technology group
GÖKTÜRK-2	2.5 m	5 m	4	Turkiye
CARTOSAT-3	0.25	1.14	4	Indian Space Research Organisation (ISRO)
Landsat-8 OLI	15 m	30 m	11	NASA & USGS (U.S. Geological Survey)
WorldView-2	0.46 m	1.84 m	8	DigitalGlobe / Maxar
WorldView-3/4	0.31 m	1.24 m	8	Maxar
GeoEye-1	~0.41 m	1.65–1.84 m	4	Maxar
Pléiades 1A/1B	0.5 m	2 m	4	Airbus
Pléiades Neo	0.3 m	1.2 m	4	Airbus
SPOT 6/7	~1.5 m	6 m	4	Airbus
Ikonos	~0.8 m	~3.28 m	4	
SkySat, SuperView-1	0.5 m	2 m	4	Beijing Space View
Kompsat-3A	0.55 m	2.2 m	4	KARI, South Korea

TripleSat	0.8 m	3.2 m	4	SSTL
Jilin-1	0.72 m	2.88 m	4	Chang Guang, China
Alsat-1B	12 m	24 m	4	Algeria
KhalifaSat	0.7 m	2.98 m	4	UAE
Kanopus-V-IK	2.7 m	12 m	4	Russia

Pansharpening seeks to integrate spatial features from PAN images with the spectral richness of MS images. Panchromatic (PAN): High-resolution, monochromatic greyscale imaging. Multispectral (MS): Several lower-resolution bands that capture distinct wavelength ranges. The data utilised in the pansharpening procedure often comprises:

Panchromatic Image (PAN)

A panchromatic image is a monochromatic greyscale image obtained by a sensor that detects a broad spectrum of wavelengths, usually encompassing the entire visible spectrum and occasionally reaching into the near-infrared range. The term "panchromatic" derives from the Greek words "pan" (meaning "all") and "chromatic" (meaning "colour"), signifying that the sensor captures light over the whole visible spectrum.

Panchromatic images provide superior spatial resolution due to the sensor's ability to capture light across a wide wavelength spectrum, facilitating greater detail than multispectral images. Satellites such as WorldView-3 and Landsat offer panchromatic images with resolutions ranging from 30 cm to 15 meters, contingent upon the sensor employed.

Panchromatic images, in contrast to multispectral images that capture various bands (e.g., red, green, blue, near-infrared), are single-band and depict the intensity of light across their whole sensitive wavelength range.

Panchromatic sensors often encompass a wide spectrum of wavelengths, typically ranging from approximately 450 nm (blue) to 800 nm (near-infrared), but this may differ based on the specific sensor. Panchromatic photographs, being single-band, are rendered in greyscale, with pixel values indicating the strength of light reflected from the surface. Panchromatic photos are frequently combined with lower-resolution multispectral images to produce high-resolution colour images. The elevated spatial resolution renders panchromatic images optimal for discerning intricate elements, including edifices, thoroughfares, and other infrastructure. Panchromatic photographs are valuable for tracking temporal changes, such as urban expansion or deforestation, owing to their great resolution. They are employed in disaster response to evaluate damage with great accuracy.

A panchromatic image is a high-resolution, single-band image that encompasses a broad spectrum of wavelengths, rendering it essential for intricate spatial analysis and as a constituent in pansharpening techniques.

Multispectral Image (MS)

Multispectral imaging is a method that enables the capture of images of an item or surface at many wavelengths, typically including visible light, near-infrared, and mid-infrared. This technique is employed to disclose information that is imperceptible to the unaided eye.

A multispectral image comprises a series of images obtained at various wavelengths of the electromagnetic spectrum, typically encompassing both visible and non-visible light, including infrared and ultraviolet. In contrast to conventional RGB images that solely capture red, green, and blue light, multispectral imaging encompasses a broader range of wavelengths, offering enhanced information regarding the scene or item being scanned.

The resolutions of multispectral images from various satellites differ based on the capabilities of their sensors and their designated applications (Alcaras, 2023:93).

The multispectral resolutions of some significant remote sensing satellites are as follows:

Resolution, band quantity, and observation frequency are essential criteria in satellite selection. Satellite data must be picked based on the intended application.

- Landsat and Sentinel-2 are utilised for the surveillance of extensive regions at medium resolution.
- WorldView-3 and GeoEye-1 are proficient in high-resolution urban and environmental assessment.
- The SPOT-6/7 and PlanetScope are appropriate for commercial and agricultural monitoring.
- MODIS is employed to observe extensive alterations in the atmosphere, ocean, and terrestrial surface.

Panchromatic images are excellent for comprehensive structural investigation owing to their high resolution, although they lack spectrum information. Multispectral images offer significant spectral information for material separation, but at reduced spatial resolution.

To achieve optimal results, both images are frequently amalgamated (pan-sharpening) to produce high-resolution multispectral images.

Table 2: Comparison of Panchromatic and Multispectral Images

Feature	Panchromatic Image	Multispectral Image |
Definition	Acquires an image in a singular, extensive spectral band, typically in greyscale (monochrome).	Acquires images over various designated spectral bands (e.g., Red, Green, Blue, Near-Infrared, etc.).
Spectral Range	Encompasses a wide array of wavelengths, typically within the visible spectrum.	Encompasses various distinct wavelength bands, including visible and infrared spectra.
Resolution	Elevated spatial resolution resulting from extensive bandwidth, yielding intricate visuals.	Inferior spatial resolution relative to panchromatic images, although possessing more extensive spectral information.
Color Information	Devoid of colour and spectral distinction.	Offers colour and spectral information, essential for material differentiation.
Applications	Optimal for high-resolution mapping, edge detection, and terrain analysis.	Utilised in vegetation analysis, water quality evaluation, land cover categorisation, and remote sensing.

In certain conditions, supplementary data may be utilised alongside panchromatic and multispectral satellite imagery in pansharpening applications. These;

Hyperspectral Data (Optional): Hyperspectral data, when accessible, can offer enhanced spectral information for sophisticated pansharpening methods.

Digital Elevation Model (DEM): Occasionally employed to enhance geometric rectification and spatial alignment during the fusion process.

Radiometric Calibration Data: Metadata pertaining to the sensor, atmospheric corrections, and radiometric calibration to guarantee precise fusion.

Ground Truth or Reference Data: High-resolution reference images or field data for validation and accuracy evaluation.

PANSHARPENING TECHNIQUES

A substantial variety of pan-sharpening techniques have been documented in the literature to far. Upon examination of these approaches, it is observed that they typically preserve either the spectral structure or the spatial detail content. Consequently, it is infeasible to discuss 'the optimal pansharpening method.

An examination of the current literature reveals the absence of a standardised classification for pan-sharpening methods. Due to the varying criteria employed for classification, it is typical for the identical pan-sharpening method to be categorised differently across various studies. Traditional pan-sharpening techniques in the literature were analysed under four categories: component substitution-based, multi-resolution analysis-based, color-based, and hybrid methods. Modern methods encompass morphology-based, sparse representation-based, deep learning-based, and metaheuristic optimization-based approaches (Şerifoğlu Yilmaz, Ç., et al., 2021:1340).

Pansharpening is a conventional method for amalgamating the spatial elements of a high-resolution panchromatic image with the spectrum information of a low-resolution multispectral image to generate a high-resolution multispectral image. A multitude of pan-sharpening techniques has been established (Du, 2007:518; Zhang, 2024:657; Garzelli et al., 2008:81; Pohl and Van Genderen, 1998:823). Pansharpening techniques are primarily classified into four categories: Component Substitution (CS), Multi-Resolution Analysis (MRA), Model-Based/Hybrid Approaches, and Deep Learning-driven methods (Kamala et al., 2024:1; Meng et al., 2019:102; Deng et al., 2021:6995; Ozcelik et al., 2021:3486).

The CS and MRA methodologies are crucial in the field of pansharpening. They have demonstrated commendable performance with an equitable computational load. The CS-based techniques depend on the principle of projecting the MS image into an alternative domain, wherein the spatial information may be readily distinguished into a component, typically referred to as the intensity component. The (potentially equalised) PAN image may be replaced with the intensity component. The enhanced form of the MS image is achieved using inverse projection, restoring the data to its original MS domain. CS-based approaches can produce results with excellent spatial fidelity, often at the expense of increased spectrum distortion. Notable examples of methods in this category include band-dependent spatial-detail (BDSD) with local parameter estimation, the robust BDSD-PC method, partial replacement adaptive component substitution (PRACS), and Gram–Schmidt (GS) spectral sharpening (Garzelli et al., 2008: 228; Vivone, 2019: 6421; Choi et al., 2011: 295; Laben and Brower, 2000; Adelwhab and Cherifa, 2025: 517).

MRA-based methodologies incorporate spatial features derived from the PAN image using an MRA framework into the MS image to achieve a high spatial resolution MS image. MRA-based devices retain spectral information but may experience spatial distortion. Examples of methods in this category include the smoothing filter-based intensity modulation (SFIM) and the additive wavelet luminance proportional (AWLP). The "à-trous" wavelet transform, the Laplacian pyramid (LP), the generalised Laplacian pyramid (GLP), the GLP with robust regression, and the GLP with full-scale regression (GLP-Reg) (Deng et al., 2021:6995; Ozcelik et al., 2021:3486; Liu, 2000:3461; Otazu et al., 2005:2376; Shensa, 1992:2464; Burt and Adelson, 1983:532).

Recently, VO methodologies have demonstrated competitive efficacy in resolving the pansharpening challenge. This class encompasses Bayesian methods, variational approaches, and compressed sensing techniques. Notwithstanding their formal mathematical sophistication, VO methodologies yield only marginal enhancements relative to the state-of-the-art CS and MRA techniques; such enhancements entail significant computational demands and necessitate extensive parameter tuning, elucidating the prevalent endorsement of CS and MRA for both benchmarking and practical applications (Jiang, et al., 2015:540, Duran, et al., 2014:761, Fang, et al., 2013:2822, Wang, et al., 2019:227, He, et al., 2014:4160).

The CNN-based approaches rely on extensive dataset training to acquire a nonlinear functional mapping between low spatial resolution multispectral (MS) pictures and high spatial resolution MS images (Deng et al., 2021:6995; Yang et al., 2017:5449; Huang et al., 2015:1037; Xie et al., 2020).

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Effects of Heavy Metal Accumulation on The Antibacterial Activity of Plants

Muazzez GÜRGAN [1]

Sevinç YEŞİLYURT[2*]

Aydın ADİLOĞLU[2]

1- Assoc. Prof.Dr.; Tekirdağ Namık Kemal University, Faculty of Arts and Sciences, Department of Biology, 59030, Tekirdağ. mgurgan@nku.edu.tr ORCID No: 0000-0002-4683-820X

2- Prof. Dr.;. Tekirdağ Namık Kemal University, Faculty of Agriculture, Department of Soil Science and Plant Nutrition, 59030, Tekirdağ *Corresponding email: sevincyesilyurt1@gmail.com ORCID No: 0000-0002-0062-0491

3- Prof. Dr.; Tekirdağ Namık Kemal University, Faculty of Agriculture, Department of Soil Science and Plant Nutrition, 59030, Tekirdağ. aadiloglu@nku.edu.tr ORCID No: 0009-0005-2006-5957

ABSTRACT

This review discusses the effects of changes in the biological characteristics of plants on their antibacterial properties in the process of removing heavy metals from polluted sites through bioaccumulation. Increasing industrial activities have led to the uncontrolled release of heavy metals into the environment, resulting in a significant increase in metal pollution on a global scale. Heavy metal pollution has persistent and far-reaching adverse effects on human health and ecosystems, and effective removal of this pollution is of paramount importance. Chemical and physical treatments can be costly and are not feasible in large areas. In contrast, bioaccumulation-based biological remediation methods are a sustainable and environmentally friendly alternative that allows the removal of heavy metals through accumulation and/or detoxification using microorganisms. While heavy metals can inhibit the growth of some plant species and reduce their bioaccumulation capacity, plants that have developed metal tolerance can play an important role in removing this pollution. Plants used in the removal of heavy metals in soil can increase the production of bioactive molecules that take place in their metabolism to eliminate heavy metal stress. In this case, antibacterial, anticancer, antioxidant and anti-inflammatory effects of plant materials increase. In some cases, the accumulation of heavy metals in plants can cause the opposite effect. These plants used in phytoremediation cannot be used as foodstuffs after cleaning the soils and become waste. However, the evaluation of the antibacterial effect in the evaluation of plant materials that become waste after phytoremediation is very important in terms of the evaluation of these waste plants in cosmetic, pharmaceutical, etc. industries and recycling of these wastes. At this point, determining the changes on antibacterial effects is an indicator that will determine the value of these waste materials in industries.

Keywords – Phytoremediation, antibacterial activity, bioactive molecule

INTRODUCTION

The environment is under continuous pollution by industrial charges, the rapid and never-ending urbanization. Although more and more agricultural land is needed to provide the large amounts of food needed by the growing population, the amount of productive agricultural land in the world is decreasing day by day. One of the biggest reasons for this is the pollution of agricultural land. Ignorance in agricultural practices like excess use of chemical fertilizers, deforestation, cultivation of same crops repeatedly already damages agricultural lands. In addition, industrial waste, municipal wastewaters, and traffic pollute the agricultural lands. Among all other pollutants, heavy metals are of special interest since they are regarded among emerging environmental chemical contaminants (Ojija, 2024). They can result in accumulation in human body in small quantities through food, drinking water, and air. There are over sixty naturally occurring heavy metals such as Cd, Cr, Co, Cu, Fe, Hg, Ni, and Zn that are commonly found in the Earth's crust in the form of compounds or complexes like carbonates, oxides, silicates, and sulfides. Exposure to these metals can cause serious health problems, including mental health issues, respiratory and cardiovascular diseases, kidney failure, abdominal pain, allergic reactions, nausea, vomiting, anemia, and fatigue (Coelho et al., 2015). The scientists estimate that 14-17% of world's agricultural lands have been contaminated by heavy metals like As, Cd, Co Cr, Ni and Pb whose concentrations exceed the thresholds (Hou et al., 2025).

The heavy metals contaminating the soils can be cleaned up via physical, chemical and biological methods. Conventional remediation approaches often depend on physicochemical processes, such as high-temperature incineration, soil leaching, chemical oxidation, air surfacing, pumping and treatment (Yeşilyurt and Gürgan, 2023). However, these traditional methods frequently result in secondary waste products that may still possess toxic characteristics and are often neither cost-effective nor environmentally sustainable. They usually destroy biological activity in soil by damaging the soil microbial flora and converting the soil into a clean but inappropriate environment for plant growth. On the other hand, biological methods, i.e. bioremediation and phytoremediation, are environmentally friendly and cost-effective ways to clean up soils. Despite being slow and applicable to soils contaminated with relatively low concentration of heavy metals, these methods are applicable to a large extend and preferable since they do not damage the soil microbiota, rather they support the soil viability and enhance the organic matter and minerals of the soil (Oubohssaine and Dahmani, 2024).

PHYTOREMEDIATION FOR HEAVY METAL REMOVAL

Phytoremediation refers to a type of bioremediation in which plants contribute to the neutralization, detoxification, or extraction of organic or inorganic contaminants from soil and water sources (Sadowsky, 1999; Yan et al., 2020). This approach provides a natural way to eliminate environmental contaminants. Numerous plant species can absorb pollutants from the soil and store them in their tissues, even in minimal amounts. Once established, phytoremediation requires little maintenance and is cost-effective. A small quantity of nutrients can yield a high biomass, making this method manageable. Typically, native plants suffice, making this approach more economical. It benefits the environment by cleaning it up and also lowers carbon emissions, adding to its advantages. Certain plants involved in this process can eliminate pollutants by as much as 95%. Additionally, this technique supports the ecosystem by maintaining biological diversity since no extra chemicals are used. The plants' root systems boost the native microbial community in the soil, and the leftover roots after harvesting further improve the soil's organic content. Therefore, in addition to removing pollutants, this remediation method enhances soil fertility (Yeşilyurt and Gürgan, 2023). Furthermore, phytoremediation allows for the simultaneous treatment of various types of pollutants, particularly those from agricultural sources like pesticides or fertilizers. While it may not be ideal for extremely high pollutant concentrations, it can effectively clean large areas in situ (Yeşilyurt and Gürgan, 2024).

Plants may perform phytoremediation via different mechanisms (Figure 1). The roots play primary role in **phytostabilization** where the mobility and availability of contaminants are decreased, hence the contaminants cannot enter plant body. The contaminants can be accumulated in the root system, or they are immobilized in the rhizosphere (Bolan et al., 2011). The characteristics of the rhizosphere can be altered by the plant via rhizodeposition which stimulates the activities of microbiota which results in the degradation of contaminants. This process is called **phytostimulation** (Souto et al., 2020). For non-degradable contaminants such as heavy metals, the roots can adsorb and precipitate the contaminants on the surface of the roots. Therefore, the contaminants become non-available for entering the tissues or for microbial activity, and this way microbiota can be less affected by the contaminant. This process is called **rhizofiltration (**Muthukumaran, 2022).

Photodegradation process is especially applicable to organic contaminants which are degraded in the rhizosphere via released enzymes or in plant tissues via the metabolic activities inside the plant tissues. The contaminants are taken up by roots and converted into less toxic compounds (Greipsson, 2011).· **Phytoextraction** is the process where the organic or inorganic soil contaminant is uptake by the roots and translocated to the harvestable organs. This technique is especially suitable for removal of heavy metals from the soil which leaves the soil cleaner after harvesting the plant (Wei et al., 2008). Besides these techniques, phytovolatilization transforms the uptake contaminants from soil to a volatile form and through transpiration from leaves the contaminants are released to the atmosphere. The soil is cleaned up to level, but if the volatilized contaminant precipitates back to the soil, this might possess a problem. Each of these techniques have their advantages and disadvantages as reviewed by (Yeşilyurt et al., 2024). The technique can be chosen by considering the type of the contaminant (such as being organic or inorganic, the concentration of the contaminant, etc.), the soil characteristics (pH, organic matter content, being contaminated by more than one pollutant, etc.), and the plant to be used (accumulator or hyperaccumulator, root system, life cycle of the plant like being annual or perennial or being a tree). Therefore, the characteristics of the phytoremediation elements should be well determined for the process to be applied.

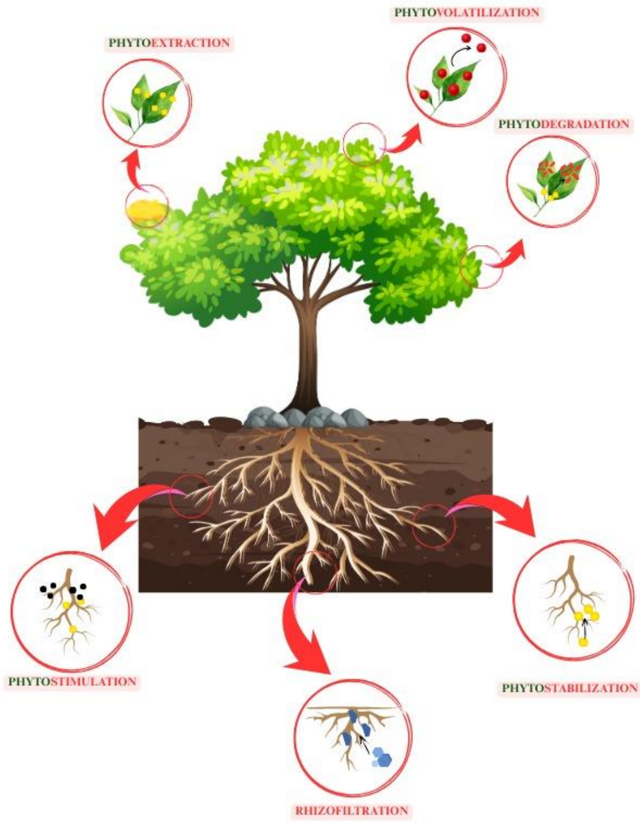

Figure 1. Phytoremediation techniques

The use of plant materials for industrial purposes comes into play especially in the case of phytoremediation where plant materials with organic or inorganic contaminants are left because of the process for the amelioration of the contaminants from the soil. For the phytoremediation to be more successful, the contaminant accumulated in the plant, especially inorganics like heavy metals which may be persistently non-transformed, should not be released back to nature. That is why the hyperaccumulator plant used in phytoremediation of heavy metals should be studied so that they can be evaluated in different industries.

EFFECTS OF HEAVY METALS TO PLANTS

Heavy metals are not biodegradable, hence neither microorganisms nor plants can degrade them. However, the effects of heavy metals can be alleviated by making them less toxic, or even immobile compounds, so that they do not enter any cells or tissues. The heavy metals can show adverse effects on photosynthesis and growth of plants. Heavy metals impair various physiological processes such as germination, vegetative growth, and respiration and photosynthesis, and this reduces the productivity. They also result in production of ROS (reactive oxygen species) in various cellular parts as a primary defense mechanism. Production of reactive oxygen species might cause impairment in metabolism such as electron transport chain, increase in lipid peroxidation and impairment in cell membrane [14]. Root systems are also affected by heavy metals present in the soil. The water uptake from soil can be impaired, osmotic disturbance in roots can occur, hence root growth deteriorates, this also results in production of ROS, eventually drastic events that may cause death might happen (Dumanović et al., 2021; Mashabela et al., 2023).

The general mechanisms for plants to combat heavy metals are accumulating in plasma membrane or chelating intracellularly or intercellular compartmentalization of the heavy metals (Raklami et al., 2021). Heavy metals, moreover, cause oxidative stress and result in ROS generation which leads to production of enzymatic and non-enzymatic antioxidants. In the molecular level, stress response genes can be expressed upon heavy metal stress, too (Feki et al., 2021). The effects of heavy metals on plants can be investigated by analyzing the antioxidant responses. Reactive oxygen species are crucial for growth and development control in plants as well as signaling upon environmental stimuli such as stress conditions and are normally produced in plants as a result of photorespiration (Das and Roychoudhury, 2014; Gill and Tuteja, 2010). The balance between the formation and breakdown of ROS is quite important for cellular metabolism. Antioxidant enzymes are triggered upon high reactive oxygen species formation in cells upon stress, sch as heavy metals. For instance, the accumulation of heavy metals leads to increased synthesis of peroxidases, catalase, superoxide dismutase or dehydroascorbate reductase. Determining the level of antioxidant enzymes gives strong ideas about the stress level of the plant, and if the plant can withstand and survive the heavy metal in question.

Heavy metals also trigger the secondary metabolites formation in plants which are essential for defense against biotic and abiotic stressors (Khare et al., 2020). Secondary metabolites are produced and derived from primary metabolites uh as proteins, carbohydrates, and lipids. Secondary metabolites such as hydrocarbons, flavonoids, terpenes, alkaloids and phenolics are quite important in protection of plants from stress (Jorjani and Karakaş, 2024).

Analyzing and revealing the biological properties of the accumulator plants used in the phytoremediation process after the clean-up of contaminant is very crucial to evaluate the potential of re-use of the plant material following phytoremediation. The heavy metal content is very crucial, especially in the plants used in traditional medicine or alternative medicine, which has been on the rise all over the world.

Medicinal aromatic plants are appealing because of their antibacterial activity. They can be cultivated using organic agriculture approaches and because of their antimicrobial effects, they can play a role in protecting the ecosystems by preserving biodiversity. Moreover, their use in traditional medicine, which is gaining popularity again, can support economic growth by cultivating more of these plants. Besides benefits for ecosystem preservation and economic contribution to societies, medicinal plants serve alternatives to medications especially in the case of reduction of synthetic antibiotic use. The unconscious and intensive use of antibiotics caused a huge antibiotic resistance issue all over the world. Recent studies focus on generating antibacterial molecules from plants to be used as alternatives to antibiotics (Ghosh et al., 2022; Yetgin, 2024). Therefore, besides many health advantages such as having anti-inflammatory, antioxidant, anti-cancer properties, these plants bear a great potential for economy and ecosystem health (Yetgin, 2024).

Moreoever, medicinal aromatic plants draw attention for the phytoremediation process since people benefit from them for hundreds of years for traditional medicine and are gaining popularity in parallel with alternative medicine applications. The worldwide trade of medicinal aromatic plants has almost doubled in the last 15 years (Zamani et al.,2025). Besides being used as spices and as food, they have numerous uses in industries such as food, pharmaceutical and cosmetics industries. These industries mainly make use of the phytochemicals extracts of medicinal aromatic plants (Yeşilyurt et al., 2024). Although increased heavy metal concentrations in plants lowered the production of essential oils, no contamination of essential oil with heavy metals makes them promise to be employed as accumulators in heavy metal contaminated agricultural lands as alternative to edible crops (Hubai and Kováts, 2024). This makes these plants appealing to be used for phytoremediation purposes.

ANTIBACTERIAL AND ANTIOXIDANT ACTIVITIES AND PHYTOREMEDIATION OF HEAVY METALS

When plants are used for phytoremediation, or naturally grown in heavy metal polluted areas, metabolic changes in the plant tissues upon heavy metal stress occur as a result. The changes give idea about the combat of the plant towards heavy metal induced stress and how the plant can overcome the stress if it can. Therefore, antioxidant system enzymes and non-enzymatic constituents of the system were under investigation in case of heavy metal accumulation. In some cases, antibacterial activity analyses were also carried out. Some studies about this topic are reviewed in the following section.

Heavy metal induced oxidative system and antioxidant enzyme levels were demonstrated in *Typha latifoila*. The plant was able to accumulate Cd, Pb, Zn and Ni found in the sediment into the roots, and this enhanced the antioxidant enzyme levels as well as phenol and flavonoid concentrations. Heavy metals in this plant were suggested to produce more antioxidant enzymes upon heavy metal stress (Torbati et al., 2021).

Plants bear different compounds that besides antioxidant effects, show antimicrobial activity. Alkaloids, terpenes, flavonoids, tannins and essential oils are found in medicinal plants which are responsible for the antimicrobial activity of the plants. Medicinal plants bear various phytochemicals which have antimicrobial activities. These are alkaloids, terpenoids, tannins, flavonoids, and essential oils. They are the products of secondary metabolism which is activated under different circumstances that exert stress. They are produced as a defense mechanism in plants under biotic or abiotic stress (Yeşilyurt et al., 2024; Isah, 2019). These compounds either disrupt microbial cell membrane and lead to leakage of cellular components or alter the structure of cell membrane and cell wall. Moreover, they can inhibit DNA replication or protein synthesis machinery, might damage nucleic acids, change cytoplasmic pH, or inhibit communication between bacteria (Khameneh et al., 2021). Since medicinal plants are rich in such phytochemicals, they are widely used in traditional medicine and are being used for industrial applications in today's world.

One of the important phytochemicals in plants for stress defense are carotenoids. Carotenoid content was found to increase in both seedlings and adult sunflowers which were grown on soil with heavy metal, but the chlorophyll a and b contents decreased. Cadmium accumulation in 1 month old seedlings roots were 3 times that of 3 months old adult plant. In this time period cadmium dispersed among organs of plants and became 1.5 times that in roots. Zinc, similarly, accumulated more in roots in young seedlings and dispersed to upper soil organs in adult plants. In both young seedlings and adult plants antioxidant enzyme levels (monodehydroascorbate, APOX, Gr, DHAR activities) were higher than the control plants grown on noncontaminated soil. This clearly exhibited the oxidative stress because of heavy metals (Nehnevajova et al., 2012).

The carotenoids in plant exert both antioxidant and antibacterial effects. For instance, carrot peel extract was shown to have strong antibacterial and antioxidant effects so that it can be used for preservation of meat. This is also a result of high phenolics and flavonoids in carrot peels (Shindia et al., 2024). The antibacterial effects of carotenoid were shown with various research (Ghosh et al., 2022; Karpiński & Adamczak, 2019; Kusmita et al., 2023; Naisi et al., 2023). Carotenoid synthesis can increase stress conditions. Hence, it might be conceivable that antioxidant and antibacterial effects of a plant would increase upon stress since carotenoids and chlorophylls tend to increase upon stress. However, increase of these phytochemicals in plants which accumulate heavy metals, and hence experience a stress, is not guaranteed (Gürgan and Adiloğlu, 2021; Gürgan 2023). Chlorophylls and carotenoids in plants are crucial for stress response. They act as antioxidants and help scavenging the free radicals in cells. They eliminate the damage caused by light by transferring electrons to different molecules in the cell and thus protect the cellular components from serious damages (Sharma et al., 2021). The levels of chlorophylls tend to increase upon a low level of stress. This helps the cell to get ready to combat a higher level of stress. However, when the stress level is high, or prolonged, such as in case of pollution, the synthesis of chlorophylls is inhibited and chlorophyll level in cells decreases, and adverse effects of stress are revealed (Agathokleous et al., 2020).

This situation suggests that revealing the antioxidant activity of a plant does not automatically suggest its antibacterial activity. Hence, antibacterial activity tests hold their crucial role for the understanding of potential of a plant material to be used for industrial purposes.

For evaluating how heavy metal accumulation affects plants, besides antioxidant enzymes, antibacterial activity testing can be performed. In fact, antioxidant enzyme levels give idea about the combat of plant with stress, but antimicrobial activity tests reveal if the plants grown on polluted soil with heavy metals can be evaluated for industrial use after phytoremediation. Although the essential oils are known not to be contaminated with heavy metals, not all the plants bear essential oils. Others can be used after some extraction protocols. Therefore, investigating the impacts of metals on extracts of plants can reveal the usability of hyperaccumulators for industrial applications. Antimicrobial testing is an easy way to uncover the potential of plant extracts. Scientific literature contains very few studies on this topic.

This study therefore aims to review the antibacterial activities of heavy metal accumulating plants directly by antimicrobial testing, or indirectly by examining the changes of compounds having antimicrobial activity capacity.

Besides antioxidant activity changes, the change in antibacterial activity was investigated in some studies, yet fewer than the antioxidant activity studies. Kunwar et al. (2015) studied the impacts of various concentrations of Cd, Cu and Pb on essential oil of *Ocimum basilicum* and *Mentha spicata*. The exposure to heavy metals increased the essential oil yield and linalool percentage in the *O. basilicum* essential oil, but the essential oil yield of *M.spicata* was not affected by heavy metal accumulation. These heavy metals were not detected in the essential oil, hence although the heavy metals were accumulated in plants, they did not adversely affect the quality of essential oil Kunwar et al., 2015). Since the antibacterial activity of mint essential oil is known (Jirovetz et al., 2009), it can be suggested that these medicinal plants can be both used for phytoremediation and their essential oils can still be evaluated in industries

A study with *Sesbania sesban* L., cadmium, and the addition of a plant growth promoter rhizobacterium were studied. The effects of heavy metal on plant physiology were drastic but the inoculation of bacteria enhanced the physiological parameters. Chlorophyll a and b contents of 200 mg/kg Cd+ bacteria group were about 50% higher than only Cd exposed group. Moreover, antioxidant enzyme levels (peroxidase, superoxide dismutase, catalase) were higher upon bacterial inoculation and non-enzymatic antioxidants were lower besides lower electrolyte leakage. The bacteria were shown to adsorb Cd and the bacteria contributed to antioxidant enzyme production which led the plant combat better with Cd and successfully accumulate Cd (Ali et al., 2021).

The medicinal aromatic plant *Houttuynia cordata*, which has been very important for Chinese traditional medicine, was tested for its cadmium accumulation in a pot experiment. Plant biomass increased with increasing cadmium in soil, stem and roots developed more upon higher Cd. Roots were the parts to accumulate Cd more. Among metabolites specific to the plant 13 of them significantly increased with Cd exposure; phenolics, alkaloids, organic acids and amino acid derivatives were among the metabolites enhanced with heavy metal Cd (Zhang et al., 2024). The antioxidant potential was not studied in the study, yet it can be estimated that the Cd accumulation of the plant and enhanced metabolites such as alkaloids and phenolics should have increased the antioxidant activity in the plant.

A study conducted about cadmium phytoremediation by *Eclipta alba* (L.) Hassk and the changes in antibacterial and antioxidant activities of the methanolic extracts. The plant was successful in accumulation of cadmium in roots and shoot. Phenolic contents, total flavonoids, lipids and fatty acids were shown to increase in methanolic extracts upon cadmium exposure. The heavy metal accumulation triggered antioxidant activity but decreased antibacterial activity towards the bacteria tested (Dwivedi et al., 2024).

Cadmium was the also subject heavy metal in another study carried out with the medicinal plant *Merwilla plumbea* in South Africa in a pot trial. Different cadmium concentrations (2, 5, and 10 mg/L) were applied to plants. Since this plant has a role in traditional medicine, especially treating children, cadmium accumulation can possess serious problems. Indeed, the bulbs of the plants were shown to accumulate 24 times higher Cd than the permitted limit. The antibacterial activity of the ethanolic extracts of the plant showed higher bacterial growth inhibition at higher Cd accumulations in plant. This was suggested to be correlated with higher cadmium in plants by the authors (Street et al., 2009). In another study with 11 South African plants obtained from markets, acetone was used as solvent, which is a polar solvent. Aluminum and iron were very high in two plant samples, the results showed that plants with higher heavy metal contents exerted a higher antibacterial activity. Moreover, total phenolics and flavonoids of the plants were determined. The heavy metal contents and antibacterial activities were found to be non-correlated. It was suggested that high heavy metal content and phytochemical contents did not mean the extract would exert a higher antibacterial activity. The different ages, locations where the plants were obtained, and the season of the plant harvest were estimated to be responsible for different antibacterial and antioxidant capacity of the plants (Okem et al., 2014).

Medicinal aromatic plants are of vital importance for the discovery of new bioactive compounds to be used for cosmetic, pharmaceutical and food industries. The prominence of medicinal aromatic plants will never cease, hence collection from nature, extracting the plant material using various solvents and methods and testing their antioxidant, anti-inflammatory actions, anti-cancer and antibacterial effects are kept going on in recent years. Generally, when the biological properties of a medicinal aromatic plant have been studied, the researchers tend to examine both the antioxidant and antibacterial effects simultaneously. Most of the time both properties were shown to be exerted (Singh et al., 2024; Elagdi et al., 2023; Messaoudi et al., 2022; Boubekeur et al., 2022; Kuttithodi et al., 2023; Tagnaout et al., 2023; Çalışkan et al., 2024a; Çalışkan et al., 2024b. Antioxidant and antibacterial activities of a plant in different solvents showed that methanol extract had the best scavenging activity. Moreover, methanolic extract exerted the highest antibacterial activity against antibiotic resistant *S. aureus* and *E. coli* (Singh et al., 2024)

However, it does not necessarily mean that the antibacterial and antioxidant activities are correlated. Although this has been suggested for some cases (Singh et al., 2024) the antibacterial analysis revealed that total phenolics were positively correlated with antioxidant activity, there are research showing no correlation between antioxidant and antibacterial activities. For instance, Rayan et al. (2020) studied 25 plants and their antibacterial effect against *S. mutans* and antioxidant effects and they were found to be non-correlated. The analysis showed that when the EC_{50} of free radical scavenging of ≤100 ppm was the case, more antibacterial activity of the extract was seen. The study suggested that antibacterial activity and antioxidant activities occur through different mechanisms of action. Moreover, the results revealed that the polar fractions of extracts showed higher antioxidant activities, while non-polar fractions exerted higher antibacterial activity. This suggests the importance of solvent selection to test the antibacterial activity. Antibacterial activities of Azolla pinnata were studied in another study. Similarly, extracts obtained with benzene, a non-polar solvent, showed higher antibacterial activity than ethanolic extracts (polar solvent), while higher antioxidant potential was observed by ethanolic extracts (Jacob et al., 2020).

The importance of selecting the right solvent to obtained plants extracts was revealed by another comprehensive study. The extracts of *Polygonum hydropiper* L. grown on soil contaminated with various heavy metals. The plant crude powder was investigated for heavy metals as well as methanolic extract and its subsequent fractions: n-hexane, n-butanol, ethyl acetate, chloroform and aqueous fractions. Heavy metal concentrations were found to differ between the extracts and in soil. For instance, Cr was found as 77 ppm in soil but around 243 ppm in plant crude powder. Zinc was found to be around 90 ppm in soil, 7 ppm in crude plant powder but around 139 in aqueous fraction, around 29 ppm in butanol fraction but could not be found in methanolic extract. Iron on the other hand was detected to be 113 ppm in soil, 95 in crude plant powder, 125 ppm in aqueous fraction, while about 156 ppm in chloroform fraction! The crude powder and all the extracts were tested against seedling germination and against two helminths. The results revealed that chloroform fraction of the methanolic extract had a high anthelmintic activity and a high anti seed germination effect compared to the other extracts. For example, IC50 for seed germination was 35 μg/mL for chloroform extract while it was 100 μg/mL for butanol extract and 485 μg/mL for aqueous extract. The concentrations of Fe and Zn in aqueous extract were the highest among all the extracts, however, chloroform extract had a very high Cr content. Aqueous extract was also found to be the one to exert anti helminthic activity in the longest period, increasing with increasing dose (Ayaz et al., 2014). The antibacterial effect of ethanolic extracts of basil grown upon different doses of Fe fertilizer was found to significantly decrease by the increase of iron fertilizer dose (Gürgan and Adiloğlu, 2021). In another study conducted on the antibacterial effects of ethanolic and methanolic extracts of various medicinal aromatic plants grown in nature in proximity to steel industry revealed that although the heavy metal (Cd, Fe, Mn, Ni, Pb, Zn) contents in the plants were detected and they were all below the permissible limits. The antibacterial activities of the extracts were suggested to be non-correlated to the heavy metal concentrations in the plants. The heavy metal concentrations were detected in the plant powder but their concentrations in the extracts were not detected; the heavy metals did not pass to the ethanolic and methanolic extracts of the plants in the study (Zoufan et al., 2017).

The essential oil and scent bearing flowers of *Elsholtzia argyi* plants were collected from Pb/Zn mined area and uncontaminated area in a study and they were compared. The phytochemicals responsible for scent were found to be higher in plants from contaminated areas. Heavy metal in the soil resulted in enhanced phytochemicals and increased the industrial value of the plant. Hence, such plants were suggested to be used to clean up contaminated sites for perfume, antibacterial and antiseptic agent production (Peng and Yang, 2005).

For evaluation of the plant material after phytoremediation process, the phytochemicals generated upon heavy metal stress should be determined. Moreover, the heavy metal accumulation in different plants parts should be investigated. A proper solvent should be selected to test antibacterial and antioxidant capacities of the plant. To test antibacterial activity, literature suggests using polar solvents to obtain extracts and non-polar solvents to investigate antioxidant activity. Generally antibacterial tests are more available for many labs. Therefore, antibacterial activity testing together with accumulated heavy metal content can give an insight about the change in phytochemical content and can be the point of start for suggesting the accumulator plants for further evaluation in industries.

CONCLUSION

Heavy metals are among the emerging chemical contaminants in soil, waters, and sediments. They are persisting since they cannot be biodegradable yet can be remediated from the contaminated source by biological systems. Phytoremediation, which employs accumulator and hyperaccumulator plants, serves as a promising alternative to costly and non-environmentally friendly chemical and physical treatments of soil. The plants used have the capability to accumulate heavy metals or convert them into non bioavailable forms. When accumulated in the plant tissues, heavy metals cause stress which results in antioxidant enzyme production as well as some secondary metabolites such as flavonoids and phenolics. These metabolites are investigated to have an idea about the survival of the plant against the heavy metal stress. Such phytochemicals also can exert antibacterial activity whose analysis is more readily available for many labs worldwide. However, the increase in antioxidants does not necessarily mean an increase in the antibacterial activity. To investigate antibacterial activity, the importance of solvent choice can be inferred from the studies conducted. In general, plant extracts obtained by polar solvents showed more antibacterial activity, while those in non-polar solvents exerted antioxidant activities. Besides the extracts, essential oils can be tested for antibacterial activity. Essential oils of plants were shown to be free of heavy metals even though the plant successfully accumulated heavy metals. Therefore, medicinal aromatic plants bearing essential oils can be suggested for the phytoremediation of heavy metal contaminates sites and their essential oil can be evaluated in different industries. The impairment of metabolism upon heavy metal accumulation beyond antioxidant capacity should be elucidated by more detailed research in the future.

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