DEODORIZATION OF LEATHER TANNERY WASTE WATER TOXIC GASES USING SPENT COFFEE GROUNDS: A COMPREHENSIVE REVIEW

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ABSTRACT. The leather tanning industry is a major contributor to economic development worldwide; however, it is also associated with significant environmental challenges, particularly the generation of toxic and malodorous gases from wastewater treatment processes. Emissions such as hydrogen sulfide (H_2S), ammonia (NH_3), and volatile organic compounds (VOCs) not only create severe odor nuisances but also pose substantial risks to human health, workplace safety, and environmental quality. Conventional odor control technologies, including chemical scrubbing, activated carbon adsorption, and biological filtration, often suffer from high operational costs, energy demands, and secondary waste generation, highlighting the need for sustainable alternatives. This review critically examines the potential of spent coffee grounds (SCG), an abundant agro-industrial by-product, as an innovative and eco-friendly adsorbent for deodorizing tannery wastewater gases. Owing to their porous structure, high carbon content, and rich surface chemistry containing hydroxyl, carboxyl, and phenolic functional groups, SCG exhibit remarkable capabilities for capturing and transforming hazardous gaseous pollutants through physical adsorption, chemisorption, and redox mechanisms. The review discusses the sources and formation pathways of toxic tannery gases, evaluates existing odor control technologies and their limitations, and explores the physicochemical characteristics and gas-removal mechanisms of SCG. Furthermore, it highlights current research advances, regeneration potential, and opportunities for integrating SCG into sustainable wastewater treatment systems. Although challenges related to adsorption efficiency, material standardization, and large-scale implementation remain, the valorization of spent coffee grounds represents a promising circular-economy strategy that simultaneously addresses waste management and industrial air pollution.

KEYWORDS: leather tannery wastewater, spent coffee grounds, odor control, adsorption, circular economy

DEZODORIZAREA GAZELOR TOXICE REZULTATE DIN APELE UZATE ALE TĂBĂCĂRIILOR FOLOSIND ZAȚUL DE CAFEA: O ANALIZĂ CUPRINZĂTOARE

REZUMAT. Industria de pielărie contribuie semnificativ la dezvoltarea economică mondială; totuși, aceasta este asociată și cu provocări ecologice majore, în special generarea de gaze toxice și urât mirositoare în procesele de tratare a apelor uzate. Emisii precum hidrogenul sulfurat (H_2S), amoniacul (NH_3) și compușii organici volatili (COV) nu doar că provoacă un disconfort olfactiv sever, dar prezintă și riscuri considerabile pentru sănătatea umană, siguranța la locul de muncă și calitatea mediului. Tehnologiile convenționale de control al mirosurilor – inclusiv spălarea chimică a gazelor, adsorbția pe cărbune activ și filtrarea biologică – implică adesea costuri operaționale ridicate, un consum mare de energie și generarea de deșeuri secundare, ceea ce subliniază necesitatea unor alternative sustenabile. Această lucrare analizează critic potențialul zațului de cafea – un produs secundar agroindustrial abundent – ca adsorbent inovator și ecologic pentru dezodorizarea gazelor provenite din apele uzate ale tăbăcăriilor. Datorită structurii poroase, conținutului ridicat de carbon și chimiei de suprafață bogate în grupări funcționale hidroxil, carboxil și fenolice, zațul de cafea prezintă capacități remarcabile de captare și transformare a poluanților gazoși periculoși prin mecanisme de adsorbție fizică, chemosorbție și reacții redox. Lucrarea discută sursele și căile de formare a gazelor toxice din tăbăcării, evaluează tehnologiile existente de control al mirosurilor și limitările acestora și explorează caracteristicile fizico-chimice și mecanismele de eliminare a gazelor specifice zațului de cafea. De asemenea, sunt evidențiate progresele actuale ale cercetării, potențialul de regenerare și oportunitățile de integrare a zațului de cafea în sisteme sustenabile de tratare a apelor uzate. Deși persistă provocări legate de eficiența adsorbției, standardizarea materialului și implementarea la scară largă, valorificarea zațului de cafea reprezintă o strategie promițătoare în cadrul economiei circulare, care abordează simultan gestionarea deșeurilor și poluarea industrială a aerului.

CUVINTE CHEIE: ape uzate din tăbăcării, zaț de cafea, controlul mirosurilor, adsorbție, economie circulară

DÉSODORISATION DES GAZ TOXIQUES ISSUS DES EAUX USÉES DE TANNERIE À L'AIDE DE MARC DE CAFÉ : UNE SYNTHÈSE APPROFONDIE

RÉSUMÉ. L'industrie du tannage du cuir contribue largement au développement économique mondial ; toutefois, elle est également associée à des défis environnementaux majeurs, notamment l'émission de gaz toxiques et malodorants lors des processus de traitement des eaux usées. Des émissions telles que le sulfure d'hydrogène (H_2S), l'ammoniac (NH_3) et les composés organiques volatils (COV) engendrent non seulement d'importantes nuisances olfactives, mais présentent également des risques considérables pour la santé humaine, la sécurité au travail et la qualité de l'environnement. Les technologies conventionnelles de contrôle des odeurs — telles que le lavage chimique des gaz, l'adsorption sur charbon actif et la filtration biologique — souffrent souvent de coûts d'exploitation élevés, d'une forte consommation énergétique et de la production de déchets secondaires, soulignant ainsi la nécessité d'alternatives durables. Cette synthèse examine de manière critique le potentiel du marc de café, un sous-produit agro-industriel abondant, en tant qu'adsorbant innovant et écologique pour la désodorisation des gaz issus des eaux usées de tannerie. Grâce à son structure poreuse, son forte teneur en carbone et la richesse de son chimie de surface (présence de groupements fonctionnels hydroxyle, carboxyle et phénolique), le marc de café présente des capacités

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remarquables pour capturer et transformer les polluants gazeux dangereux via des mécanismes d'adsorption physique, de chimisorption et de réactions redox. L'article aborde les sources et les voies de formation des gaz toxiques de tannerie, évalue les technologies existantes de contrôle des odeurs ainsi que leurs limites, et explore les caractéristiques physico-chimiques du marc de café ainsi que les mécanismes d'élimination des gaz associés. Il met également en lumière les avancées actuelles de la recherche, le potentiel de régénération du matériau et les opportunités d'intégration du marc de café dans des systèmes durables de traitement des eaux usées. Bien que des défis subsistent concernant l'efficacité d'adsorption, la normalisation du matériau et la mise en œuvre à grande échelle, la valorisation du marc de café constitue une stratégie prometteuse d'économie circulaire, répondant simultanément aux enjeux de gestion des déchets et de pollution atmosphérique industrielle.
MOTS-CLÉS : eaux usées de tannerie, marc de café, contrôle des odeurs, adsorption, économie circulaire

INTRODUCTION

The centuries' old leather tanning industry is essential for producing leather goods used worldwide in fashion, automotive, furniture, and various other sectors [1]. However, leather processing is known to generate significant environmental pollution, particularly through its wastewater discharges and gaseous emissions [1, 2]. Tannery wastewater typically contains a complex mixture of toxic chemicals, including heavy metals like (chromium), organic pollutants, sulfides, and nitrogen compounds. These contaminants not only pollute aquatic ecosystems but also contribute to the release of malodorous and hazardous gases such as hydrogen sulfide (H_2S), ammonia (NH_3), and volatile organic compounds (VOCs) during wastewater treatment and sludge handling. These gases pose serious health risks to tannery workers and neighboring communities, including respiratory issues, eye irritation, and in severe cases, toxicity or suffocation [1, 3].

Current conventional deodorization techniques for controlling these toxic gases largely rely on chemical scrubbers, bio-filtration, or activated carbon adsorption. While these approaches can be effective, they often involve high operating costs, generation of secondary waste, and complex disposal issues. Additionally, chemical scrubbers sometimes introduce harmful by-products, and activated carbon is costly and requires energy intensive regeneration. Therefore, developing cost effective, eco-friendly, and sustainable methods to deodorize tannery wastewater gases remains a serious task for environmental management in the leather tanning industry [3, 4].

In this review, spent coffee grounds (SCG) are being studied as a favorable bio-adsorbent material for environmental cleansing purpose. SCG is the residue left after brewing coffee and is generated in massive quantities worldwide estimated at several million tons annually [3, 5]. Valorization of SCG as a resource aligns with global sustainability and circular economy goals, turning waste into value added products. Chemically, SCG are rich in lignocellulosic materials, phenolic compounds, lipids, proteins, and nitrogen containing groups, which impart a variety of surface functional groups such as hydroxyl (-OH), carboxyl (-COOH), and amine ($-NH_2$) groups. These characteristics make SCG an effective adsorbent for a wide range of pollutants, including heavy metals, dyes, and organic contaminants [6, 7]. More recently, research has extended toward the application of SCG for the adsorption and neutralization of malodorous and toxic gases. Studies have demonstrated that SCG can physically adsorb gases due to their porous structure and chemically interact with gas molecules via surface functional groups. Additionally, the antioxidant properties of phenolic compounds present in SCG may contribute to chemical reduction reactions that degrade toxic gases [7, 8].

Despite these advantageous features, the use of SCG specifically for deodorization of leather tannery wastewater gases remains an evolving and relatively unrevealed study. There is a critical need to comprehensive review and consolidate existing knowledge on the effectiveness, mechanisms, and practical applicability of SCG for this purpose. Understanding the molecular level interactions

between SCG surface groups and tannery gas constituents is essential for optimizing adsorbent performance and designing scalable deodorization systems. The researcher discussed the nature and sources of tannery wastewater gases, the physicochemical properties of SCG relevant to gas adsorption, underlying removal mechanisms, integration strategies into existing wastewater treatment frameworks, and the challenges and future prospects of this SCG deodorization. By valorizing spent coffee grounds for tannery wastewater gas deodorization, the leather industry can move towards more sustainable wastewater management practices, reduce its environmental footprint, and promote circular waste utilization.

COMPOSITIONS OF TANNERY WASTEWATER

Leather tannery wastewater contains a diverse mixture of organic and inorganic pollutants. These pollutants originate from the wide range of chemical and mechanical operations involved in the conversion of raw hides into finished leather [1]. Each stage of the tanning process such as soaking, liming, deliming, pickling, tanning, and finishing contributes specific pollutants to the wastewater stream [9]. On average, tanneries generate approximately 30 to 50 cubic meters of wastewater per ton of raw hides processed, although this number can vary significantly based on the type of tanning process used (chrome tanning or vegetable tanning), the level of process automation, and the degree of water recycling or reuse implemented within the facility [10, 11].

Organic Compounds

These organic substances are introduced during early stages of processing, especially during soaking and liming, where blood, flesh, and decomposed skin tissues are removed [12]. The degradation of these animal derived materials in wastewater not only increases (biological oxygen demand) BOD and (chemical oxygen demand) COD but also contributes to the production of malodorous compounds and potential pathogen production if not properly treated [13]. High BOD values indicate a substantial presence of biodegradable organic matter, which consumes oxygen during microbial decomposition. COD represents the total quantity of oxygen required to chemically oxidize both biodegradable and non-biodegradable organics. The major contributors to this organic load include proteins, fats, carbohydrates, and residual organic tanning agents such as vegetable tannins or synthetic substitutes. Incomplete removal or degradation of these compounds can severely impact downstream biological treatment systems and pose environmental hazards when discharged into natural water bodies [1, 9].

Inorganic Compounds

In addition to the organic load, tannery wastewater contains a wide array of inorganic pollutants derived from the numerous chemicals used in tanning processes. Notable, among these are high concentrations of salts, including sodium chloride (NaCl), which is commonly used in the curing and pickling stages to preserve raw hides and facilitate the penetration of tanning agents [1]. Excessive salt concentrations contribute to raise total dissolved solids (TDS), which can inhibit microbial activity in biological treatment systems and increase the salinity of receiving water bodies, leading to ecological imbalances [14]. Alkalinity is introduced primarily through the use of calcium hydroxide (lime) during the liming stage, where it serves to loosen hair and swell collagen fibers in the hide [15]. Conversely, acidity arises from the use of strong acids such as sulfuric acid (H_2SO_4) or formic acid (HCOOH) during pickling and pH adjustment processes [1]. These opposing chemical conditions high pH from liming and low pH from pickling can result in fluctuations in wastewater pH, complicating treatment and posing challenges to maintaining neutralization and buffer capacity [16]. Other inorganic components include chromium salts, particularly trivalent chromium (Cr^{3+}), used in chrome tanning. Although chromium is less volatile, it poses long-term

environmental and health risks if not properly removed, especially if it oxidizes to hexavalent chromium (Cr^{6+}), a known carcinogen [17].

SOURCES AND FORMATION OF TOXIC GASES IN TANNERY

In leather tannery wastewater, both organic and inorganic pollutants, many of which can undergo biochemical and chemical transformations to produce hazardous gaseous emissions under aerobic and anaerobic conditions [18]. The raw effluent from various stages of the tanning process contains significant concentrations of sulfide compounds, ammonia, volatile fatty acids (VFAs), proteins, lipids, and other biodegradable organics [1]. Under anaerobic conditions, microbial degradation of these organics leads to the production of biogases such as methane (CH_4), hydrogen sulfide (H_2S), and ammonia (NH_3) [19].

Hydrogen Sulfide (H_2S)

Hydrogen sulfide (H_2S) is among the most hazardous and environmentally significant gaseous emissions associated with tannery wastewater treatment. The generation of H_2S in tannery effluents is primarily the result of anaerobic microbial processes, specifically the dissimulator's sulfate reduction by sulfate-reducing bacteria (SRB) [20]. These microorganisms utilize sulfate (SO_4^{2-}) or organic sulfur compounds such as amino acids containing sulfur (cysteine and methionine) as terminal electron acceptors during the degradation of organic matter under anoxic conditions, producing H_2S as a metabolic byproduct [21]. The concentration of H_2S in tannery wastewater environments can vary significantly depending on factors such as the organic load, temperature, pH, redox potential, and the presence of sulfate or sulfide-containing compounds (sodium sulfide, commonly used in the liming process) [1]. Despite this variability, H_2S levels can frequently exceed occupational safety thresholds. The gas is acutely toxic; concentrations as low as 10–20 parts per million (ppm) can cause eye and respiratory tract irritation, while prolonged or repeated exposure may lead to chronic neurological and pulmonary complications [22].

Ammonia (NH_3)

Ammonia (NH_3) is a significant volatile emission associated with tannery wastewater, primarily arising from the degradation of nitrogen containing organic compounds such as proteins, peptides, amino acids, urea, and ammonium salts [23]. These nitrogenous substances originate from animal residues (blood, skin, flesh) and chemical additives used during processes such as deliming and bating. Under aerobic and especially anaerobic conditions, microbial and enzymatic breakdown of these compounds leads to the formation and release of free ammonia into the gaseous phase [24]. In the context of tannery operations, ammonia emissions are especially concerning due to the high nitrogen (N) load in the effluent and the potential for volatilization during wastewater handling, storage, and treatment [25].

Volatile Organic Compounds (VOCs)

Volatile organic compounds in tannery emissions include a variety of hydrocarbons, aldehydes, ketones, and sulfur containing organic compounds. These arise from the decomposition of organic matter and chemicals used in tanning, such as solvents and degreasing agents [26]. Volatile Organic Compounds (VOCs) in tannery emissions comprise a diverse group of hydrocarbons, aldehydes, ketones, and sulfur-containing organic molecules that originate from both the degradation of organic matter and the volatilization of chemicals utilized throughout the leather processing stages [19]. These compounds are generated through multiple pathways. The microbial anaerobic and aerobic decomposition of proteinaceous and lipid-rich residues in wastewater releases various low-molecular-weight VOCs, while chemical solvents, degreasing agents, and tanning additives volatilize during mechanical agitation, heating, and drying processes [27]. Specifically, the breakdown of fats and oils produces ketones and aldehydes, whereas

sulfur-containing tanning agents and organic sulfur compounds can degrade into thiols and other sulfur-based VOCs. The emission of VOCs contributes significantly to the characteristic malodors associated with tanneries and poses potential health risks due to the carcinogenicity and toxicity of several compounds, such as benzene derivatives and formaldehyde [28, 29].

Other Sulfur Compounds

In addition to hydrogen sulfide (H_2S), tannery wastewater and associated processes can emit a range of other sulfur containing volatile compounds, including carbonyl sulfide (COS), methyl mercaptan (CH_3SH), and dimethyl sulfide (DMS). These sulfurous gases arise primarily from the microbial degradation and chemical transformation of sulfur containing organic matter and additives used in leather processing [30]. Carbonyl sulfide is typically formed through the oxidation of carbon disulfide (CS_2), a compound sometimes present in tanning formulations, or through microbial metabolism of sulfur-containing substrates under both aerobic and anaerobic conditions [21]. Methyl mercaptan and dimethyl sulfide are generated via the microbial breakdown of sulfur-containing amino acids such as methionine and cysteine, as well as through methylation reactions mediated by specific bacterial consortia in anaerobic sludge environments [31].

Nitrogen Oxides (NOx) and Carbon Oxides (COx)

Nitrogen oxides (NO_x) and carbon oxides (CO_x), although not typically generated directly from tannery wastewater itself, can be significant byproducts of tannery waste management practices, particularly during thermal treatment processes such as sludge incineration, combustion, or pyrolysis [32]. NO_x species, primarily nitric oxide (NO) and nitrogen dioxide (NO_2), are formed via high-temperature oxidation of nitrogenous compounds present in the sludge or combustion air, through mechanisms including the thermal fixation of atmospheric nitrogen (thermal NO_x) and the oxidation of fuel-bound nitrogen (fuel NO_x) [33]. Similarly, carbon oxides carbon monoxide (CO) and carbon dioxide (CO_2) are produced from the incomplete and complete oxidation of organic carbonaceous matter contained within tannery sludge and other solid wastes [34].

Table 1: Summary of gas Emission Sources within Tannery Processes [1, 35]

Process Steps	Emission Sources	Major toxic Gases
Soaking	Decomposition of residual blood, manure, and skin tissue	VOCs, NH_3
Liming	Hair removal using sodium sulfide and lime	H_2S
Deliming	Neutralization of lime using ammonium salts	NH_3
Pickling	Application of sulfuric acid and salt to prepare for tanning	Acidic fumes, VOCs
Tanning	Use of chromium (III) salts or vegetable tannins	VOCs, NH_3
Post-tanning (Drying, Fatliquoring)	Thermal decomposition and chemical reactions with oils and fats	VOCs
Sludge Treatment	Anaerobic breakdown of organic sludge from wastewater systems	H_2S, NH_3, VOCs

ODOR CONTROL TECHNIQUES

As global attention shifts toward more sustainable and inclusive industrial practices, aligning tannery emission controls with both regulatory standards and practical field realities becomes paramount [36]. So, the control of gaseous emissions, particularly malodorous compounds originating from tannery wastewater, is a complex task that needs a strategic, sustainable and specific approach [1]. Effective odor management must therefore balance technical efficiency, economic feasibility, and environmental sustainability [37]. To this end, a range of control technologies has been developed and applied, including physical methods (ventilation, and gas condensation), chemical treatments (scrubbing, with oxidants or alkaline solutions), biological processes (biofilters and bio-trickling filters), and adsorption-based systems (activated carbon and bio-based adsorbents) [38].

Physical Methods

In this method a range of mechanically driven processes aimed at reducing the concentration or presence of airborne pollutants through dilution, separation, or phase change mechanisms [39]. Unlike chemical or biological methods, physical techniques do not involve chemical reactions or microbial degradation but instead rely on physical principles such as air movement, temperature control, and mass transfer to mitigate odor emissions [40]. Due to their operational simplicity, relatively low cost, and immediate effectiveness, physical methods are commonly used to rapidly reduce odorous gas concentrations or to condition emissions prior to further treatment [41]. However, they are typically limited in their ability to address complex mixtures of gases, high concentration emissions, or substances with low odor thresholds. Their effectiveness is highly dependent on factors such as pollutant solubility, volatility, temperature, humidity, and flow rate, which must be carefully considered during system design and implementation [36].

Ventilation

Ventilation is one of the most basic physical methods employed for odor control. It operates by displacing odorous or contaminated air with ambient or treated fresh air to reduce the concentration of gaseous pollutants to levels below odor detection thresholds [38]. This approach is commonly applied in large, open processing areas, sludge handling zones, or during temporary peak emission events. The method is valued for its low cost, simplicity, and immediate effectiveness, especially in non-enclosed environments. However, ventilation alone does not neutralize or capture odorants it merely disperses them. This can shift rather than solve the pollution problem, potentially impacting nearby communities if not carefully managed [42]. Moreover, its effectiveness decreases significantly with high-load emissions or in enclosed spaces where proper airflow dynamics are difficult to maintain. As a result, ventilation is typically used in combination with other control systems, such as filters or scrubbers, to improve overall efficiency [43].

Condensation

Condensation is another physical method used for odor control, particularly targeting volatile organic compounds (VOCs) [19]. This technique involves cooling the gas stream to a temperature where condensable vapors undergo a phase change from gas to liquid, allowing for their collection and removal [44]. Condensation is especially useful for treating high-boiling-point VOCs and is often employed in pre-treatment or recovery processes, such as solvent reclamation. In odor control systems, condensation is typically used to pre-concentrate VOCs before further treatment [45].

Chemical Methods

Chemical odor control methods are based on the application of reactive agents that chemically neutralize, oxidize, or transform odorous compounds into less harmful or non-odorous substances [19]. These techniques are particularly effective against a wide range of volatile and reactive compounds, including hydrogen sulfide (H_2S), ammonia (NH_3), and various volatile organic compounds (VOCs) [43]. Common chemical treatment approaches include oxidation, acid-base neutralization, and chlorination. For example, oxidizing agents such as sodium hypochlorite, hydrogen peroxide, or potassium permanganate are frequently employed to degrade sulfur containing compounds and nitrogenous odorants [19]. Similarly, acidic or alkaline solutions are used to neutralize basic or acidic gases, respectively such as using sulfuric acid to neutralize ammonia or sodium hydroxide to scrub acidic gases [39].

Scrubbing

Scrubbing, particularly wet scrubbing is a widely adopted physical-chemical method in industrial odor control. This process involves passing odorous gases through a scrubbing

liquid commonly water, acidic, or alkaline solutions that absorbs or reacts with soluble pollutants. Wet scrubbers are particularly effective for treating water-soluble gases such as ammonia (NH_3) and hydrogen sulfide (H_2S), which are prevalent in tannery emissions [46]. In tannery operations, alkaline scrubbers (sodium hydroxide based) are often used to neutralize acidic gases, while oxidative scrubbers may employ agents like hydrogen peroxide or sodium hypochlorite to break down reactive sulfur compounds [1]. Although scrubbing offers high removal efficiency and flexibility, it requires regular monitoring of pH and chemical concentrations, generates secondary liquid waste, and demands additional treatment infrastructure for handling spent scrubbing fluids. The system's design must also consider gas-liquid contact time, temperature, and flow rates to ensure optimal performance [47].

Oxidation

Oxidation processes utilize strong oxidizing agents such as ozone (O_3) and chlorine (Cl_2) to chemically degrade odor causing molecules by breaking down complex sulfur and nitrogen containing compounds into less odorous or non-odorous substances [19]. These oxidants function through electron transfer reactions that alter the molecular structure of malodorous compounds, often converting them into inorganic species such as sulfate or nitrate ions [48]. Oxidation is particularly effective in targeting volatile sulfur compounds (hydrogen sulfide) and nitrogenous gases (ammonia, amines), which are common in tannery emissions. However, the use of chlorine can lead to the formation of chlorinated organic by-products, some of which are toxic or carcinogenic, necessitating stringent effluent monitoring and disposal protocols. Additionally, ozone, while a powerful oxidant, is highly reactive and can pose occupational safety risks if not properly controlled [39].

Neutralization

Neutralization techniques contain the addition of acidic or alkaline reagents to adjust the pH of the gas or liquid phase, facilitating the chemical conversion of odorous gases into less volatile or non-odorous salts [46]. For instance, the introduction of acidic agents can convert gaseous ammonia (NH_3) into ammonium salts (NH_4^+), effectively reducing its volatility and odor potential. Conversely, alkaline reagents are used to neutralize acidic gases such as hydrogen sulfide and sulfur dioxide, converting them into soluble sulfides or sulfates. The productivity of neutralization processes is highly dependent on precise dosage control, adequate mixing, and continuous monitoring of system parameters such as pH and reagent concentration [43]. Inadequate or excessive dosing can lead to incomplete neutralization or the formation of secondary pollutants, which can complicate waste handling and disposal. Moreover, neutralization reactions often generate secondary waste streams that require additional treatment, thus increasing operational complexity [47].

Biological Methods

Biological odor control technologies harness the natural metabolic capabilities of microorganisms to biodegrade, transform, or integrate odorous gaseous pollutants into less harmful substances, often converting them into carbon dioxide, water, and biomass. These methods are widely regarded as environmentally sustainable and cost-effective, especially for treating continuous, low- to moderate-concentration emissions typical of industrial processes such as tannery wastewater treatment and solid waste management [49, 50].

Biofilters

Bio filtration implicates passing contaminated air through a moist, porous medium commonly composed of natural materials such as compost, peat, wood chips, or soil which serves as a habitat for specialized microbial communities capable of degrading odorous compounds [51]. The biological oxidation of pollutants occurs as gases diffuse into the biofilm layer that coats the packing material, where aerobic microorganisms

metabolize target substances such as hydrogen sulfide (H_2S), ammonia (NH_3), and volatile organic compounds (VOCs) [43]. Biofilters are particularly effective under aerobic conditions, leveraging the metabolic pathways of chemoheterotrophic and autotrophic bacteria to convert malodorous gases into non-toxic end products like sulfate, nitrate, carbon dioxide, and biomass. However, biofilters require careful moisture management to prevent drying out or anaerobic zones, and the porous medium may degrade or compact over time, necessitating periodic replacement or transformation [19].

Bio-scrubbers

Bioscrubbers combine the gas absorption efficiency of wet scrubbers with the biological degradation capabilities of bioreactors, offering a two-stage process for odor control. In this system, the contaminated air is first passed through a liquid phase where soluble pollutants are absorbed [52]. The resulting liquid solution, enriched with absorbed contaminants, is then circulated through a bioreactor containing microbial populations that biodegrade the dissolved odorants. This separate design allows for independent control of gas liquid mass transfer and microbial activity, improving treatment efficiency and operational stability compared to conventional biofilters [53]. Bioscrubbers are particularly advantageous for treating gases with low solubility or those requiring controlled pH and nutrient conditions. However, the increased complexity of infrastructure, higher capital costs, and the need for continuous monitoring of microbial health, oxygen supply, and liquid parameters represent operational tasks [54].

Adsorption-Based Methods

Adsorption is a surface phenomenon where gaseous odor molecules are physically or chemically bound onto the surface of solid adsorbents, thereby removing them from the air stream. This process is highly effective for taking a wide variety of odorous compounds, including volatile organic compounds (VOCs), sulfur-containing gases (hydrogen sulfide), and nitrogenous compounds (ammonia) [55]. Adsorption-based methods are among the most widely applied odor control technologies due to their versatility, high removal efficiency, and relatively straightforward operation [56]. The success of adsorption depends primarily on the surface area, pore structure, and chemical properties of the adsorbent material. Common adsorbents include activated carbon, zeolites, silica gel, and bio-based materials [57].

Activated Carbon

Activated carbon which is widely regarded as the standard adsorbent due to its exceptionally high specific surface area (normally 500–1500 m^2/g) and well developed porous structure, which provide numerous active sites for the adsorption of volatile organic compounds (VOCs), hydrogen sulfide (H_2S), ammonia (NH_3), and other odor causing gases [58]. The adsorption mechanism on activated carbon primarily involves physical adsorption via van der Waals forces, accompanied by chemical interactions when soaked with reactive agents such as potassium iodide or metals to target specific pollutants [59].

Zeolites

Zeolites are micro-porous alumino silicate minerals characterized by uniform pore sizes and high ion exchange capacity, which enable selective adsorption of small molecules such as ammonia and certain VOCs [60]. Their crystalline structure imparts hydrophilic or hydrophobic properties, making some zeolites more resistant to moisture interference compared to activated carbon [61]. This moisture tolerance is advantageous in treating humid emissions common in tannery environments. However, zeolites generally exhibit lower adsorption capacities for sulfide gases such as hydrogen sulfide, limiting their standalone use in certain odor control applications [62].

LIMITATIONS OF CONVENTIONAL ODOUR CONTROL METHODS

Table 2: Overall summary of limitations of conventional odour control methods [63-66]

Odor control Technique	Mechanism of odor removal	Advantages	Limitations/gaps
Physical (Ventilation, Condensation)	Dilutes or condenses gases to lower odor concentrations	Simple, low cost, fast implementation	Not effective for high concentration or reactive gases
Chemical Scrubbing	Absorption of gases using liquid chemicals (NaOH, H_2O_2)	High removal efficiency for specific gases (H_2S, NH_3)	Chemical consumption, sludge generation, operational costs
Biological Filtration (Biofilters, Bio trickling filters)	Microbial degradation of pollutants in a packed bed or biofilm	Eco-friendly, low operational cost, suitable for continuous flow	Sensitive to environmental conditions (pH, moisture, temperature)
Activated Carbon Adsorption	Adsorbs VOCs and sulfur compounds onto porous carbon surface	High efficiency, compact system	Carbon replacement/regeneration needed, costly for large volumes

Strategies to Overcome Limitations

In recent years, the pursuit of sustainability in industrial pollution control is increasingly driven by both environmental imperatives and economic feasibility. In the context of the leather tanning industry a sector known for its intensive use of chemicals and high emission potential there is an urgent demand for eco-friendly and cost-effective deodorization technologies that do not transfer pollution from one medium to another (from air to water or solid waste), a challenge often observed in conventional treatment systems [67].

Spent Coffee Grounds (SCG)

Spent coffee grounds (SCG), a major byproduct of the coffee brewing industry, have recently gained attention as a sustainable, low cost adsorbent material for environmental applications, including the deodorization of toxic gases from industrial wastewater effluents [6]. The unique physicochemical properties of SCG make them particularly suitable for capturing and neutralizing harmful gases [68, 69].

Chemical Composition of (SCG)

Spent coffee grounds (SCG) primarily consist of lingo cellulosic biomass, forming a complex matrix of organic compounds that contribute to their adsorption capabilities. The main constituents include cellulose, hemicellulose, lignin, proteins, lipids, residual caffeine, and phenolic compounds. This diverse chemical composition provides a variety of functional groups on the SCG surface that serve as active sites for gas adsorption [70]. Among these, hydroxyl groups (-OH), mostly found in cellulose and hemicellulose, play a crucial role by facilitating hydrogen bonding and polar interactions with polar gases such as ammonia (NH_3) and hydrogen sulfide (H_2S). These polar interactions enhance the affinity of SCG for such gases, making them effective adsorbents in capturing malodorous and toxic compounds [71].

Additionally, carboxyl groups (-COOH), largely contributed by lignin and oxidized cellulose, enable acid-base interactions and can form ionic bonds with basic gases like ammonia, thereby improving adsorption capacity through electrostatic attraction. Phenolic groups, derived from lignin and residual antioxidant compounds in SCG, act as electron donors or acceptors, which allows them to participate in redox reactions that may aid in the transformation or neutralization of toxic gases [70]. Furthermore, nitrogen-containing groups from residual proteins and caffeine provide amine or amide functionalities capable of hydrogen bonding with acidic gases, further broadening the spectrum of interactions SCG can engage in. Together,

these chemical features support the potential of SCG as a versatile and effective adsorbent for industrial gas treatment applications [71].

Porous Structure and Surface Area of SCG

The adsorption efficiency of spent coffee grounds (SCG) is significantly influenced by their unique physical structure, which is characterized by a naturally porous and fibrous texture. This structure is a result of cellular wall degradation and water-soluble component removal during the brewing process, leading to increased surface exposure and internal void formation [70]. The porous nature of SCG serves as a critical feature in their function as an adsorbent. Firstly, the high specific surface area of SCG, often reported in the range of 1.2 to 5.4 m^2/g for raw grounds and exceeding 300 m^2/g after activation, provides a large number of adsorption sites, enhancing the material's capacity to capture gas molecules. Secondly, the presence of both micro-pores (<2 nm) and meso-pores (2–50 nm) enables the adsorption of a wide variety of gaseous pollutants, including hydrogen sulfide (H_2S), ammonia (NH_3), and volatile organic compounds (VOCs) [72]. These multiscale pore distributions improve adsorption kinetics by facilitating gas transport and diffusion throughout the matrix. Finally, the highly accessible surface of SCG ensures rapid contact between pollutant molecules and the material's functional groups (hydroxyl, carboxyl), allowing for efficient physisorption and chemisorption processes [72]. This combination of pore structure and accessible surface area makes SCG a compelling and sustainable alternative to conventional adsorbents, particularly for the treatment of odorous gases in industrial applications such as tannery emissions [73].

Surface Chemistry and Charge of SCG

The surface chemistry and electrostatic properties of spent coffee grounds (SCG) play a pivotal role in determining their gas adsorption behavior, particularly in environments such as tannery wastewater treatment, where acidic or basic gases are prevalent. SCG are composed of a complex matrix of lingo-cellulosic components primarily cellulose, hemicellulose, and lignin which contain a variety of oxygen- and nitrogen-containing functional groups [70]. These include hydroxyl (-OH), carboxyl (-COOH), amine ($-NH_2$), and phenolic (-PhOH) moieties that contribute to surface reactivity and charge distribution. At the slightly acidic to neutral pH values typical of tannery effluents (pH 5.5–7.5), carboxylic acid groups on the SCG surface can dissociate, imparting a negative surface charge [71]. This facilitates electrostatic interactions with positively charged species, such as ammonium ions (NH_4^+), or polar basic gases like ammonia (NH_3), via ion exchange or hydrogen bonding mechanisms. Moreover, the presence of redox-active phenolic groups inherited from the lignin and residual antioxidants in coffee grounds provides additional functionality [74]. These phenolic moieties can act as electron donors or acceptors, enabling redox reactions that may contribute to the oxidative degradation or transformation of sulfur-containing gases such as hydrogen sulfide (H_2S) into less volatile or less toxic forms (elemental sulfur or sulfate) [73]. Overall, the interplay between surface charge and functional group chemistry endows SCG with a dual adsorption mechanism: physisorption through surface area and porosity, and chemisorption through electrostatic and redox interactions, making them highly effective for capturing and neutralizing a range of odorous and hazardous gases from industrial sources [72, 73].

Mechanisms of Gas Removal Using Spent Coffee Grounds (SCG)

Spent coffee grounds (SCG) have emerged as promising bio-based adsorbents for the removal of odorous and toxic gases, particularly those associated with leather tanning wastewater such as ammonia (NH_3), hydrogen sulfide (H_2S), and volatile organic compounds (VOCs) [70]. The effectiveness of SCG in gas removal stems from a synergistic combination of physical adsorption, chemical interactions, and redox activity, all of which are mediated by the material's rich surface chemistry, porosity, and functional group diversity [72]. A mechanistic understanding of these processes is essential to optimize SCG

preparation, activation, and deployment strategies in sustainable odor control technologies [73].

Physical Adsorption

Physical adsorption refers to the non-covalent, reversible adherence of gas molecules onto the surface of SCG through weak intermolecular forces such as van der Waals attractions. SCG's high specific surface area and porous morphology comprising micro- and mesoporous enable the trapping of gas molecules by pore-filling mechanisms [75]. These pores provide abundant active sites and facilitate gas diffusion into the adsorbent matrix. The adsorption efficiency increases with the availability of fine pores that closely match the kinetic diameters of gas molecules like NH_3 (~2.6 Å) and H_2S (~3.6 Å) [68, 76].

Moreover, surface adherence plays a crucial role in the initial capture of VOCs and other weakly polar compounds. The interaction is primarily governed by dispersion forces, making the process rapid and non-selective. Environmental parameters such as temperature, pressure, and humidity significantly influence the adsorption dynamics. Moderate moisture levels may aid gas capture by forming a hydrated layer on SCG surfaces, which can increase the solubility of hydrophilic gases (e.g., NH_3), thereby enhancing their uptake. However, excessive water content can obstruct pore accessibility, reducing overall adsorption efficiency [75, 77].

Chemical Adsorption (Chemisorption)

In addition to physical adsorption, spent coffee grounds (SCG) facilitate chemical adsorption (chemisorption) through their diverse surface functional groups. Chemisorption involves stronger, often irreversible chemical bonds between gas molecules and the reactive sites on SCG, leading to more selective and effective removal of odorous gases [78]. One key mechanism is acid-base interaction, where basic gases like ammonia (NH_3) react with acidic groups such as carboxyl (-COOH) present in lignin and oxidized cellulose fractions of SCG. This interaction typically involves proton transfer or ionic bond formation, resulting in the generation of ammonium salts (NH_4^+) that become immobilized on the adsorbent surface. Additionally, hydrogen bonding plays a significant role: gases like NH_3 and hydrogen sulfide (H_2S) can form hydrogen bonds with hydroxyl (-OH) and amine (-NH) groups in SCG, which increases their adsorption affinity and retention time. Under alkaline or neutral pH conditions, electrostatic attractions occur as negatively charged carboxylate groups ($-COO^-$) on SCG surfaces attract positively charged gas species or ions, further enhancing selective adsorption capacity [79].

Redox Reactions and Gas Transformation

A distinctive advantage of SCG lies in their content of phenolic and other antioxidant compounds, which confer redox activity capable of chemically transforming toxic gases into less harmful species. For example, the reduction of hydrogen sulfide (H_2S) is facilitated by phenolic groups donating electrons, thereby converting H_2S into elemental sulfur (S^o) or other less volatile sulfur compounds. This redox transformation not only immobilizes sulfur gases but also reduces their toxicity and odor impact [80]. Similarly, although less extensively studied, SCG's redox-active functional groups may participate in the oxidation or breakdown of ammonia and volatile organic compounds (VOCs), potentially leading to mineralization or conversion into less harmful forms. These redox-mediated pathways add a layer of detoxification beyond simple adsorption, improving the overall sustainability and regeneration potential of SCG as bio-based deodorization agents [81].

Multimodal Adsorption and Synergistic Effects

The effectiveness of spent coffee grounds (SCG) in treating complex gaseous emissions from tannery wastewater systems is largely attributed to their capacity to engage in multimodal adsorption mechanisms, where physical, chemical, and redox interactions occur simultaneously or sequentially [82]. This synergistic behavior enhances the overall

adsorption efficiency, particularly in mixed-gas environments. For instance, sequential adsorption and transformation may occur when a gas such as ammonia (NH_3) is first captured through acid-base interactions with carboxylic groups, followed by chemical alteration via redox-active phenolics [83]. Additionally, competitive adsorption is an important factor; various gas species may vie for overlapping active sites on the SCG surface, which can influence the adsorption selectivity and kinetics. The presence of moisture also plays a crucial role by enhancing gas solubility, enabling hydrolysis reactions, and supporting protonation processes that aid in gas immobilization or conversion. These interdependent effects contribute to the robustness of SCG as a versatile adsorbent in dynamic industrial emission settings [84].

Regeneration and Reusability

The regeneration and reusability of SCG are critical parameters in assessing their feasibility as sustainable gas adsorbents. After saturation with odorous gases, regeneration can typically be achieved through mild thermal desorption (heating at 100–150°C) or solvent washing, especially for physically adsorbed species. This restores the porous structure and surface activity of SCG without significant degradation of the material [85]. However, the chemical stability of adsorbed compounds particularly those bound via chemisorption or transformed through redox reactions may limit complete regeneration. In such cases, stronger desorption methods or partial loss in adsorption capacity over cycles may be observed. Despite these limitations, SCG demonstrate promising recyclability, especially when used in systems where physical adsorption predominates. Optimizing regeneration protocols balancing temperature, treatment duration, and chemical additives can enhance both the economic viability and environmental performance of SCG-based odor control technologies [76].

Application Studies of Spent Coffee Grounds (SCG) for Deodorization

Studies involving SCG and SCG-derived materials have demonstrated the potential of these materials to interact with gaseous pollutants through physical adsorption, chemisorption, and related surface interactions. Reported performance depends strongly on the characteristics of the adsorbent and operating conditions, including particle size, surface modification, moisture content, gas concentration, flow rate, temperature, and contact time. Consequently, removal efficiencies reported under controlled laboratory conditions cannot be directly extrapolated to complex tannery wastewater gas streams [86].

For example, studies on modified coffee-ground materials and related bio-based systems have reported measurable removal of sulfur- and nitrogen-containing odorants under controlled experimental conditions. Such findings provide useful evidence for the adsorption potential of coffee-derived materials but do not, by themselves, demonstrate equivalent performance for real tannery wastewater emissions [87]. Surface modification methods, including thermal activation, chemical activation, and incorporation of additional functional materials, may improve surface area, porosity, and the availability of active functional groups. Nevertheless, the effectiveness of these modifications must be evaluated using standardized experimental conditions and, ultimately, under realistic tannery emission conditions [88].

Overall, existing studies support the potential of SCG as a sustainable adsorbent for odor-control applications, but direct evidence for the removal of H_2S, NH_3, and VOCs specifically from tannery wastewater gas remains limited. Further research using real tannery gas streams, representative gas mixtures, continuous-flow systems, and pilot-scale experiments is therefore required before quantitative removal efficiencies can be reliably assigned to tannery-specific applications [89]. Additionally, regeneration studies suggest that SCG can retain a significant

proportion of their adsorption capacity after multiple thermal desorption cycles at 100–150°C, thereby improving their lifecycle performance and economic feasibility [85].

CHALLENGES AND FUTURE DIRECTIONS

Despite the promising adsorption capacity of spent coffee grounds (SCG) for removing toxic gases from leather tannery wastewater, several challenges hinder their large-scale application. Raw SCG has relatively low surface area and porosity compared to commercial adsorbents like activated carbon, limiting its efficiency. Moreover, the variability in SCG composition due to differences in coffee types, roasting levels, and brewing methods can affect adsorption consistency and reproducibility. Additionally, the high moisture and oil content of SCG may require pre-treatment steps such as drying, carbonization, or chemical activation, which increase operational complexity and cost. There are also concerns regarding the regeneration and safe disposal of spent SCG adsorbents after use, particularly when saturated with hazardous substances. Future studies should focus on optimizing SCG modification techniques, such as pyrolysis, acid/base activation, or incorporation with other biomaterials, to enhance surface area, functional groups, and gas adsorption efficiency. Research is also needed to standardize SCG collection and treatment protocols to ensure consistent quality and performance. Moreover, integrating SCG-based adsorbents into hybrid systems with membranes or biofilters could improve removal efficiency and operational flexibility. Life cycle assessments and techno-economic analyses are essential to evaluate the sustainability and feasibility of SCG use at industrial scale. Lastly, in-depth studies on adsorption mechanisms, regeneration cycles, and long-term stability will be critical to establish SCG as a reliable, low-cost, and eco-friendly solution for treating tannery gas emissions.

CONCLUSIONS

The control of toxic and malodorous gases associated with leather tannery wastewater remains an important environmental challenge, particularly because emissions may contain hydrogen sulfide (H_2S), ammonia (NH_3), and volatile organic compounds (VOCs). Spent coffee grounds (SCG) represent a potentially sustainable bio-based adsorbent because of their lignocellulosic structure, surface functional groups, and availability as an agro-industrial residue.

Available studies indicate that SCG and SCG-derived materials can interact with gaseous pollutants through physical adsorption and chemical surface interactions. However, the reported removal efficiencies are highly dependent on experimental conditions, including adsorbent preparation, gas composition, pollutant concentration, humidity, temperature, flow rate, and contact time. Importantly, much of the available evidence has been obtained under controlled laboratory conditions or from applications involving gas streams and odor sources other than tannery wastewater. Therefore, these results should not be interpreted as direct evidence of equivalent removal performance for real tannery wastewater gases.

The specific application of SCG for tannery wastewater gas deodorization remains insufficiently validated. In particular, direct experimental data obtained using real tannery gas, streams are limited. Accordingly, SCG should currently be regarded as a promising research candidate rather than a fully demonstrated tannery-specific gas treatment technology.

Future research should prioritize systematic experiments using representative and real tannery waste water gas streams containing H_2S, NH_3, VOCs, and relevant gas mixtures. Studies should evaluate adsorption capacity, removal efficiency, selectivity, regeneration, long-term stability, and performance under realistic humidity, temperature, flow, and concentration conditions. Pilot-scale and field-based investigations, together with life cycle and

techno-economic assessments, will be necessary to determine the practical feasibility of SCG-based deodorization systems.

Within these limitations, the valorization of SCG remains consistent with circular-economy principles and provides a promising research direction for developing potentially low-cost and sustainable approaches to odor and gaseous-pollutant management in the leather industry.

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