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Review Article

Tobacco, tobacco by-products and waste valorization opportunities

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Abstract

Tobacco holds huge potential as a source of bioactive compounds, edible proteins, terpenoids, antioxidants and other active components beyond the mass production of cigarettes and other smoking products. Tobacco production and processing generates a large amount of waste and by-products, such as flower buds and seeds, stems, stalks, and leaves. Waste like cigarette butts has significant role in the environment pollution globally. Implementing sustainable and circular economy-oriented methods to the whole chain of tobacco life (harvesting – processing – usage – waste) is crucial to minimize litter and pollution and to fully valorize the plant. The value of tobacco is high in the pharmaceutical industry due to its chemical components. Tobacco is the richest source of solanesol, which is a key intermediate in coenzyme Q10 and vitamin K2 synthesis. Derived compounds of tobacco include alkaloids (anabasine, anatabine, nicotine, nicotine derivatives), phenolic compounds (chlorogenic acid, scopoletin, rutin), cellulose, and pectin. The phytoremediation feature of tobacco should be highlighted as a powerful method for soil detoxification. Furthermore, tobacco could be used for natural pesticides and biocontrol agents' production. Many studies point out opportunities for bioenergy produced by tobacco waste. Recycling cigarette butts is researched and worked on. Challenges include toxicity management.

Keywords
tobacco, tobacco waste and by-products, tobacco valorization, phytoremediation, cigarette butts, circular economy

Abbreviations
CB – cigarette butts; CCE – Column-chromatographic extraction; GC/MS – Gas Chromatography / Mass Spectrometry; HPLC – high performance liquid chromatography; PET – polyethyleneterephtalate.RRLC – Rapid resolution liquid chromatography; SCF – Supercritical fluid CO_2; SPE – Solid phase extraction; UHPLC – ultra-high-performance liquid chromatography;

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Introduction

Tobacco's ancient origin comes from America. By the time Christopher Columbus reached the shores of the western continent at the end of the XV century, local cultures had long been using tobacco widely for recreational purposes as well as in various rituals and ceremonies. Tobacco was sniffed, smoked, chewed, eaten, drunk, and coated over the body. It was blown into the warrior's face before battle, over fields before planting, and over women before sexual intercourse (Musk and De Klerk 2003). These rituals suggest that tobacco has deep roots in anthropogenic beliefs, as it is used for gaining strength and fertility. Aside from the diversity of ceremonies, tobacco was used as a cure for different ailments due to its analgesic and antiseptic properties. However, smoking has always been the most popular usage of tobacco. At first, tobacco was brought to Europe because of its medicinal properties, but Europeans were unable to withstand its addictive nature, and smoking became popular. With the first manufactured cigarettes appearing in the 1850s, their production and usage have become worldwide (Musk and De Klerk 2003).

The global tobacco market size was about 8.8 million tons in 2024 (https://www.imarcgroup.com/tobacco-processing-plant). More than one hundred countries with diverse climatic and soil condition are growing tobacco and China (2391.0 million kg for 2017), Brazil (880.88 million kg for 2017) and India (799.96 million kg for 2017) are the biggest worldwide producers (Nagargade et al. 2023). The tobacco production system is highly developed although around 30% of the tobacco plant end up as wastes or by-products not mentioning the waste cigarette buts (Manthos and Tsigkou 2025). Yet many governments take measures against cigarettes and smoking products due to their negative impact on human health (Geist 2021). In the middle of the XX century, the USA, followed by the UK, confirmed the causal relation between smoking and lung cancer. Later research has identified smoking as a major cause of heart disease, stroke, peripheral vascular disease, COPD, cancers of the lung, oral cavity, larynx, oesophagus, stomach, kidney, bladder, pancreas, cervix, vulva, penis, anus, and possibly others (Musk and De Klerk 2003). Passive smoking is also a risk to human health. Cigarette butts (CB) are one of most common form of solid litter, which was estimated to be over 1.2 million tons across the world per year considering of as high as about 5.6 trillion cigarettes annual consumption (Hossain et al. 2022). Although usually produced in urban, CBs can easily enter aquatic system by rain, river water and marine currents, resulting a global spread. Wide spread of CBs is not only unsightly nuisance, but also important source for environmental pollution since CBs would trap thousands of toxicants during cigarettes combustion such as polycyclic aromatic hydrocarbons, phenolic compounds, pyridines and so on. Toxic chemicals in CBs can be leached out by water and cause contamination in aquatic environment, posing a serious threat to humans and wildlife. Besides, most of CBs are made of cellulose acetate with poor biodegradability, which can take up to several years to break down thus often show long term effects on the environment. Normal disposal methods for solid litter like landfilling or incineration are not sustainable or economically feasible for CBs. Therefore, exploration of appropriate methods for waste CBs reclamation is urgent and significant (Zhang et al. 2021). Cigarette smoke consists of agricultural chemicals (which can be toxic in various environments), ethyl phenol (highly absorbed by cellulose acetate and increasing its concentration in the cigarette filter). Nicotine, which is 0.6-3% of dry tobacco weight, is known to be extremely toxic to humans and animals (Novotny and Slaughter 2014). Currently, due to the highlighting of the importance of the circular economy's principles, much research and development are being conducted to valorize by-products of tobacco production and to recycle its litter. More than 20% of tobacco material is discarded as tobacco waste. Because of the high content of nicotine and total organic carbon, it cannot be disposed of in a landfill (Banožić et al. 2020). Unsustainable disposal practices, including landfilling and incineration, result in the loss of valuable resources and contribute to environmental contamination by releasing nicotine and other toxic substances that degrade soil integrity and compromise water and air quality (Beutel et al. 2021). Existing valorization approaches, including chemical extraction and microbial nicotine degradation, typically focus on isolating individual compounds rather than enabling full utilization of tobacco biomass. Although ethanol production through microbial fermentation, for example using

Saccharomyces cerevisiae, has been demonstrated (Martín et al. 2002), it offers limited economic viability compared with conventional feedstocks such as corn stover and produces secondary waste streams, such as wastewater and gaseous emissions, that require additional treatment. Consequently, there is an urgent need to develop innovative, integrated bioprocessing strategies that support sustainable, low-carbon tobacco waste valorization in line with global circular bioeconomy goals (Zhang et al. 2026). One of the primary challenges in tobacco waste valorization is nicotine, a persistent and toxic alkaloid that suppresses microbial activity. Research indicates that nicotine concentration can significantly influence microbial performance and functional processes (Ruan and Liu 2015).

Thousands of metabolites have been isolated from tobacco plants, and chemically and biologically characterized. Researchers are continuing to explore more about their chemical compounds (Zou et al. 2021a). The tobacco plant's metabolism produces a lot of high-value compounds such as alkaloids, essential oils, polyphenols, triterpenes, aromatic substances, fatty alcohols, and phytosterols, which could find variety of applications in agricultural, pharmaceutical and medical fields (Zhang et al. 2024). The important secondary metabolites found in some of the parts of tobacco are presented in Table 1 (Esentürk-Güzel et al. 2022).

Table 1. Secondary metabolites in some of the parts of tobacco plant

Tobacco plant part	C1
Leaves of the tobacco plant	Alkaloids; nicotine, nicoteine, nicotimine, anabasine, anatabine, anatalline, and nornicotine; glucosides, tahacinin, tahacilin and isoquercitrin, 1-quinic, chlorogenic, caffeic, and oxalic acids
Roots	Anatabine and (+) nornicotine
Flowers	Quercetin-3,3′-dimethyl ether, quercetin-3-methyl ether, gibberellins-nicotiana α, β and γ and gibberllins A and A3
Seeds	Cycloartanol, cycloartenol 24-daturadiol, solavetivone, cholesterol, cholest-7-enol, 24-methylenecholesterol, campesterol, stigmasterol, sitosterol, 28- isofucosterol, lanosterol, 31-norlanosterol, lanost-8-enol, obtusifoliol, 31-norcycloartenol, cycloeucalenol, granisterol, citrostadienol, β-amyrin, lupeol, cycloartanol and 24-methylenecycloartanol.

Aside from its addictiveness and toxicity, at some doses nicotine plays a huge role in neurodegenerative disorders studies (Zhang et al. 2024). Other alkaloids, isolated from tobacco, have similar properties. The key compound in coenzyme Q10 and vitamin K2, solanesol, was isolated from tobacco. Phenolic compounds such as chlorogenic acid, rutin and scopoletin have shown serious potential in the research and treatment of various disorders. Cembranoids found usually in the inflorescences are found to suppress and kill harmful insects and are promising compounds for development of biopesticides (Wang et al. 2021). Tobacco residue is often directly burned after harvesting the leaves, causing serious air pollution and wasting potentially useful biomass (Zou et al. 2021a). Diversity of methods are applied to extract natural compounds from plants, and more sustainable and ecologically beneficial techniques are sought to be developed. Valorization of tobacco achievement includes: The extraction of high-value compounds from plant, by-products and waste; the investigation of its chemical composition further, developing bioenergy technologies that tobacco fits, and the usage of its phytoremediation properties in combination with phytomining to purify the soil and obtain valuable heavy metals are all required to achieve optimal valorization (Fig. 1.).

The aim of the present review article is to gather, summarize, and critically evaluate the knowledge in the field of the tobacco industry and production



Figure 1. Valorization opportunities of tobacco, tobacco products and waste

worldwide and to discuss the major problems, challenges and perspectives. By this way tobacco, tobacco by-products and tobacco waste can be seen as a raw material with wider applications beyond its traditional use.

Methodology

The review article is based on a thorough literature search in the Science Direct, AGRICOLA, Scopus, SpringerLink, PubMed and AGRIS databases. The experience and expertise of the Tobacco and Tobacco Products Institute (Agricultural Academy of Bulgaria), databases and expert consultations were also included in the reviewing process. The archives of the University of Food Technology in Plovdiv, Paisii Hilendarski University of Plovdiv and the Bulgarian Academy of Sciences were searched. Preliminary search of information for the past 50 years was performed in August-September 2025 with key words for the bibliographic research "tobacco", tobacco by-products", "tobacco spent biomass", tobacco wastes", "tobacco waste and by-products valorization", "cigarette butts", "tobacco polyphenols", and "tobacco alkaloids". Additionally, further studies were identified through the reference list in these articles, suggestions from the search engines, and Google search engine was used to find reports or conference proceedings. After pre-reviewing the collected data, a novel narrow search for the publication period 2010-2026 was performed in the period September 2025 – February 2026 and 143 sources were selected for the review. The choice of the publications was made on the basis of the relevance of publications, the research methodology, the research results and the year of publication. Based on the methods of valorization of the tobacco industry by-products and wastes, the selected publications were grouped in three major fields (with the subsequent division by groups of methods), and the manuscripts with a different subject were placed under "others". Each group of valorization approaches was summarized and reviewed according to the following structure: importance of the method, technological approach and industrial relevance, critical evaluation of the methods and prospects for further developments.

Discussion

Chemical compounds from tobacco – properties, applications, value. The tobacco plant, *Nicotiana tabacum* L., belongs to the Solanaceae family. It has been widely studied chemically and biologically, and more than 2500 metabolites have been reported. Phytochemical analyses show that tobacco is rich in alkaloids, terpenoids, lignans, flavonoids, phenylpropanoids, chromanones, and coumarins (Gui et al. 2024).

Alkaloids are organic compounds that include at least one nitrogen atom (outside or in a ring system). The main source of alkaloids is the plant kingdom. Alkaloids are secondary metabolites and don't play a direct role in the plant's metabolism. The term "alkaloid" was presented in the XIX century by W. Meisner to describe natural substances reacting like bases, like alkalis – from Arabic alkali, soda and Greek eidos, appearance. Plants containing alkaloids have been used for over 3000 years by man as medicines, teas and more; however, the first characterization and isolation of them was in XIX century (Bribi 2018; Zareena et al. 2021). The basic character of alkaloids allows the formation of salts with mineral or organic acids. Alkaloid salts are soluble in water and dilute alcohols, and most of them are not soluble in organic solvents. The common commercial form of alkaloids is the crystallized salts that can be conserved well. The properties of solubility of alkaloids and their salts are very important to the pharmaceutical industry. Alkaloid substances are often administered in solution, and the difference in insolubility between alkaloids and their salts contributes to the methods of their isolation from plants (Bribi 2018).

Plants of the genus *Nicotiana* are rich in alkaloids. The alkaloid constituents in tobacco are nicotine, nicoteine, nicotimine, anabasine, anatabine, anatalline, and nornicotine which are found in the leaves of the tobacco plant (Esentürk-Güzel et al. 2022). The ratios of the various alkaloids vary greatly among the different species of *Nicotiana* (Dewey 2013). Between 2% and 4% of the dry weight of tobacco comprise alkaloids (Dewey and Xie 2013).

Whereas nicotine is the major pyridine alkaloid in *Nicotiana tabacum* L. (accounting for over 90 % of the total alkaloid content), anabasine, which is a piperidine alkaloid, is the major one in the *Nicotiana glauca* (Dewey 2013; Kukula-Koch and Widelski 2017; Massadeh et al. 2022).

Nicotine is the dominant alkaloid in *Nicotiana tabacum* L., but several alkaloids are also present, in relatively lower amounts (Kukula-Koch and Widelski 2017). Nicotine is synthesized in the root and transported through xylem to leaves. Tobacco produces three other major alkaloids: nornicotine, anabasine and anatabine (Guo et al. 2021; Shoji et al. 2024; Wu 2025). Nornicotine, typically comprises approximately 2-5% of the total alkaloids in leaves, whereas anatabine and anabasine together account for the most of the remaining approximately 5% of total alkaloids (Kaminski et al. 2023; Shoji et al. 2024). The conversion of nicotine to nornicotine occurs through a demethylation reaction catalyzed by nicotine N-demethylase (Shoji et al. 2024). A total of 20 alkaloids were isolated from *Nicotiana tabacum* for 2011-2022 (Gui et al. 2024).

Terpenoids, belonging to the isoprenoids, are the most numerous and structurally diverse among natural compounds. The generic name “terpene” was originally applied to the hydrocarbons found in turpentine, the suffix “ene” indicating the presence of olefinic (double) bonds. Terpenoids are built of isoprene units (Ludwiczuk et al. 2017). They possess antitumor, anti-inflammatory, antibacterial, and antiviral activities (Yang et al. 2020). A total of 31 new sesquiterpenoids featuring diversified skeletons were isolated from *Nicotiana tabacum* between 2011 and 2022, and 10 new diterpenoids and sterols (Gui et al. 2024).

Phenolic is a general term for plant components bearing hydroxyl groups, widely distributed in plants’ tissues. Simple phenols are grouped into coumarins and phenolic acids. Flavonoids, tannins, lignans and stilbenes are also phenolic compounds. The function of plant polyphenols is to protect plants from ultraviolet radiation, fungal pathogens, and to avoid cells damage by oxidative stress (Zou et al. 2021a). Over 100 phenolic compounds such as benzofuran derivatives, coumarins, flavones, and others were isolated from *Nicotiana tabacum* between 2011-2022 (Gui et al. 2024).

Alkaloids. Nicotine is an oxygen-free alkaloid in liquid form (Zhang et al. 2024). Nicotine accounts for more than 90% of the total alkaloid content of tobacco. It is synthesized at the roots and transported to the leaves. Due to its excellent properties as an antiherbivore toxin, nicotine has wide application as an insecticide and is one of the first compounds used for pest control in agriculture (Wu et al. 2025). It can interact with the acetylcholine receptors in the nervous systems of animals (Steppuhn et al. 2004). Herbal pesticides are biodegradable and eco-friendly. Formulation of tobacco extract as a concentrated emulsion for commercial production of pesticides has been researched (Puripattanavong et al. 2013). The emulsion is capable of destroying aphids without causing crop damage at a 1:100 dilution. Nicotine is a compound with high potential in biological pesticides production.

Nicotine has some potentially therapeutic and beneficial effects and has multiple applications in the medical field. It shows a positive effect on neurodegenerative diseases (Lin et al. 2025; Zhang et al. 2024). Neurodegenerative diseases are diseases of the nervous system – selective degeneration and loss of neurons. Problems in independent mobility, cognitive and memory decline are main symptoms. Alzheimer’s disease is the most common form of dementia. A strong connection is found between cognitive dysfunction and the loss of nicotinic receptor binding in temporal and frontal cortices and hippocampus. Many studies bring significant evidence that nicotine improves attentional driven tasks and that stimulation of nicotine receptors can improve acquisition and retention of verbal and non-verbal information in humans (Newhouse and Kelton 2000). Smokers are approximately 50% less likely to develop Alzheimer’s disease and Parkinson’s disease than non-smokers who are age- and gender-

matched (Fratiglioni and Wang 2000). Improvement in motor tasks in Parkinson's disease patients with nicotine treatment is also noted. The higher percentage of schizophrenia and attention deficit hyperactivity disorder diagnosed that are smokers provokes thoughts that smoking is a kind of self-medication. It is found that nicotine administered decreases adult attention-deficit/hyperactivity disorder (ADHD) symptoms such as inattention, restlessness and hyperactivity. In schizophrenia cases, nicotine improves cognitive symptoms. Nicotinic stimulation is studied in Tourette's syndrome. Nowadays, obesity is a worldwide problem that can be solved with nicotine. In different ages, smokers weigh less than non-smokers. Also, quitting smoking possibly leads to weight gain. Nicotine affects obesity through four mechanisms. Nicotine regulates energy intake and reduces appetite by acting on hypothalamic neurons and the neuropeptide system related to food intake; reduces the size of fat cells and fat content by fat decomposition and synthesis; regulates insulin levels; alleviates steatohepatitis induced by adipose inflammation and obesity (Zhang et al. 2024). Nicotine has a variety of applications and huge potential in innovative research in medicine. In addition, nicotine has cognitive benefits (Alhowail 2021), anti-inflammatory and pro-inflammatory effects (Lakhan and Kirchgessner 2011; Zhang et al. 2022), analgesic / anti-nociceptive properties (Luo et al. 2023).

Anatabine is a structural analogue of nicotine and may represent a potentially safer alternative to nicotine with distinct pharmacological properties. Its effectiveness in attenuating nicotine dependence and clinical use as an anti-arthritic dietary supplement to alleviate arthritis supports its medicinal potential (Guo 2026).

Minor tobacco alkaloids (nornicotine, anatabine, anabasine) also are potential candidates for novel obesity pharmacotherapies. All three minor tobacco alkaloids produced effects on body weight and body composition, with the most prominent effects with the administration of nornicotine and anatabine. Anabasine slowed body weight gain and prevented increases in fat mass, whereas nornicotine and anatabine reduced both body weight and fat mass (Grebenstein 2022). Anabasine, is more potent than nicotine by several folds (Massadeh et al. 2022).

Nicotine is usually obtained by extraction of the dried leaves of the tobacco plant. Various solvents such as alcohols, chloroform, ether, petroleum ether, kerosene and water can be used for solvent extraction method (Kheawfu et al. 2021). Currently, a new trend is development of new methods to extract nicotine not only from the tobacco plant but from tobacco waste generated from tobacco products manufacturing.

Terpenoids - Solanesol. Solanesol is mainly found in plants of the Solanaceae family, and *Nicotiana tabacum* is its richest source, in about 1-4% of the plant dry weight. Due to its complex synthesis, it is mainly extracted from tobacco (Zhang et al. 2024). Structurally, solanesol is composed of nine isoprene units, representing a 45-carbon unsaturated all-trans nanoprenol terpenoid (Taylor and Fraser 2011). Solanesol is used as an intermediate in the synthesis of ubiquinone (coenzyme Q10) and vitamin K2. Coenzyme Q10 can be obtained through food sources such as meat, poultry, fish, vegetables, and fruits; however, less than 10% can be absorbed in this manner (Lee et al. 2012). It is released as a dietary supplement. Deficiency of coenzyme Q10 has been documented in patients with cardiovascular diseases. Treating them with coenzyme Q10 supplementation benefited their condition. A study showed that coenzyme Q10 supplements can decrease oxidative stress and increase antioxidant enzyme activity in patients with coronary artery disease (Lee et al. 2012). It is perceived to benefit relieving migraine headache sufferers (Taylor and Fraser 2011). Some research on treatment of Parkinson's disease with Q10 supplements have shown a positive effect, but wider studies are needed (Fratiglioni and Wang 2000; Shults et al. 2002). All forms of vitamin K serve as a cofactor for the post-translational enzyme γ-glutamate carboxylase. Studies reported that vitamin K2 improves bone health, preventing osteoporosis, reduces vascular calcification and cardiovascular risk and prevents and treats type 2 diabetes mellitus (Beulens et al. 2013; Li et al. 2018). Solanesol is an essential part of recently developed anticancer drug N-solanesyl-N,N′-bis(3,4-dimethoxybenzyl) ethylenediamine (Yan et al. 2019). Solanesol is noticed to be a potential treatment for the hereditary autosomal dominant disorder of the central nervous system, Huntington's disease. Its antioxidant, anti-

inflammatory and antimicrobial activities are highlighted by some studies (Yan et al. 2019). Solanesol has potential as a therapeutic agent for the treatment of oxidative stress-related liver diseases, particularly those associated with diabetes (Liu et al. 2023).

Polyphenols (Phenolic compounds). Plants produce a variety of secondary metabolites in response to different environments. The largest, diverse and most broadly distributed secondary metabolites are polyphenols. Thousands of polyphenolic compounds have been identified in plants, which share the basic structure consisting of hydroxyl groups attached to benzene ring. These polyphenols could be further divided into several groups, including flavonoids, phenolic acids, stilbenes, lignans, etc. (Cheynier et al. 2013; Kumari et al. 2021; Singh et al. 2021; Wang et al. 2023b).

Polyphenols are important flavoring substances in tobacco, accounting for approximately 7% of dry weight. There are many phenolic compounds in tobacco leaves including the chlorogenic acid of tannins, scopoletin, hyoscyamine (from coumarin) rutin (flavone), among which chlorogenic acid, rutin, and scopoletin account for over 80% of the polyphenols in tobacco (Dewey and Xie 2013; Wang et al. 2023b; Zou et al. 2021b). Polyphenolic compounds (flavonoids and polyphenols) were found to possess significant antioxidant activity measured by several methods, namely hydroxyl, superoxide anion, 1,1-diphenyl-2-picrylhydrazyl (DPPH) and 2,2'-azino-bis(3-ethylbenzthiazoline-6-sulphonic acid) (ABTS) radicals (Ru et al. 2012).

Chlorogenic acid, rutin, scopoletin are the most abundant phenolic compounds, accounting for 80 % of the total phenolics in tobacco leaves (Dewey and Xie 2013). Chlorogenic acid possesses antidiabetic and anti-obesity properties linked to the metabolism of glucose. It is suggested that it decreases the blood glucose in the general circulation, resulting in less insulin activity. The second source of energy is fat reserves. Antioxidant and anti-inflammatory effects of chlorogenic acid are noted. Studies showed that chlorogenic acid can prevent mice from Con A-induced hepatitis. Administration of chlorogenic acid to wounded mice accelerated the wound healing without leaving any adverse effects on the heart and kidney. Chlorogenic acid is suitable for a preservative and food additive. Studies indicated that it has bactericidal effects against *Stenotrophomonas maltophilia* resistant to trimethoprim/sulfamethoxazole, *Klebsiella pneumoniae*, *Helicobacter pylori*, *Escherichia coli*, *Staphylococcus epidermidis*, and *Staphylococcus aureus*. It can also exert an antifungal effect against *Candida albicans*. Chlorogenic acid is not sensitive to probiotic bacteria (Naveed et al. 2018).

Rutin is a glycoside comprising of flavonolic aglycone quercetin along with the disaccharide rutinose. It was discovered in 1842, and firstly reported in *Ruta graveolens* L, where its name comes from. Rutin is also known as vitamin P (Frutos et al. 2019). Rutin has demonstrated the neuroprotective effect on brain ischemia. It has huge potential in the pharmaceutical and medical fields, as it demonstrates positive impact on the central nervous system – promotion of neural crest cell survival, sedative activity, anticonvulsant activity, anti-Alzheimer activity and treatment of hyperkinetic movement disorder, antidepressant effects; endocrine system – antidiabetic effects, anti-hypercholesterolemic effects, thyroid uptake promotion; cardiovascular system – hypertension, blood coagulation, antiplatelet aggregatory effect; gastrointestinal system – antiulcer effects; respiratory system – antiasthmatic activity and other associated effects; bones – antiosteoporotic and antiosteopenic effect; eyes – anticataract and ophthalmic effect; excretory system – diuretic effect; reproductive system – effect on sperm quality and male reproductive organs; hair; skin – sunscreen effects, in atopic dermatitis; body strength – anti fatigue activity (Ganeshpurkar and Saluja 2017; Gullón et al. 2017). Rutin shows analgesic and antiarthritic activities; anticancer effects, chemotherapeutic activity, immune effects, and organ protective effects (Ganeshpurkar and Saluja 2017).

Scopoletin is one of the naturally occurring coumarins (a secondary metabolite that is characterized as 1,2-benzopyrones, distributed in plants and fungi). Scopoletin is presented by two fused aromatics rings substituted with a hydroxyl group together with a methoxy group and one oxo group in the pyran ring. Its presence in plants is connected to their defense mechanism towards infection by parasites and microbes. Scopoletin has antioxidant and antimicrobial activity. It is also demonstrated anti-inflammatory and

immunomodulating properties. Many studies have explored scopoletin's impact on diabetes mellitus. It showed a positive effect on both diabetes type 1 and type 2 (Antika et al. 2022). Anticancer, hypotensive and anti-atherosclerotic activities are also reported. Scopoletin has a positive effect on liver diseases. Scopoletin demonstrated promising potential in neurodegenerative disorders studies. Alzheimer's disease, Parkinson's disease and Huntington's disease can potentially be treated with scopoletin. Mental conditions such as anxiety, schizophrenia and depression improvements are observed (Gao et al. 2024). Scopoletin has suitable properties to be included as a drug in gout therapy (Ding et al. 2009).

Extraction of biologically active substances from raw plant, by-products and waste. Studies related to tobacco plants and their metabolites revealed that leaves and flowers of tobacco plants can be used for novel causes other than the production of cigarettes (Banožić et al. 2020). Tobacco processing waste is usually defined as solid waste (tobacco powder and low-quality leaves). Roots, leaf veins, stem and leaves with lower than standard quality can also be considered as waste. Multiple methods are classically used for extraction of tobacco and tobacco waste, using ethanol, methanol, ethyl acetate, acetone, hexane, or methylene chloride solvent extraction for tobacco extracts with antimicrobial activity, methanol solutions for polyphenols-rich extract or acetone and water solvent extraction to result in chlorogenic acid-rich extracts (Zou et al. 2021a). Many new and innovative ways of extraction of these valuable compounds are being studied on currently. An investigation by Lu et al. (2025) reported an economically efficient and simple method of silica gel column chromatography for the separation of nicotine from tobacco extract. Other research developed a technique for simultaneous extraction of nicotine and solanesol from tobacco waste material at room temperature and with minimum volume of solvent, followed by automatically separation and simple purification (Hu et al. 2015). Solanesol can be extracted by several methods such as ammonia leaching pretreatment assisted extraction, dynamic saponification extraction, ultrasonic assisted extraction, molecular distillation extraction, supercritical fluid extraction, bio-enzymatic extraction, molecular imprinted polymers extraction etc. (Yan et al. 2019).

Salting of nicotine from its aqueous solutions was studied by Meng et al. (2022). Various salts, including sodium and potassium chlorides and bromides, and sodium carbonate and sulfate, were employed at 25°C. The results clearly suggested that all investigated salts, as salting-out media, provoked an expansion of the two-phase region and showed potent partition yield for the separation of nicotine from its aqueous solutions. Similarly, Guan et al. (2025) used aqueous two-phase systems containing low molecular alcohol (ethanol or propanol) and salt (sodium sulfate or citrate). Nicotine was found to transfer to an alcohol-rich layer preferentially via an endothermic spontaneous process, influenced by increase of entropy. The salting-out-assisted extraction procedure was employed for quantification of nicotine in commercially available oral tobacco products by liquid chromatography coupled with mas-spectrometry (Aldeek et al. 2023). By this way the salting method for extraction of nicotine turned out to became in the last years un important technique for obtaining and determination of nicotine in tobacco wastes and products.

Acid-base maceration extraction method followed by liquid-liquid extraction technique has the highest amount of nicotine (Kheawfu 2021). Wang et al. (2022) extracted the alkaloids (nicotine, anatabine, nornicotine, and anabasine) using water under stirring, followed by alkalization and liquid–liquid extraction with chloroform. One study focuses on nicotine extraction using supercritical carbon dioxide and compares it with conventional hexane extraction. Three supercritical extraction conditions were evaluated: low pressure and temperature (120 bar, 28°C), elevated temperature at the same pressure (120 bar, 60°C), and elevated temperature and pressure (170 bar, 80°C) (Ikhsanov 2019).

The quantitative determination of nicotine is carried out by high-performance liquid chromatography (HPLC), gas chromatography (GC) or chromatographic techniques coupled with mass spectrometry (HPLC–MS/MS) (Aldeek et al. 2023; Guan et al. 2025; Ikhsanov 2019; Kheawfu 2021; Meng et al. 2022; Wang et al. 2022; Zhang et al. 2011; Zou et al. 2021b).

Other research reported development of technique for simultaneous extraction of nicotine and solanesol from tobacco waste material at room

temperature and with minimum volume of solvent, followed by automatically separation and simple purification (Hu et al. 2015).

Solanesol can be extracted by several methods such as ammonia leaching pretreatment assisted extraction, dynamic saponification extraction, ultrasonic assisted extraction, molecular distillation extraction, supercritical fluid extraction, bio-enzymatic extraction, molecular imprinted polymers extraction etc. Determination methods of solanesol primarily include liquid chromatography (LC), liquid chromatography-mass spectrometry (LC-MS), GC, thin layer chromatography (TLC), near infrared diffuse reflectance spectrophotometry (NIRDRS), colorimetric titration, and indirect iodometry (iodometric titration) (Yan et al. 2019).

Ultrasound-assisted extraction is a commonly used method for extraction of plant materials (Torras-Claveria et al. 2011; Wang et al. 2010; Xiang et al. 2010; Xie et al. 2011; Zang 2011). The method works on the principle of cavitation resulting from ultrasound pressure waves passing through the solvent (Banožić et al. 2020). Optimization of ultrasonic-assisted extraction of chlorogenic acid from tobacco waste by repeated freeze-thawing method was achieved by Zeng et al. (2022). A key drawback of this method is that its industrial implementation requires additional advanced technologies to be feasible and effective. Ultrasound-assisted extraction is suitable for obtaining of phenolic compounds such as rutin. Some researchers further purify the extract using solid-phase extraction (Xie et al. 2011; Zang 2011).

The most commonly used solvents for the extraction of polyphenols from tobacco and tobacco waste are aqueous methanol mixtures, such as 70% and 80% methanol. For the extraction of phenolic acids, acidified aqueous methanol can also be used (Ncube et al. 2014; Torras-Claveria et al. 2011; Wang et al. 2010; Xiang et al. 2010; Xie et al. 2011; Zang 2011).

Supercritical fluid extraction is considered "green extraction" due to its low-energy requirement, resorting to non-hazardous alternative solvents and renewable natural products (Da Silva et al. 2016). Carbon dioxide is widely used as a supercritical fluid extraction solvent due to its safety, availability and affordability (Ikhsanov et al. 2019). This method is used for nicotine and solanesol extraction. Tobacco essential oil can be obtained this way, as it has application in the fragrance industry (Banožić et al. 2020). Such an extraction is industrially performed by the biggest distillery on the Balkan peninsula situated in Zelenikovo village (Brezovo, Plovdiv, Bulgaria). The leaves of the Bulgarian oriental tobacco variety "Plovdiv 7" contain various triterpenes and polyphenol compounds (phenolic acids and flavonoids) with potent biological activity (Popova et al. 2018). Unlike the concretes and resinoid-extracts found in other tobacco varieties (such as Oriental, Virginia and Burley), each extract was found to possess unique volatile substances. The "Plovdiv 7" variety is considered as a valuable source for extracting aromas and biologically active compounds with application in cosmetic, perfumery and other industries. Microwave-assisted extraction reduces extraction time, however it is not appropriate for extraction of heat-sensitive compounds. Phenolic compounds, solanesol and volatile compounds can be extracted this way (Banožić et al. 2020).

The most preferred method for the separation and quantification of tobacco polyphenols is HPLC. In recent years, ultra-high-performance liquid chromatography (UHPLC) and high-performance liquid chromatography coupled with a mass-selective detector have been widely used (Banožić et al. 2020; Torras-Claveria et al. 2011; Wang et al. 2010; Xiang et al. 2010; Xie et al. 2011; Zhang 2011). Gas chromatography has limited application for the separation and identification of polyphenols. The large number of hydroxyl groups in polyphenol molecules increases their melting points and decreases their volatility. In addition to the mandatory extraction steps, the method also requires purification and derivatization (including preliminary hydrolysis of ester and glycosidic bonds) (Ignat et al. 2011).

The volatile compounds found in the tobacco represent additional interest. In a comparative study Banožić et al. (2021) investigated the composition of tobacco leaves and wastes (scrap, dust and midrib) by applying ultra-sound assisted extraction. The authors found that the most abundant compounds in tobacco leaves and wastes (scrap and dust) were nicotine (up to 87.5%), 4,8,13-duvatriene-1,3-diol (up to 16.2%), and neophytadiene (up to 9.4%). Only nicotine was present in all extracts from midrib waste.

Polysaccharides represent significant portion of the tobacco and tobacco wastes. Beside cellulose and hemicelluloses tobacco leaves contain pectic type polysaccharides (Ru et al. 2012). Employing water extraction at 100°C Ru et al. (2012) obtained polysaccharides (46.61±3.11 $mg.g^{-1}$ DW neutral polysaccharides and 3.21±0.22 $mg.g^{-1}$ DW acidic polysaccharides) which were investigated for their antioxidant activity. Although the results showed that compared to tobacco polyphenols the purified polysaccharide exhibited lower antioxidant capacity, the polysaccharide fractions could be further investigated for its physico-chemical or immunomodulating properties.

Table 2 summarizes extraction of bioactive compounds from tobacco and tobacco related material.

Other circular economy and green opportunities and valorization technologies. In the context of the limited energy sources as coal and oil, lignocellulose gains attention for its potential as an alternative energy source (Bareschino et al. 2021). Lignocellulose is composed of cellulose, hemicellulose, and lignin, and tobacco stems are rich in this lignocellulosic material. Cellulose from tobacco can be hydrolyzed and processed to obtain levulinic acid, which is a very important chemical platform compound. Furfural and 2,5-furandicaroboxylic acid can be obtained by dehydration and aromatization of hydrolyzed hemicelluloses and can be used for flavor compounds, lubricants, adhesives, fibers, films, polyethyleneterephtalate (PET) alternatives and more (Dussan et al. 2013; Ilkaeva et al. 2018; Morone et al. 2015; Rajesh et al. 2019). Lignin, with 2% constitute of tobacco, is structured by guaiacyl propane units and can be used for phenolic resin adhesives, nanocarriers, phenolic foam and adsorbents production. Bio-coal from tobacco stalks can replace coal, its energy efficiency of burning biomass surpasses that of coal combustion. Some studies highlight the opportunity for bio-oil production from tobacco biomass. Tobacco waste can be used as a carbon source for microorganisms in the production of a variety of enzymes (Shen et al. 2024). Sophanodorn et al. (2022) investigated the potential of tobacco waste as a raw material for bioethanol production by combined degradation and subsequent fermentation. The results suggested the highest ethanol amounts of 75.74 ($g.L^{-1}$) were obtained after 48 h fermentation.

Phytoremediation is a biological treatment method which uses plants for cleaning the environment (Khan et al. 2023). Heavy metal contaminants, resulting from human activities as mining, industrial processes, the use of metal-containing fertilizers and more, can be treated with phytoextraction. The extraction of the metal contaminants is happening through the roots and their translocation to the above-ground biomass (Bi et al. 2011). Tobacco grows rapidly, has a deep root system and large heavy metal accumulation capacity and is spotted as a very good choice for phytoremediation (Wu et al. 2021). The plant is able to purifies soils from several heavy metals such as cadmium, arsenic, copper and lead (Chaney and Baklanov 2017; Khan et al. 2023). Decontamination of soils polluted with Cd^{2+} with biochar prepared on the basis of tobacco waste stalks was investigated by Yu et al. (2021). The investigation confirmed the great potential of the tobacco and its by-products as a potent bioremediation plant. The addition of 2% (by weight) tobacco biochar to red soils significantly increases the pH and reduces the exchangeable Cd fractions thus reducing the accumulation in the tobacco leaves. Hristozova et al. (2020) investigated the accumulation of lead and zinc in mature tobacco leaves of tobacco plants grown on contaminated soils and found by correlation/regression analyses statistically significant linear relationships between the total content in leaves and mobile forms of Pb and Zn in soils. Additional approach for enhancement of accumulation of heavy metals by tobacco plant was investigated by Zheng et al. (2022). The results suggested that expression of a multifunctional inducible protein HsMT1L in tobacco could significantly enhance the accumulation of Zn^{2+} and Cd^{2+} in both the aboveground parts and the roots compared to wild-type tobacco plants and provided a higher tolerance to Zn and Cd in gene-modified tobacco plants. Similarly, Nahar et al. (2017) by cloning a gene (expressing the enzyme arsenic reductase 2) of *Arabidopsis thaliana* into the genome of tobacco (*Nicotiana tabacum*, var Sumsun) achieved better survivability of the modified tobacco compared to the wild type.

Table 2. Extraction of bioactive compounds from tobacco and tobacco related material

Source	Compound	Method/ Techniques	Solvent	Material/ solvent ratio	Temperature	Time	Analysis	References
Tobacco	Alkaloids -Nicotine	SCF extraction	hexane	raw materials / extractant 1:10	28ºC / 150 bar 60ºC / 150 bar 60ºC / 170 bar 60ºC / 120 bar 80ºC / 170 bar 80ºC / 120 bar	72 h	GC / MS	(Ikhsanov et al. 2019)
		maceration extraction	water ethanol	50 g in 750 ml	25 ± 2°C	48 h × 3 times	HPLC	
Tobacco	Alkaloids -Nicotine	1) acid-base extraction 2) liquid-liquid extraction	1) water 2) 10 g of Na_2CO_3 added 3) pH 12 using NaOH 4) chloroform	1) 50 g in 750 ml 4) 100 ml	1) 80 ± 5°C 2) 80°C	1) 20 min 2) 10 min	HPLC	(Kheawfu et al. 2021)
Tobacco	Alkaloids - nicotine anatabine, nornicotine, and anabasine	1) mechanical stirring 2) liquid-liquid extraction	1) Water 2) pH 13 (NaOH) 3) chloroform	1) 50 g in 600 ml 3) 300 ml	60°C	1) 5 h 3) 30 min × 3 times	HPLC-MS/MS	(Wang et al. 2022)
Tobacco	Flavonoids – total flavonoid content	1) reflux extraction 2) purified with macroporous adsorption resin	1) 85% ethanol 2) ethanol	50 g	80°C	60 min	colorimetric method	(Ru et al. 2012)
Tobacco	Polyphenols - rutin, esculetin, chlorogenic acid (3-O-CA, 4-O-CA, 5-O-CA), caffeic acid, scopoletin, quercitrin, pyrocatechol, kaempferol (KF), KF-3-R, aesculin Organic acids - succinic acid, lactic acid, citric acid, oxalic acid, DL-malic acid	1) ultrasonic extraction 2) purified with SPE cartridge	1) 80% methanol pH 2 2) directly collecting the extract	0.1 g in 10 ml	-	30 min	UPLC/ MS/MS	(Xiang et al. 2010)
Tobacco	Polyphenols – rutin, esculetin, chlorogenic acid, caffeic acis, scopoletin, quercitrin	1) ultrasonic extraction 2) purified with SPE cartridge	1) 80% methanol containing 2 ml of acetic acid	50 mg in 100 ml	-	30 min	UPLC/MS/MS	(Zhang et al. 2011)
Tobacco	Phenolic acids – p-coumaroylquinic acids, caffeoylquinic acids, caffeoylglycoside and feruloylglycoside, di-caffeoylquinic acid and caffeoylquinic acid glucoside	sonicaton	80% methanol	2 g in 20 ml	-	15 s x 4 cycles	UPLC	(Ncube et al. 2014)

Source	Compound	Method/ Techniques	Solvent	Material/ solvent ratio	Temperature	Time	Analysis	References
Tobacco waste	Alkaloids - nicotine Polyphenols – p-coumaroylquinic acids, feruloylquinic acids, chlorogenic acids, scopolin, quinic acid, caffeic acid, rutin, isoquercitrin and luteolin-7-rutinoside	ultrasonic extraction	70 % methanol	150 g in 500 ml	-	30 min × 4 times	LC-MS/MS	(Wang et al. 2010)
Tobacco	Polyphenols – -O-caffeoylquinic acid, chlorogenic acid rutin, 4-o-caffeoyl-quinic acid, caffeic acid, scopoletin, kaempferol-3-rutinoside, quercitrin	1) ultrasonic extraction 2) purified with SPE cartridge	70 % methanol	0.25 g in 40 ml	-	30 min	RRLC	(Xie et al. 2011)
Tobacco	Polyphenols – hydroxycinnamoylquinic acids, benzoic and hydroxycinnamic acid glucosides, flavonoid derivatives, hydroxycinnamic acid amides	ultrasonic extraction	methanol /water (3% acetic acid) (1:1)	1 g in 3.5 ml	RT	30 min	LC–MS/MS	(Torras-Claveria et al. 2011)

SCF – Supercritical fluid CO_2; SPE – Solid phase extraction; UPLC – Ultra-high performance liquid chromatography; GC/MS – Gas Chromatography / Mass Spectrometry; HPLC – High-Performance Liquid Chromatography; HPLC-MS/MS – High-Performance Liquid Chromatography coupled with Tandem Mass Spectrometry; UPLC/MS/MS – Ultra-Performance Liquid Chromatography coupled with Tandem Mass Spectrometry; RRLC – Rapid resolution liquid chromatography; CCE – Column-chromatographic extraction; RT – room temperature

Besides, the accumulation of arsenic in the in the roots of transgenic plant was significantly higher (2400 μg.g^{-1} DW) than that of wild type plants (2100 μg.g^{-1} DW). Not only the plants can be applied as bioaccumulators of pollutants but the waste parts of the plant could also be used in this regards. Prokopov et al. (2019) used tobacco stalks as low-cost, biodegradable and renewable adsorbent for the purification of water systems from heavy metals (Cr^{6+}). Recently, after the COVID crisis, due to the economic situation and global powers opposition, certain important raw materials (such as cobalt, copper, magnesium, rare earth elements, platinum group metals, etc.) became a great priority for the countries. These materials became known as "Strategic and critical raw materials" and their mining and technology for obtaining and purification was in the core priorities of EU, USA, China and all the other biggest producers of modern equipment (https://ec.europa.eu/commission/presscorner/detail/en/ip_23_1661). Besides the usual technologies and strategies, utilization of plants, higher fungi or microorganisms is a promising opportunity. Phytomining is the accumulation of economic metal value in plant biomass. A combination of phytoremediation and phytomining can result in purifying contaminated soils from heavy metals and obtaining these heavy metals as a resource (Kozak and Antosiewicz 2023; Selwal et al. 2023).

Tobacco waste is phytotoxic due to the alkaloid content. Composting tobacco waste with chicken manure decreased the alkaloid content from ~6,000 to ~200 mg.kg^{-1}. The compost treatments (0, 10, 15, and 20 t.ha^{-1}) were combined fertilizer with phosphorus (40 kg.ha^{-1}), nitrogen (60 kg.ha^{-1}) and potassium (90 kg.ha^{-1}) for leaf mustard (*Brassica integrifolia*). The yield increased from ~17 to ~29 t.ha^{-1} with the amount of compost applied, and the nitrate concentration decreased concomitantly from ~67 to ~42 mg N.kg^{-1} fresh weight, presumably due to ongoing composting (nitrogen drawdown). Organoleptic evaluation showed a preference for the crops grown with the compost amendments. Tobacco waste was converted into a useful soil amendment by composting with poultry manure. Adding a culture of *Bacilus subtillis* and *Trichoderma harzianum* accelerated the composting and raised the temperature sufficiently to suppress the transmission of disease and weeds. With 0.2 t of chicken manure of ingredients, composting decreased the alkaloid content from ~6,000 mg.kg-1 in the tobacco waste to just ~200 mg.kg^{-1}, although the C/N ratio remained high (19:1). Despite causing N-drawdown, soil amendments with the mixture increased yields of leaf mustard almost linearly to the maximum treatment applied (20 t.ha^{-1}) and improved the palatability. Further study is required to learn whether small additions of urea to the mixture before composting might achieve the desired 12:1 C/N ratio and eliminate both the requirement for a large proportion of poultry manure and minimize N drawdown. It also remains to be seen whether one-off compost applications >20 t.ha^{-1} and/or repeated large applications provide additional, long-term production benefits, or if the benefits may be outweighed by the accumulation of persistent, phytotoxic alkaloids (Nguyen et al. 2022). Composting of tobacco waste stems and stalks poses difficulties due to the toxicity of nicotine – according to the European Union legislations nicotine-rich waste (>500 mg.kg^{-1}) is classified as toxic and hazardous material (Abdellah et al. 2025). A promising strategy using the enormous potential of microorganisms was assessed by Mandić et al. (2023). The authors investigated composting of waste tobacco leaves with the addition of the species *Brevibacillus* at different conditions. The initial nicotine content in the tobacco waste was around 17000 mg per kg. After the fermentation process in all the experiments using nicotine-degrading bacteria, the amount of nicotine was below 10 mg.kg^{-1}. In this regard a comprehensive review on the subject was recently published by Li et al. (2024) summarizing and commenting on the main bacteria and fungi able to degrade nicotine and their practical application. According to the review article the main nicotine degrading bacteria belonging to the *Pseudomonas*, *Arthrobacter*, and *Ochrobactrum intermedium* genera while among the main nicotine degrading fungi are *Cunninghamella echinulata*, *Microsporum gypseum*, *Streptomyces griseus*, *Streptomyces*

platensis, and *Pellicularia filamentosa*. The deeper understanding of the bacteria and fungi metabolism allowed clarification of the main pathways and mechanisms standing behind denicotinification processes: pyrolidine pathway utilized by *Pseudomonas* species and *Cunninghamella echinulate*; the pyridine pathway used in *Arthrobacter* species and some hybrid pathways (such as demethylation pathway) characteristic for tobacco plants and fungi. The most usual places from which the nicotine degrading species are isolated are tobacco plant parts (leaves, stems, etc.) and soil where tobacco has been grown (Wang et al. 2023a). This knowledge is helping not only for nicotine removal and making composting more efficient but lately was used for treatment of tobacco products and producing valuable intermediates and products on the basis of nicotine (Liu et al. 2015).

A study reports the engineering of insecticide films based on two mineral clays, montmorillonite and kaolinite, combined to chitosan and/or cellulose acetate originating from cigarette butts and subsequently impregnated with tobacco essential oil extracted from tobacco dust. The two clay minerals showed different kinds of interaction with chitosan: intercalation in the case of montmorillonite versus adsorption on the external surface for kaolinite. Secondly, the nicotine release from the composites films at different temperatures was studied by *in situ* infrared spectroscopy (IR). The montmorillonite composites, particularly the ternary one, showed a better encapsulation of nicotine which release was limited. Finally, the insecticidal activity of the composites was evaluated against the *Tribolium castaneum* a common wheat pest. The differences observed between montmorillonite and kaolinite composites were rationalized in relation to the nature of interaction between the components. The fumigant bioassay showed promising insecticidal effects in the case of the ternary composite cellulose acetate/chitosan/ montmorillonite. Therefore, these eco-friendly nanocomposites can be used efficiently for the sustainable protection of stored cereals (Missaoui et al. 2023).

The tobacco stalks, a by-product from the field which is usually mechanically crushed during plowing, was used for production of nanofibrilated cellulose by employing steam explosion pulping process (Tuzzin et al. 2016). The nanofibrilated cellulose was further used for production of hydrogels and its properties were compared with hydrogels obtained from eucalyptus kraft pulp, processed under the same conditions. Scanning electronic microscopy revealed a higher presence of nanofibers in the tobacco stems pulp than in commercial eucalyptus kraft pulp. Further analyses (IR, XRD, etc.) suggested that the tobacco waste stalks could be successfully valorized for production of nanofibrilated cellulose and hydrogels. The waste tobacco leaf stems could be used for production of energetic briquettes (Peševski et al. 2010) or for reconstituted tobacco films for production of cigarettes (Tuzzin et al. 2016). The remaining industrial tobacco dust is difficult to dispose since it is considered an excise good. Usually it is valorized by transformation in tobacco foil which is further utilized for cigarette and cigars production (Nenov 2007).

In recent decades, there has been considerable interest in the synthesis of nanoparticles with specific sizes and morphologies. Nanomaterials based on particles with a size below 100 nm, such as nano-sheets, nano-tubes, nano-strings, nano-coatings, etc., possessing unique and valuable properties have the potential to be used in medicine, for biosensors, for catalysts for the elimination of harmful substances, for the detection of extremely low concentrations of various substances, in the development of fuel cells and sensors, etc. (Lazarova et al. 2023). The use of biodegradable waste raw materials for the "green" synthesis of nanoparticles is one of the relatively new and up-to-date approaches in this direction and has two main advantages – it represents an environmentally friendly approach to obtaining nanoparticles, as well as a method for valorization of the large amounts of waste plant materials. For example, Prasad et al. (2011) successfully synthesized silver nanoparticles using tobacco leaf extracts and investigated their antibacterial properties. Suharto et al. (2024) obtained and investigated copper nanoparticles using various tobacco leaf extracts, showing the advantage of using water-methanol

systems. These biogenically synthesized nanoparticles have the potential to be used to combat diseases of the tobacco plant itself, such as tobacco mosaic virus.

Tackling cigarettes butts – major ecological challenge and decisions. Cigarettes are the globally consumed product that contribute significantly to global public health problems (Shah et al. 2023). Cigarette butts are among the most prevalent forms of waste worldwide (Rubio 2020). It is estimated that approximately 1.2 billion tons of cigarette butts are released into the environment. Waste from this industry is widespread globally, creating a significant environmental challenge due to the difficulty of collection and the complexity of proper disposal. In urban environments, cigarette butts are unevenly distributed and can be transported through waterways, lakes, seas, and soils (Arat 2024). Their persistence in the environment poses toxic risks because they contain numerous chemical compounds introduced during cultivation and manufacturing, such as fungicides, herbicides, insecticides, and pesticides, as well as harmful substances including tar, hydrogen cyanide, nitrates, and ammonia, among others (Morales-Vera et al. 2024). Recycling of tobacco product waste, such as cigarette butts (CB), is a crucial step for a greener way of life. The cigarette consists of tobacco, cigarette paper, filter, tipping paper, and additives (Fig. 2).



Figure 2. Composition of cigarette

The filter, typically made of cellulose acetate is designed to reduce the amount of smoke, tar and fine particles inhaled during the combustion and to reduce the harshness of the smoke and keep tobacco flakes out of the smoker's mouth (Kurmus and Mohajerani 2020; Marinello et al. 2019). When a cigarette is smoked, it is converted into particulate and volatile phases. A portion of the particulate phase is trapped in the cigarette filter (Rodgman and Perfetti 2013). Cigarette butts are a major source of approximately 4000 toxic chemicals, of which 69 are carcinogenic including nicotine, alkaloids, compounds specific to the *Solanaceae* family, catechols, aromatic hydrocarbons, polycyclic aromatic hydrocarbon, aromatic amines and others (PAH) (Rodgman and Perfetti 2013).

In addition to their impact on human health, cigarettes also pose a significant environmental threat. Nowadays cigarette butts become widespread forms of anthropogenic waste on the planet. Even if there is no remaining tobacco, the cigarette butts are still harmful to the environment due to the toxic chemicals left over from smoking (Bonanomi 2020; Shah et al. 2023). Cigarette butts affect the health of wildlife, humans, and the environment and their decomposition can take years due to the resistance of cellulose acetate to bacterial and fungal degradation (Shah et al. 2023).

Cigarette butts are resistant to biodegradation in natural environments. Due to the plasticized cellulose acetate filters, they exhibit poor biodegradability and may take up to 18 months or longer to decompose under normal environmental conditions. Cigarette butts pose short- and long-term toxicity threats due to rapid leaching when wet, while their slow decomposition with periodic wettings results in prolonged environmental contamination, posing a serious dilemma in terms of toxic waste and litter disposal (Kurmus and Mohajerani 2020; Soleimani et al. 2023).

Different ways of recycling tobacco cigarette butts are being sought. In general, work is being done in several areas. A number of studies have been realized on recycling cigarette butts, including recycling of cigarette butts in fired clay bricks, asphalt concrete, as a carbon source, sound-absorbing material, corrosion inhibitor, biofilm carrier, and many more.

Mixing in fired clay bricks. Recently, several reasonable methods were explored for CBs recycling or reusage, such as incorporating CBs into building materials like fired clay bricks, transforming CBs into insecticides against mosquitoes, highly fluorescent carbon dots, and into carbon-based material. Yadav and Chandrakar (2022) investigated the possibility of recycling cigarette butts into fired clay bricks. Adding cigarette butts to the raw materials reduced the dry density of fired clay bricks. Low-density or light-weight bricks have great advantages in construction including lower structural dead load, easier handling, lower transport costs, lower thermal conductivity and a higher number of bricks produced per tons of raw materials. Light bricks can be substituted for standard bricks in different applications according to the required strength. Cigarette butts can also be regarded as a potential addition to the raw materials used in the manufacture of light-weight fired bricks. Therefore, manufactured clay-cigarette butts' bricks are appropriate for these applications.

The use of cigarette butts in fired clay bricks in amounts of up to 5% w/w is capable of forming porosity in the samples, making the part lighter, in addition to possibly reducing thermal conductivity and sound transmission, being an economical and sustainable alternative for the final disposal of cigarette butts (Paulista et al. 2024).

Since cigarette butts contain a large number of chemical substances, some researchers have focused their attention on investigating the chemical composition of the resulting products. During the firing process almost 100 % combustion of cigarette butts occurred. Almost all carbon in the fired clay bricks – cigarette butts' mixture was effectively eliminated during firing at 1050°C. However, further research is needed to investigate the emissions of volatile organic compounds during the production of fired clay bricks containing cigarette butts (Kurmus et al. 2021). In fired clay bricks production, the concentration of heavy metals, including arsenic (As), selenium (Se), mercury (Hg), barium (Ba), cadmium (Cd), chromium (Cr), lead (Pb), silver (Ag), zinc (Zn), copper (Cu), and nickel (Ni), remained below the standard acceptable limits. The low levels detected in leaching can be attributed to the high firing temperature during the firing process of the clay bricks incorporating cigarette butts (Kadir and Mohajerani 2012).

Mixing in asphalt concrete. Some studies aimed to investigate the recycling of cigarette butts in asphalt using bitumen encapsulated CBs. Asphalt concrete, which is also known as asphalt have the low chemical reactivity and the large volume used in road and pavement construction. The addition of small quantities of waste materials, such as cigarette butts, may result in viable applications in construction of flexible pavements while ridding the environment of this waste material (Dehaghi et al. 2024; Mohajerani et al. 2017; Rahman and Mohajerani 2020).

Encapsulating cigarette butts with bitumen and incorporating them into asphalt concrete is technically feasible under certain conditions. When

cigarette butts were encapsulated with bitumen, the addition of 10 $kg.m^{-3}$ and 15 $kg.m^{-3}$ satisfied the mechanical and volumetric requirements for light, medium, and heavy traffic conditions. The higher contents (25 $kg.m^{-3}$) did not fully meet the performance criteria. When cigarette butts were encapsulated with paraffin wax, the incorporation of 10 $kg.m^{-3}$ met the requirements only for light traffic conditions, indicating lower structural performance compared to bitumen encapsulation. The incorporation of encapsulated CBs reduced the bulk density of the asphalt concrete and increased its porosity. This increase in porosity led to lower thermal conductivity of the pavement material. As a result, such modified asphalt mixtures may contribute to mitigating the Urban Heat Island effect in urban environments (Mohajerani et al. 2017).

Other authors investigated encapsulation with asphalt binder and mixing with hot asphalt binder. Encapsulated cigarette butts negatively affected durability compared to cellulose fibers. However, when cigarette butt fibers were directly mixed with hot asphalt binder for 8 min, the performance of mixtures improved, showing enhanced water resistance, better fracture characteristics, and improved rutting resistance. Environmental assessment testing demonstrated that incorporating cigarette butt fibers into stone matrix asphalt mixtures does not result in harmful environmental impacts. The findings suggest that cigarette butt fibers, when properly mixed with hot asphalt binder, can be considered a viable alternative to conventional asphalt binder stabilizers (Dehaghi et al. 2024).

The use of encapsulated cigarette butts in stone mastic asphalt samples manufactured improved the stability and resistance to permanent deformation. The leaching of heavy metals from encapsulated cigarette butts compared with those of unprocessed cigarette butts reduced significantly (Rahman and Mohajerani 2020). In additionally the results associated with the physical and rheological properties of cigarette butts modified bitumen showed that cigarette butts could be used as a fiber modifier for bitumen (Rahman et al. 2020). Acoustics and insulation materials. There has been growing interest in developing sustainable construction materials, including sound-absorbing products for room acoustics and insulation. Cigarette butts has significant potential as an acoustic absorbent, with absorption coefficients exceeding 0.8 for frequencies above 2000 Hz (Escobar, 2019). Cigarette butts have demonstrated high acoustic performance, suggesting that their use in producing sound-absorbing materials is a promising and effective strategy for waste reuse (Escobar et al. 2021).

Maderuelo Sanz (2018) investigated the physical properties and acoustical performance of a cellulose acetate material produced from cigarette filters. The cellulose acetate was manually separated of the outer and inner paper, shredded into short fibers and then mixed to form a homogeneous mixture where no specific bonding method was used. The study found that the acoustic performance of a cellulose acetate material made from cigarette butts is similar or better compared to that of other commercial fiber materials, suggesting that recycled cigarette filters could serve as a viable alternative to conventional sound-absorbing products in building construction.

Some authors find that it is possible to produce cellulose pulp from cigarette butts. According to Teixeira et al. (2017), the produced cellulose pulp can be utilized by the paper recycling industry, either used on its own or blended with pulps from various sources, depending on the quality requirements of the final paper product. The method of separating all the cellulose content in the cigarette butt is structured by four processes. The ash and all chemicals absorbed in the filter are dissolved, then cellulose acetate is hydrolyzed into cellulose, lignin is removed from the remaining tobacco and its cellulose is liberated, the remaining paper is disaggregated. After filtration in the resulting mixture, cellulose pulp and dark liquor needing treatment are obtained. This approach represents an environmentally friendly solution for managing this solid waste, which is generated in large quantities worldwide.

Bioremediation. Typically, after use, cigarette filters enter the natural environment, where they become a source of persistent, poorly degradable toxic pollutants, thereby contributing to environmental contamination. The role of microorganisms for environmental detoxification has always been crucial, but with the growing pollution rates the need for environmentally friendly and effective way for detoxification is emerging. Recently, scientists turned their gaze towards the

mycoremediation – a promising approach involving fungi that are able to degrade toxic compounds to less harmful or no harmful at all forms. Mycoremediation is an economical and environmentally safe technique that produces no toxic byproducts. Its success largely depends on carefully selecting and applying the most suitable fungal species for the specific heavy metal or contaminant involved. This method represents a practical and affordable solution to the escalating issue of soil and water pollution (Akhtar et al. 2020). As a form of bioremediation, mycoremediation employs fungi to remove or neutralize hazardous substances and can involve both filamentous fungi (molds) and macrofungi (mushrooms). Consequently, it serves as a biological tool for the degradation, transformation, or immobilization of pollutants (Bosco and Mollea 2019).

As a biological agent, fungi offer several advantages in the bioremediation process in comparison with bacteria for example. Wood rot fungi have been used on many occasions to degrade various organic and inorganic compounds (Kameshwar and Qin 2018). Firstly, fungi are extremely flexible organisms and are able to survive in harsh conditions such as drastic pH levels, extreme temperature and moisture conditions which makes them applicable in hostile environments. Secondly, fungi can produce a variety of enzymes involved in the degradation pathways of a large number of toxic pollutants. Due to the ability of producing ligninolytic enzymes, white-rot fungi, such as *Pleurotus ostreatus* and *Trametes versicolor* are often employed in bioremediation research (Dave et al. 2025; Marmanillo et al. 2024; Su et al. 2016). Also, fungi can be employed in both *in situ* and *ex situ* processes at various contaminated sites, such as soil, water or air.

Although cigarette filters have been mass-produced and widely used since the 1950s, scientific attention to the environmental and biological impacts of CBs emerged relatively recently, with the first documented studies appearing only in the late 2000s. This significant time gap highlights a long-standing lack of awareness regarding their potential ecological risks. Between 2006 and 2022, merely 36 toxicological investigations were conducted to assess the effects of CBs, underscoring the limited scope of research in this area. Notably, 28 of these studies concentrated on the toxicity of aqueous leachates released from CBs, reflecting growing concern about the harmful substances that can leach into aquatic environments and pose risks to living organisms (Green et al. 2022). To date there is significant amount of available research dealing mostly with the detoxification and the degradation of the CBs. Most authors have attributed the detoxification and biodegradation abilities to the enzymatic complex, produced by the white-rot fungi. The ligninolytic enzymes laccase, manganese peroxidase and lignin peroxidase comprise the ligninolytic degradation system of these fungi. *Trametes versicolor* is distinguished in production of ligninolytic enzymes and has proven biodegradation abilities towards large number of persistent pollutants. This mushroom, alongside with *Trametes hirsute* and *Phanerochaete chrysosporium* were able to degrade nicotine and lignin from tabacco stalks. In this research the degradation and the detoxification led to higher enzyme production, which might be due to enzyme induction based on the chemical nature of the substrate (Su et al. 2016). Dave et al. (2025) have demonstrated that *T. versicolor* has the ability to degrade and detoxify nicotine with high degradation rates even when in extreme conditions such as low pH and high temperatures. The degradation effectiveness was even higher (up to 99%) at 25°C and pH 5.2. Pilar Núñez et al. (2023) investigated the detoxifying effect of two fungal strains isolated from Argentinean rainforests, namely *Trametes* sp. BAFC4767 and *Irpex lacteus* BAFC4766 and found that most of the mycelium developed around the paper wrapper (piercing through the CBs paper), which displayed signs of degradation and is supposed to be a good food source for the fungus. This observation confirms degree a high of fungal invasion on the inside of the CBs, and this part is where most of the toxic chemicals are concentrated which is related to the ability of the white rot fungi to degrade and detoxify phenolic compounds and aromatic hydrocarbons.

Other methods for valorization of CBs. The recovered cigarette butts can be used to produce a wide consumption fashion product, such as eyeglass frames. This process involves a two-step procedure: washings in water, followed by subsequent washings in ethanol, and then drying the cigarette butts in an oven at 60°C for 60 min (De Fenzo et al.

2020). Since the first major role of the CBs is to filter the cigarette smoke it is reasonable to be used for the same purpose after purification and denicotinification. Kakoria and Sinha-Ray (2022) proposed a method for preparation of ultrafine nanofiber-based air filters made from waste CBs cellulose acetate. After purification of the CBs the polymer was electrospun in a form of nanofibers serving for preparation of sandwich type filter for removal of particles from air. The results suggested high efficiency purification: more than 99.5% at 90 $L.min^{-1}$ air velocity.

Ribeiro et al. (2025) decompose the cigarette butts and obtain lignin-like solids and bio-oil. Lignin-like solids was found to contain chemically relevant compounds, making it a promising feedstock for biorefining applications and supporting resource cycling. Analysis of the bio-oil revealed a complex composition, with cyclic and branched hydrocarbons as the main fraction, indicating potential applications beyond biofuel production, such as fine chemicals. From an environmental perspective, this approach provides a sustainable method for converting cigarette butts into valuable chemical products, feedstocks and energy, while being consistent with the environmental management and responsible use of municipal solid waste.

Considering that main component of CBs is cellulose acetate with a high degree of carbon atoms, the waste CB is obviously a good candidate precursor for carbon materials, which have wide applications in various fields. A simple, low cost, and highly efficient approach to recycle waste CBs as carbonaceous adsorbents for heavy metal removal was developed. The feasibility of using CBs-derived carbonaceous adsorbents to remove lead (Pb^{2+}), chromium (Cr^{3+}), cobalt (Co^{2+}), nickel (Ni^{2+}) and cadmium (Cd^{2+}) from water was investigated. The prepared CBs-derived activated carbon is a potential absorbent for heavy metal removal with the advantages of low cost, simple synthesis pathway, rapid equilibrium and excellent adsorption capacity, providing an environmental friendly, economical way for discarded cigarette butts recycling (Zhang et al. 2021).

Perhaps the most difficult part tackling the waste CBs is their collection when disposed improperly in the nature. Some countries rely on a cheap labor for collection of CBs and their further valorization but in developed countries the amount of payment for cleaning CBs is quite high. For example, in Sweden more than 1 billion CBs are thrown away on the streets each year, which represents 62% of all litter. Södertälje, a small city near Stockholm spends 20 million Swedish kronor (€ 1.88 million) cleaning the CBs (Boffey 2022). For this reason, the city had started a pilot project including city's crows to pick up waste CBs and deliver them to a disposal machine which in rewards give the birds a small portion of food. This led to lowering the allocated finances for cleaning the CBs from the streets. It seems that the most difficult part in this project is to teach the crows to get included and collect the CBs but the results suggested that the birds had learned fast and did successfully the cleaning tasks. Ironically, it seems more difficult to teach some people to dispose the waste CBs properly…

In addition to the scientific part of the problem, another important aspect is the cooperation with the administration and the public, which can significantly support the efforts to collect and reduce the amount of improperly disposed CBs. Bulgaria, unfortunately, lags significantly in this respect and the National Waste Management Plan lacks information and a strategy for the prevention, collection and utilization of CBs. Good examples worldwide are the company Waste4Change (Indonesia), the joint initiative of Terracycle and Santa Fe Natural Tobacco Company® (USA) (https://www.terracycle.com/en-US/brigades/cigarette-waste-recycling), the actions taken by the local administration in Victoria, Australia (Cigarette bUtts - Waste Management in Australia (weebly.com)), the presence of projects aimed at prevention for the disposal of cigarette butts (Microsoft Word – CBPP Just the Facts 2013.doc (filesusr.com)), etc. For this reason, the European Commission is going to take the respective actions and is trying to find alternatives replacing the cigarette filters based on plastic type materials (Available at: https://www.who.int/europe/news/item/30-05-2022-eu-ban-on-microplastics-stubs-out-cigarette-butt-pollution).

Conclusions

Tobacco's whole path from a plant through manufacturing to waste, as litter like cigarette butts, is full of potential ways of adding value to the starting source. The circular economy's voice stably borders the basis on which humanity should build its future in harmony with nature. Many valuable compounds have already been found and placed under investigation for beneficial effects on human health. Due to the limitations of currently used energy sources, many researchers are observing alternative options. The litter from smoking products is still a challenge for recycling systems, and additional work is needed on this issue. If one day the whole population quits smoking tobacco products due to the detrimental effects on health, the tobacco plant will not lose its value. Tobacco has high potential in purifying contaminated soils by its phytoremediation properties and actively participates in the development of sustainable practices through the combination of phytoextraction and phytomining. Tobacco is a source of diverse compounds with proven positive effects and many applications in agricultural, pharmaceutical and medicinal fields. Biotechnological approaches such as microbial cultivation and enzymatic bioconversion enable the transformation of tobacco residues into high-value bioproducts. Cigarette butts can be utilized as a nutrient source for fungal cultivation, enabling their sustainable detoxification and transformation. The plant kingdom has much to give, and tobacco is a bright example of that.

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Author Contributions

Conceptualization, A.S., P.K., V.P., T.I., M.D. and G.A.; methodology, A.S., I.H., P.K., M.D., T.I. and V.P.; formal analysis A.S., M.D. and P.K.; investigation, P.K., M.D., A.S., M.B., M.K. and V.P.; resources, A.S., P.K., M.D., T.I., and I.H.; data curation, A.S., M.D. and P.K.; writing - original draft preparation, P.K., A.S., M.D., V.P. and T.I.; writing – P.K., A.S., M.D., V.P., T.I., G.A. and S.S., review and editing, A.S., M.D., V.P., G.A., M.B., I.H., P.K. and M.K.; visualization, A.S. and I.H.; supervision, A.S. and M.D.; project administration, A.S., P.K., and M.D.; funding acquisition, A.S. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement

The experimental protocol used in this study was designed in compliance with the guidelines of the European and Bulgarian legislation regarding the protection of animals used for experimental and other scientific purposes (Directive 2010/63; EC, 2010 - put into law in Bulgaria with Regulation 20/2012). The protocol was based on the permit for the use of animals in experiments No. 277 of the Bulgarian Food Safety Agency (Statement No. 193 of the Bulgarian Animal Ethics Committee, prot.No.18/02.07.2020, 2 July 2020).

Informed Consent Statement

Not applicable.

Data Availability Statement

The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding authors.

Conflicts of Interest

The authors declare no conflicts of interest.

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