ISSN 2956-1051 (ONLINE) • VOLUME 3 • NO. 1 (2025)

# GLOBAL SUSTAINABILITY CHALLENGES

***Publisher***
Faculty of Ecology and Environmental Protection, University "Union-Nikola Tesla", Belgrade, Serbia

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ГЛОБАЛНИ ИЗАЗОВИ ОДРЖИВОСТИ

Издавач: Универзитет „Унион-Никола Тесла“

Ко-издавач: Универзитет Exeter, Stocker Rd, Exeter EX4 4PY, UK
https://www.exeter.ac.uk/

Адреса: Цара Душана 62-64, 11158 Београд

Телефон: 011 2180-271

E-mail: vladanka.gsc@unionnikolatesla.edu.rs

info@unionnikolatesla.edu.rs

Веб-сајт: https://www.unionnikolatesla.edu.rs/sr

ISSN: 2956-1051 (Online), Број 1/2025, vol. 3, година III

Часопис излази једном годишње електронски и радови се објављују на енглеском језику

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CONTENTS

– – – – – – – – – – – – – – – – – – – –

САДРЖАЈ

**Global sustainability challenges**
2025; 3(1): 1-7
https://gsc.unionnikolatesla.edu.rs/index.php/gsc
UDC: 628.477.033
ISSN: 2956-1051 (Online)

# Possibilities of using waste originating from cigarette butts

**Bojana Božilović[1], Hadi Waisi[1,2,*], Bojan Janković[3], Vladimir Dodevski[3], Stevan Blagojević[2], Marko Jovanović[2], Goran Plazonić[4]**

[1]Faculty of Ecology and Environmental Protection, University Union-Nikola Tesla, Cara Dušana 62-64, Belgrade, Serbia
[2]Institute of General and Physical Chemistry, Studentski trg 12-16, Belgrade, Serbia
[3]Vinča Institute of Nuclear Sciences, National institute of the Republic of Serbia, University of Belgrade, Mike Petrovića Alasa 12-14, Belgrade, Serbia
[4]Henkel D.O.O., Bulevar Oslobođenja 383, Belgrade, Serbia

[*]**Corresponding author:** hadiwaisi@yahoo.com

**To cite this article:**
Božilović, B. (2024). Possibilities of using waste originating from cigarette butts. *Global sustainability challenges, 3*(1), pp. 1-7

**Received**: Jun 20, 2023; **Accepted**: Jun 30, 2023; **Published**: Dec 22, 2025

**Abstract:** The present review paper systematically explores the innovative and sustainable applications of waste derived from discarded cigarette butts (CBs). As one of the most widespread forms of litter worldwide, cigarette butts pose a significant ecological challenge due to their slow decomposition process and the presence of toxic components. This paper aims to illuminate the potential of repurposing CB waste into valuable resources for various applications, thereby mitigating its environmental impact. Through a meticulous analysis of existing literature, we identify and discuss promising avenues for CB waste utilization, highlighting the versatility and potential of this underexplored waste material. The review underscores the necessity for further research and development to optimize the identified applications, address associated challenges, and unlock new possibilities for CB waste utilization. Ultimately, this paper seeks to contribute to the growing body of knowledge on sustainable waste management practices, promoting innovative solutions for one of the most pervasive environmental issues of our time.

**Keywords:** cigarette butt waste, sustainable practices, waste utilization, innovative applications, environmental impact

## 1. Introduction

Cigarette butts (CB) are one of the most important wastes in the world (Murugan et al., 2018; Murugan et al., 2018) and it is considered as a serious environmental concern due to toxic effects on living organisms (Kadir et al., 2014). It is claimed that 4,5 trillion CBs are being produced annually across the globe, weighing 0.8 to 1.2 million tons, and it is expected to increase by 50% in 2025 (Kadir & Mohajerani, 2011a).

CB is made up of a cigarette filter and the remaining tobacco containing chemicals and environmental contaminants (Dieng et al., 2013; Chevalier et al., 2018). The main problem associated with CBs is their slow degradation rate and the high concentration of toxic content (Marinello et al., 2020). The main toxic agents include polycyclic aromatic hydrocarbons, formaldehyde, argon, carbon monoxide, nitrogen oxides, benzene, hydrogen cyanide, ammonia, phenol, acetaldehyde, argon, acetone, and pyridines (Kurmus & Mohajerani, 2020).

The major compound used in cigarette filters is cellulose acetate which is a biodegradable resistant material and will remain in the environment under normal conditions for 18 months (Dieng et al., 2013).

Collecting CBs is challenging and expensive, costing millions of dollars in some cities. It is estimated that approximately 5.5 trillion cigarettes are being produced annually in the world and the CB wastes would reach 1.2 million tons and increase by 50% until 2025. (Torkashvand et al., 2020).

Cigarette butt waste can be utilized to synthesize novel bioinsecticides that are effective against mosquitoes and other insect pests. The toxic chemicals present in cigarette butts can act as larvicides and disrupt insect life cycles. Further research is needed to develop safe insecticide products from cigarette butts without harming beneficial insects or causing environmental toxicity. Dieng et al., 2013 proposed CB waste as a material for a new insecticide product.

Cellulose and nanocelluloses (Fig 1) extracted from cigarette butts can be used to fabricate fibrous mats, nanofibers, and other materials. The cellulose from cigarette filters provides a raw material source for generating sustainable celluloses rather than utilizing wood pulp.

Nanocelluloses from cigarette butts have potential uses in composites, bioplastics, packaging, and pharmaceuticals. The work of Benavente et al., 2019 talks about source for cellulose acetate recovery, and Hemamalini et al., 2019 as a source for cellulose acetate nanofibrous mat. The study of Ogundare et al. (2017) talks about the fishing of nanocrystalline cellulose.

**Figure 1.** Fibers obtained from used cigarette filters

This type of waste can be incorporated into construction materials like fired clay bricks (Mohajerani et al., 2016), concrete blocks (Wadalkar, 2018), asphalt and gypsum composites (Mohajerani et al., 2017a). Adding small percentages of cigarette butts reduces production energy and provides a means of waste disposal. However, cigarette butts can negatively impact the mechanical properties and strength of construction materials if added at high levels.

Another application is converting waste into activated carbons (Koochaki et al., 2020), hydrochars (Lima et al., 2018), and catalyst supports for use in water treatment and pollution remediation (Chen et al., 2015; Dorosti et al., 2020). The materials can adsorb heavy metals, dyes, pharmaceuticals, and other water pollutants. Cigarette butts can also be used to synthesize nanocomposites (Gupta & Pandey, 2018) and catalysts for degrading contaminants and enabling green chemistry (Wang et al., 2016)

Carbon and nanomaterials derived from cigarette butts can be used to produce electrodes and electrolytes for supercapacitors and energy storage devices. The high surface area and conductivity of cigarette butt carbons are advantageous for supercapacitor performance. Doping cigarette butt carbons with elements like nitrogen and sulfur further enhances their electrochemical properties for energy applications (Meng et al., 2019).

Cigarette butt waste provides a source of sustainable carbon that can be used in anodes, cathodes, and separators for lithium-ion batteries (Yu et al., 2018a). The carbon can be tailored with dopants and engineered into high-performance nanostructured morphologies. Cellulose from cigarette filters also has utility as a separator component improving lithium-ion battery function.

Additional examples of potential applications include oil spill absorption (Xiong et al., 2018), soundproofing (Gómez Escobar & Maderuelo-Sanz, 2017), bioimaging (Bandi et al., 2018), and waste-to-fuel conversion. Nanomaterials like carbon quantum dots and nanocellulose isolated from cigarette butts enable novel uses in sensing and imaging. The versatility of cigarette butt waste provides many possibilities for sustainability that need further research and development.

This paper aims to provide an exhaustive review of the current state of CB waste research, examining the potential applications, challenges, and future directions in this emerging field. Through an in-depth analysis of existing literature and critical assessment of the methodologies and findings reported in previous studies, this paper seeks to contribute significantly to the body of knowledge on CB waste utilization, promoting sustainable practices and innovative solutions for addressing one of the most pervasive environmental issues of our time.

# 2. Materials and Methods

### *2.1. Literature search and data collection*

In this research, a systematic methodology was employed to investigate articles published up to January 1, 2023, focusing on the potential applications of waste derived from discarded cigarette butts. This search encompassed global academic journals, utilizing Web of Science, Science Direct and Scopus online platforms, with specific search phrases "cigarette butts," "cigarette butt waste," and "utilizing cigarette butts," primarily within article titles.

To maintain objectivity and minimize personal biases, predetermined inclusion criteria were established. These criteria ensured the selection of articles that significantly contributed to our understanding of cigarette butt waste utilization while rigorously excluding irrelevant results. This comprehensive and structured approach aimed to provide a reliable and unbiased review of the current knowledge on the subject.

To narrow the search, we used item type filters. We processed only the review articles and research articles. The following steps were taken to ensure the robustness and reliability of the review process:

#### *2.1.1. Title and abstract evaluation*

Firstly, an initial screening of all retrieved articles was performed based on the title and abstract. This preliminary assessment aimed to gauge the relevance of each article in relation to cigarette butt waste and the potential applications of this waste. Articles that did not align with the central focus of this review were excluded.

#### *2.1.2. Full Abstract Examination*

Subsequently, articles that passed the title and abstract evaluation underwent a more in-depth examination of their abstracts. This step was conducted to further assess the relevance and significance of each article to our review objectives. Articles deemed non-applicable or lacking relevance were eliminated from consideration.

#### *2.1.3. Full Content Review*

Finally, the selected articles from the previous step were subjected to a comprehensive review of their full content. This stage involved a thorough examination of the entire research articles, including methods, results, discussions, and conclusions. The purpose was to ensure that only studies providing valuable insights into the possibilities of utilizing cigarette butt waste were included in this review.

# 3. Results and discussion

After a careful screening process, our focus was narrowed to approximately 100 references. In this section, through eleven studies, we list the most common potential applications for the use of this waste.

### *1.1. Recovering cellulose acetate*

Hemamalini et al., 2019 explores the possibility of recovering cellulose acetate from discarded cigarette butts and regenerating it into nanofibrous mats through electrospinning. Nicotine was first extracted from the cigarette butts using methanol. Solutions of cellulose acetate from 8-12% were electrospun into nanofibers, with 12% concentration producing uniform, bead-free fibers. Silver nitrate was incorporated to impart antimicrobial properties. Characterization with SEM, TEM, FTIR, XRD, and TGA confirmed successful electrospinning of cellulose acetate nanofibers with silver nanoparticles distributed throughout. The mats showed antimicrobial activity against both Gram positive and Gram negative bacteria. The research demonstrates that cellulose acetate waste from cigarette butts can be recycled into functional nanofiber mats, representing a way to recover value from this prevalent form of litter while also reducing its environmental impact.

A similar study was conducted by Benavente et al., 2019. They investigate the potential to recover and repurpose cellulose acetate from used cigarette butts through extraction and purification methods.

Cellulose acetate is a valuable polymer with many industrial uses including textiles, plastic products, films, membranes, and controlled drug release. The research demonstrates that the cellulose acetate polymer can be isolated from cigarette butt waste using aqueous solutions, solvents like ethanol and acetone, and precipitation techniques.

The recovered cellulose acetate could then potentially be utilized to manufacture new consumer products or materials, representing a sustainable application for this common form of plastic waste. Repurposing the cellulose acetate in cigarette butts, rather than allowing the butts to persist as environmental litter, provides opportunities for creating value from the waste. The research highlights the possibility of developing recycling processes to reclaim the cellulose acetate for manufacturing into textiles, bags, packaging materials, biomedical devices, and other beneficial applications.

### *1.2. Bioinsecticide production*

Cigarette butts have the potential to serve as a source material for insecticide production. Nicotine, a primary component of tobacco products such as cigarettes, is an alkaloid and can be used as an insecticide. Several studies have explored the extraction of nicotine from discarded cigarette butts and its utilization as a natural pesticide. Balie Achmad Hambali Nasution, 2016 explores the potential for reusing cigarette butts (CB) as a pesticide in agriculture. CB contain chemicals like nicotine that are toxic to insects. The authors previously conducted field research showing CB extracts can kill caterpillars faster than other natural pesticides. This paper proposes soaking CB in water for 10-15 days to create an insecticide solution. This would provide farmers, many of whom are smokers, with a free alternative to costly chemical pesticides. It would also reduce environmental pollution from improper CB disposal. The concept of adaptation is referenced for getting farmers to change habits and use CB pesticides. Overall the results present a feasible method for reusing CB waste to benefit farmers and the environment. More field testing is needed on efficacy and potential risks before broad implementation.

Study conducted in Ethiopia aimed to extract nicotine from discarded cigarette butts and utilize it as an insecticide. Gudeta et al., 2021 found that nicotine, the primary component of tobacco products such as cigarettes, is an alkaloid and can be used as an insecticide. The researchers used a solvent combination of ethanol and methanol in various ratios, with a 3:1 ratio yielding the best results. Temperature, extraction length, and sodium hydroxide concentration were the independent variables studied for extraction parameters, and the optimal conditions were determined using Design-Expert, response surface approach central composite design (RSM-CCD). The extracted product was evaluated using a gas chromatography–mass spectrometry (GC-MS) and a UV/visible spectrophotometer. The ideal crude extract yield and nicotine content were 17.75 and 3.26%, respectively, at the optimal conditions of temperature 60°C, time 4 hrs, and NaOH concentration 2.83 M with desirability of 0.832. The nicotine extracted was emulsified by combining the crude extract with a combination of palm oil and surfactants. The emulsified concentrated extract performed best at a ratio of 1:100 (emulsified concentrated to solvent) on cabbage aphids. This study provides evidence that waste originating from cigarette butts can be used to produce bioinsecticides.

### *1.3. Chemisorption*

Lima et al., 2018 reports on converting cigarette butt waste into activated hydrochar adsorbents for removing organic pollutants from water. Hydrochars were synthesized via hydrothermal carbonization of cigarette butts at 463K without inert gas. The materials were activated with NaOH which enhanced their negative surface charge. Adsorption capacity was increased at higher pH due to greater electrostatic attraction between the negatively charged hydrochar and the cationic pollutant methylene blue. Despite low surface areas, adsorption capacities were high (303-635 mg/g) due to the surface functional groups. The research demonstrates hydrochars from cigarette butt waste can effectively remove organic pollutants from water through chemisorption, highlighting possibilities for converting this problematic waste into sustainable adsorbents. Significantly, the activated hydrochar adsorbents utilize waste materials, require only low temperature processing, and do not need inert gases, providing a sustainable option for water treatment. The adsorbents can be applied for removing various organic water pollutants through tuning of the surface charge. Overall, the methodology provides a green synthesis route for transforming abundant cigarette butt waste into functional adsorbent materials for water purification.

Hamzah & Umar, 2017 reports on the preparation of activated carbon from cigarette filter waste using microwave-induced KOH activation. The filters were treated thermally, crushed into powder, and activated with KOH at different ratios using microwave irradiation. Characterization with XRD showed a semi-crystalline structure, and SEM revealed a porous microstructure. Optimal conditions (KOH ratio of 3,630W microwave power for 20 min) yielded a BET surface area of 328 m2/g and high methylene blue adsorption capacity of 88 mg/g, indicating potential use of this waste material to produce activated carbon adsorbent. The results demonstrate microwave irradiation enables rapid and effective production of activated carbon from cigarette filter waste.

### *1.4. Construction Materials*

In a study conducted by Mohajerani et al., 2017b, the potential incorporation of cigarette butts (CBs) into asphalt concrete for road construction was investigated. This was achieved by encapsulating CBs using various classes of bitumen and paraffin wax. This encapsulation method effectively mitigates the risk of chemical translocation from CBs into the surrounding environment. To assess the efficacy of this novel approach, the researchers conducted a comparative analysis between the performance of asphalt concrete incorporating CBs and a control sample devoid of CBs. A comprehensive evaluation of various mechanical and volumetric properties, including stability, flow, resilient modulus, bulk density, maximum density, air voids, and voids in mineral aggregates, was carried out. The results indicated that the proposed solutions met the specifications for road construction, accommodating light, medium, and heavy traffic conditions when bitumen was utilized, while paraffin wax demonstrated suitability for light traffic scenarios. The authors hailed this innovative solution as a valuable contribution to combat the urban heat island effect in urban settings, primarily attributable to the reduction in bulk density, the augmentation of porosity, and the decreased thermal conductivity.

Kadir & Mohajerani, 2011b investigates the incorporation of cigarette butt waste into fired clay bricks as a means of recycling this hazardous waste material. Cigarette butts were incorporated into a clay soil mixture at 2.5-10% by weight (10-30% by volume) and fired into bricks. Increasing cigarette butt content linearly decreased brick density up to 30% and compressive strength significantly from 25.65 MPa to 3 MPa, but produced lightweight bricks with adequate strength for non-loadbearing masonry. Water absorption increased from 5% to 18% with cigarette butt content, remaining within acceptable limits per standards.

Thermal conductivity decreased 21-58% with 2.5-10% cigarette butts, providing energy savings benefits. Leaching tests using TCLP and SLT methods showed only trace amounts of heavy metals well below regulatory limits, indicating immobilization. Scanning electron microscopy revealed increased porosity with cigarette butt content. Overall, the study provides strong evidence that incorporating cigarette butt waste into fired clay bricks is a practical and promising approach to produce lightweight masonry bricks while addressing this major environmental waste problem.

Morales-Segura et al., 2020 explored the feasibility of incorporating different percentages of crushed cigarette butt waste into gypsum composite building materials. The cigarette butts were dried, cleaned, and crushed before being mixed with gypsum and water. Composites with up to 2.5% cigarette butts by weight were tested for properties including density, hardness, flexural and compressive strength, bonding strength, and sound absorption. The results showed that low percentages of cigarette butts increased the density, hardness, flexural and compressive strength compared to regular gypsum, with 1.5% addition providing the best improvement in mechanical performance. However, bonding strength decreased slightly with cigarette butt additions. The sound absorption did not change significantly compared to plain gypsum. The cigarette butts reduced the amount of raw gypsum needed by up to 7%. This research indicates that cigarette butt waste can be viably incorporated into gypsum at low percentages to create precast panels and other construction products, providing a use for this problematic waste while improving the sustainability and properties of the resulting gypsum composite. Further work is needed to optimize the gypsum/cigarette butt ratios for performance.

### *1.5. Electric Materials*

Ghosh et al., 2017 reports a simple one-step pyrolysis method to convert the cellulose acetate from used cigarette filters into a carbonaceous electrically conducting material. The pyrolyzed cigarette butt product was characterized using FTIR, Raman, XRD, FESEM, UV-vis absorption, and zeta potential measurements. The analyses confirmed the presence of sp2 carbon, oxygen functional groups, and metal oxide phases with an expanded porous morphology in the product. Aqueous dispersions of the pyrolyzed product exhibited significantly enhanced electrical conductivity compared to pure water, with nonlinear current-voltage characteristics, lower impedance, and higher capacitance and conductance. These promising electrical
properties indicate potential applications of the recycled cigarette butt product in electronics, sensors, energy storage devices, etc. Specifically, the high conductivity could make the pyrolyzed product suitable for uses such as conductive coatings, wiring, electromagnetic shielding, and electrodes. The capacitive properties suggest applications in supercapacitors and batteries. And the porous carbon structure could be beneficial for catalytic supports, absorbents, or filters.

Yu et al., 2018b used a simple one-step carbonization method to convert the cellulose acetate from waste cigarette filters into an N-doped carbon material for use as a lithium ion battery anode. Analysis of the recycled cigarette butt carbon (WCBC) using SEM, N2 adsorption, XPS, etc. revealed a porous, flake-like morphology with a high surface area of 1285 m2/g along with retained N and O functional groups.

When tested as a lithium ion battery anode, the WCBC demonstrated excellent electrochemical performance including high reversible capacities of 528 mAh/g at 25 mA/g and 151 mAh/g at 2000 mA/g along with good cycling stability over 2500 cycles and rate capability from 25-2000 mA/g. The N-doping and oxygen functional groups were credited with contributing to the superb anode behavior. The WCBC also showed decent performance when coupled in a full cell with LiCoO2 cathode. The recycled cigarette butt carbon could provide a sustainable high-performance anode material while reducing environmental waste. The simple strategy offers inspiration for converting common wastes into energy storage materials.

This section should provide a concise and precise description of the experimental results, their interpretation, as well as the experimental conclusions that can be drawn.

# 4. Conclusion

This work highlights the significant and diverse potential of waste derived from discarded cigarette butts for various innovative and sustainable applications. By studying the existing literature, the paper points to promising opportunities for utilizing this specific type of waste in different sectors, contributing to sustainable practices and innovative solutions. Cigarette butt waste, which is a serious environmental concern, can be transformed and utilized in ways that contribute to sustainability and innovation. Various studies reviewed in this paper have shown that cigarette butt waste can be employed for different purposes, providing environmental and economic benefits. Further research and development in this field are essential to fully understand and optimize the processes of utilizing cigarette butt waste, as well as to overcome existing challenges and explore new possibilities. Through continuous efforts and innovations in research, cigarette butt waste can become a valuable resource in the pursuit of a more sustainable and environmentally responsible society.

# Acknowledgements

This research was funded by financial support of Ministry of Science, Technological Development and Innovation of the Republic of Serbia, under Contract numbers 451-03-47/2023-01/200017 ("Vinča" Institute of Nuclear Sciences—National Institute of the Republic of Serbia), 451-03-47/2023-01/200051 (Institute of General and Physical Chemistry).

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# Mogućnosti upotrebe otpada koji potiče od opušaka cigareta

**Bojana Božilović[1], Hadi Waisi[1,2,*], Bojan Janković[3], Vladimir Dodevski[3], Stevan Blagojević[2], Marko Jovanović[2], Goran Plazonić[4]**

[1]Fakultet za ekologiju i zaštitu životne sredine, Univerzitet Union-Nikola Tesla, Cara Dušana 62-64, Beograd, Srbija
[2]Institut za opštu i fizičku hemiju, Studentski trg 12-16, Beograd, Srbija
[3]Institut za nuklearne nauke "Vinča", Institut od nacionalnog značaja za Republiku Srbiju, Univerzitet u Beogradu, Mike Petrovića Alasa 12-14, Beograd, Srbija
[4]Henkel D.O.O., Bulevar Oslobođenja 383,11040 Beograd, Srbija

[*]**Autor za korespondenciju:** hadiwaisi@yahoo.com

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**Apstrakt:** Ovaj pregledni rad sistematično istražuje inovativne i održive primene otpada koji potiče od odbačenih opušaka cigareta (CB). Kao jedan od najrasprostranjenijih oblika smeća širom sveta, opušci cigareta predstavljaju značajan ekološki izazov zbog svoje sporog procesa razgradnje i prisustva toksičnih komponenata. Ovaj rad ima za cilj da osvetli potencijal ponovne upotrebe otpada od CB i pretvaranja istog u vredne resurse za različite namene, čime se umanjuje njihov ekološki uticaj. Kroz pažljivu analizu postojeće literature, identifikujemo i razmatramo obećavajuće puteve za korišćenje otpada od CB, ističući raznovrsnost i potencijal ovog nedovoljno istraženog otpadnog materijala. Pregled ističe neophodnost daljeg istraživanja i razvoja kako bi se optimizovale identifikovane primene, rešili povezani izazovi i otkrile nove mogućnosti za korišćenje otpada od CB. Na kraju, ovaj rad ima za cilj doprinos rastućem telu znanja o održivim praksama upravljanja otpadom, promovišući inovativna rešenja za jedan od najraširenijih ekoloških problema današnjice.

**Ključne reči:** otpad od opušaka cigareta, održive prakse, korišćenje otpada, inovativne primene, ekološki uticaj

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**Global sustainability challenges**
2025; 3(1): 8-14
https://gsc.unionnikolatesla.edu.rs/index.php/gsc
UDC: 502.3:613.15
640.43:711.4
ISSN: 2956-1051 (Online)

# The Influence of Restaurant Zones on Local Air Quality: Evidence from Novi Sad

**Ivana Stošić[1, *], Tatjana Kosić[1, 2]**

[12] Faculty of Construction Management, Union Nikola Tesla University, Belgrade, Serbia

[*]**Corresponding author:** istosic@unionnikolatesla.edu.rs

**To cite this article:**
Stošić, I. & Kosić, T. (2025). The Influence of Restaurant Zones on Local Air Quality: Evidence from Novi Sad. *Global sustainability challenges, Vol. 3(1)*, pp. 8-14.

**Received**: Sep 4, 2024; **Accepted**: Sep 8, 2025; **Published**: Dec 22, 2025

**Abstract:** This research examines how restaurant activity might influence local air quality in the urban area of Novi Sad. The study was designed to assess air pollution levels in proximity to restaurant clusters, with a focus on the impact of these establishments during critical times of the day. Air pollution data were gathered at four central sites near these clusters during two daily periods: midday (12:00 PM) and evening (7:00 PM). The results reveal that nitrogen dioxide ($NO_2$) levels were significantly higher in areas with dense restaurant activity during the evening hours. This highlights the relationship between increased human activity, cooking emissions, and delivery traffic associated with restaurants. In contrast, green spaces and pedestrian-friendly zones consistently maintain lower pollution levels, suggesting that urban design and planning can mitigate some of the adverse effects of air pollution. Furthermore, a comparative analysis of weekday and weekend measurements, alongside an evaluation of a 24-hour city-wide air quality trend, indicates that pollutant levels tend to rise during peak restaurant hours, especially in the evening. These findings highlight the significance of acknowledging that restaurants can impact localized air quality changes, particularly during peak operational periods. Although the research is based on limited data, it emphasizes the pressing need to consider the environmental impact of hospitality venues in urban planning and sustainability efforts, promoting a healthier urban environment for all residents.

**Keywords:** Air quality, restaurants, Novi Sad, PM2.5, PM10, $NO_2$, $O_3$

## 1. Introduction

An international environmental issue that directly impacts the quality of life for city residents is air pollution (Thomas, 2017)

In addition to harming physical health, it negatively affects social interactions, outdoor activities, and mood, collectively diminishing the city's vitality. For city residents, dining out is a significant social activity (Gao et al., 2020). Chronic exposure to air pollution, especially PM2.5 and NO2, is linked to higher incidence of cardiovascular disorders such ischemic heart disease, heart attacks, and strokes as well as respiratory conditions like lung cancer, asthma, and chronic obstructive pulmonary disease (Hilly et al., 2024).

This highlights the need to address further the factors that influence the quality of air in areas frequently used for dining out.

First it is important to state the adverse health effects of PM10 and PM2.5 and the associated health risks that are highlighted by Chang et al. (2021) and (Shah et al., 2020), who emphasize the connection between cooking and exposure to these types of air pollutants. Compared to places far from charcoal grill restaurants, it was discovered that the outdoor air near these establishments was more polluted with VOCs like BTEX and n-alkanes. As a result, nearby households and pedestrians may be exposed to high concentrations of pollutants and the secondary by-products they produce (Kim & Lee, 2012). The findings of a study by Sofuoglu et al. (2015) demonstrated that using deep-frying margarine in small-scale businesses could result in significantly higher amounts of particulate matter exposure during deep-frying.

While burning natural gas resulted in an increase in the concentration of CO2, burning charcoal resulted in a significant increase in the CO level. Additionally, the dining area's air quality was determined to be the worst at the restaurant with the worst ventilation, and this was greatly impacted by the kitchen ventilation's operational state (Zhao et al., 2020). Lyu et al. (2022) emphasize that different type of food causes different amount of air pollutants. While Lee et al. (2001) already in 2001 noted that the way food is prepared influence the air quality. It indicates that both several factors should be taken into account when addressing this topic and that the influence of the restaurants is acknowledged in studies for some time now.

The general public is unaware that culinary operations kitchens can generate hazardous substances. It appears that restaurant owners often overlook the importance of occupational health in kitchens, as they fail to comprehend the impact of heat on food and the creation of hazardous compounds that can harm the environment (Durban, 2022). Cooking methods (such as frying versus wet cooking), pan size (smaller pans are better), oil type (the best type depends on smoking temperature), cooking temperature, food type and additives, heating source surface area (smaller burners are better), ventilation, and cooking temperature all affect the type and abundance of PM and ultrafine particles produced by both electric and gas cooking (Nassikas et al., 2024).

Globally, cooking uses a significant amount of energy, particularly in developing nations. Natural gas, charcoal, wood, kerosene, electricity, liquefied petroleum gas, biogas, and biomass are among the fuels that are typically used for cooking. As a result, the cooking procedures release significant amounts of hazardous air pollutants and greenhouse gases every day, explain ElSharkawy and Ibrahim (2022).

Durban (2022) further explain that cooking produces biomass smoke, which contains particulate matter (PM), carbon monoxide (CO), nitrogen dioxide ($NO_2$), formaldehyde, and various hazardous organic compounds, including benzene and other polycyclic aromatic hydrocarbons (PAHs). Especially in the winter, $NO_2$ concentrations were much greater when cooking than when cleaning (for example, frying versus handwashing and running the dishwasher by nearly 60%) (Keller et al., 2024)

Zhang et al. (2025) are stating that cooking activities have a significant negative impact that is frequently neglected, especially in specific contexts such as in commercial buildings. Cooking fumes have been a major source of concern for several years, particularly in densely populated cities where restaurants are often situated in close proximity to sensitive structures and residential areas. Restaurants emit pollutants as a result of heating and cooking operations that use a variety of fuels and cook a variety of food types. Cooking materials, cooking methods, and even cooking fuel have a significant impact on the quantity of pollutants released from those sources (ElSharkawy & Ibrahim, 2022).

Further it is important to emphasize that due to the rapid growth of the restaurant industry, cooking fume emissions have gotten worse. Restaurant emissions significantly contribute to outdoor air pollution levels, in addition to endangering the health of patrons and employees (ElSharkawy & Ibrahim, 2022). All these aspects demonstrate the need to put this topic into the focus of research and to analyze the impact on the air quality in the area full of restaurants.

Gao et al. (2020) adds that pollutant emissions from restaurant chimneys significantly and directly impact the ambient air outside, especially during the grilling process, which releases pollutants at a much higher rate than other cooking methods used in restaurants. The external atmosphere can change in response to any modifications, whether favourable or unfavourable, in the internal cooking methods or combustion efficiency of restaurants.

It is essential to acknowledge that restaurant-related activities have a detrimental impact on the environment, particularly in terms of air quality. The degree of these adverse effects and their implications for health underscore the need to examine the impact of this research on air quality in outdoor areas near restaurants. Furthermore, it is crucial to tailor the research to the local context. Consequently, the research is focused on four areas in Novi Sad, city in Serbia, where popular and busy restaurants are situated. The aim of the paper is to explore potential impact of restaurant presence and related urban activity on local air quality in Novi Sad. To achieve this, the following methods are employed.

## 2. Materials and Methods

This research aims to assess the level of air pollution in areas surrounding restaurants in Novi Sad, focusing on whether the presence and activity of restaurants might influence local air quality. The research is based on the expected influences of cooking emissions, increased foot and vehicle traffic, and other restaurant-related factors that may contribute to changes in pollution levels in urban microenvironments, due to the impact of frying and grilling on the emission of PM2.5 and NO2. Additionally, the presence of delivery vehicles, waste management activities, and increased human density can further contribute to localized air pollution. This suggests that it is crucial to focus more closely on areas with numerous restaurants in relation to air pollution.

Air quality data were collected on June 20th, 2025 (Friday), and June 22nd, 2025 (Sunday), using the AirCare mobile application, which provides real-time pollution measurements from public sensors. The app reports concentration of pollutants, including PM2.5, PM10, O3 (ozone), NO2 (nitrogen dioxide), CO (carbon monoxide), and the overall AQI (Air Quality Index).

By measuring pollution levels at selected locations near the restaurant, research aims to conclude if restaurant-related activity (such as cooking, increased traffic, and pedestrian density) contributes to changes in air pollutant concentrations. The research also compares weekdays and weekends to assess whether differences in daily activity patterns affect pollution levels. Additionally, broader 24-hour air quality trends are analyzed to contextualize localized findings.

### *2.1. Data collection*

Data were recorded manually from the AirCare app, to ensure consistency, all readings were taken during stable weather conditions-clear skies, mild temperatures, and little wind, which may have contributed to lower pollution levels

Measurements were taken at two time intervals: 12:00 PM (before lunch period)

7:00 PM (lunch –diner period)

Four locations across Novi Sad were selected based on their proximity to restaurants that are frequently visited. The names of individual restaurants are not recorded, but all sites are known to host multiple restaurants with moderate to high activity. The location varied in terms of their environmental setting, including:

A park-adjusted area

A pedestrian commercial street

A mixed-use urban street

A traffic-heavy area with high restaurant density.

Figure 1 shows the wider area around the location of measurement.

Additionally, data from the last 24 hours were analyzed to observe any changes in the trends of air pollution in the analyzed locations (Figure 2).

To explore potential differences between workdays and weekends, measurements are collected on a workday (Friday) and on Sunday at a similar time (midday, around 12PM).

### *2.2. Data analysis*

Data collected on air quality in selected locations is organized and presented in a table, allowing for easy comparison and analysis of the results. Descriptive analysis is used to observe trends in pollutant levels. Air Quality Index values were interpreted using standardized U.S. AQI categories (e.g., good) with color coding applied to differentiate pollution levels. Special attention is given to variations in NO2, and particulate matter, as these pollutants are most closely linked to combustion sources and urban activity, including restaurant operation and traffic density.

The analysis focused on identifying environmental patterns and potential localized pollution hotspots in areas with a high concentration of restaurants. This approach enabled the identification of possible links between environmental characteristics, human activities, and air pollution, even within relatively short geographical distances.

## 3. Results

This section should provide a concise and precise description of the experimental results, their interpretation, and the experimental conclusions that can be drawn.

### *3.1. Analysis of air quality and pollution levels*

Air quality measurements were collected at four selected locations in Novi Sad, Serbia, during midday to assess baseline pollution levels near dining areas. In all of these sites, there are restaurants and dining areas that were focus of this

research. Restaurants observed are located in the regions of Danube Park, Futoška Street, Jevrejska Street, and Zmaj Jovina pedestrian zone.

At the Danube Park area, the Air Quality Index (AQI) measures 49, indicating good air quality. Particulate matter concentrations are very low, with PM2.5 at 7 μg/m³. Ozone levels are higher (104 ppb), which is consistent with sunlight exposure in open areas. Carbon monoxide (CO) and nitrogen dioxide ($NO_2$) levels are minimal at 0.2 ppm and 2 ppb, respectively.

In the urban street zones of Futoška Street and Jevrejska Street, AQI values were similar at 43. Both locations recorded comparable PM2.5 (6 μg/m3) and PM10 (8-9 μg/m3) levels to other places. Notably, NO2 concentrations at these sites were elevanted to 13 ppb.

The Zmaj Jovina Pedestrian street zone showed an AQI of 45 with particulate matter concentrations comparable to other locations (PM2.5 at 7 μg/m3, PM10 at 8 μg/m3). Nitrogen dioxide levels were considerably lower at 1 ppb, reflecting the reduced traffiic in the area.

The generally good air quality results may also reflect the favorable weather conditions on the day of the measurement, including clear skies and stable temperatures.

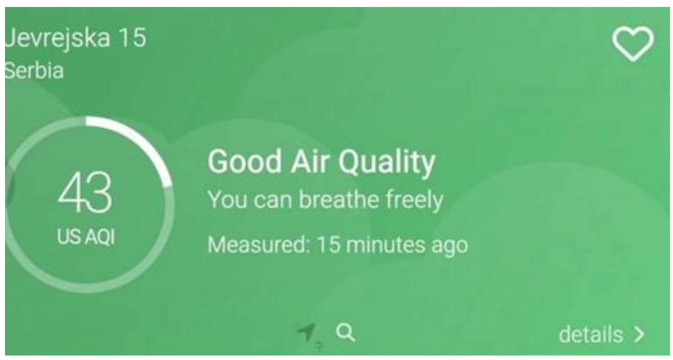


**Figure 1**: Air Quality 12 PM- Jevrejska street Friday.

**Table 1:** Air Quality Measurements Near Dining Areas in Novi Sad 12 PM.

| Location | AQI | PM2.5 | PM10 | O3 | CO | NO2 | Color Code |
|---|---|---|---|---|---|---|---|
| Danube Park | 49 | 7 | 8 | 104 | 0.2 | 2 | |
| Futoška Street | 43 | 6 | 8 | 94 | 0.2 | 13 | |
| Jevrejska Street | 43 | 6 | 9 | 94 | 0.2 | 13 | |
| Zmaj Jovina Pedestrian Street | 45 | 7 | 9 | 95 | 0.2 | 1 | |

To assess potential changes in air quality during peak restaurant hours, additional measurements were taken at 7:00 PM at the same areas. The evening data revealed increased nitrogen dioxide levels in areas with more intense traffic and restaurant-related activity, suggesting a potential link between environmental conditions and human behavior patterns during dinner hours.

At the Danube Park, the air quality remained stable, with all values nearly identical to the midday measurements. The AQI remained at 49, and pollutant concentrations remained low, confirming that this location, surrounded by greenery and away from major streets, was less affected by urban activity.

In contrast, Futoška Street showed a notable increase in nitrogen dioxide, from 13 ppb at 12:00 PM to 26 ppb at 7:00 PM. PM2.5 and PM10 slightly decreased. This may reflect higher traffic volumes during the evening rush, along with intensified restaurant operations.

Jevrejska street experienced the most significant spike, with NO2 rising from 13 ppb at midday to 41 ppb in the evening. This location, characterized by its dense restaurant presence and vehicle access, is likely to accumulate emissions from both cooking activities in restaurants and increased motor traffic during dinner hours.

Meanwhile, Zmaj Jovina, a pedestrian zone, continued to demonstrate minimal pollution levels. Both AQI and individual pollutant concentrations remained consistent, with NO2 at just 3 ppb, reinforcing the positive environmental impact.

These evening results underscore the environment sesitivity of restaurant in conext of air pollution and importance of monitoring pollution exposure during periods of high commercial activity.

**Table 2:** Air Quality Measurements Near Dining Areas in Novi Sad 7 PM.

| Location | AQI | PM 2.5 µg/m$^3$ | PM10 µg/m$^3$ | O3 µg/m$^3$ | CO mg/m$^3$ | NO2 µg/m$^3$ | Color Code |
|---|---|---|---|---|---|---|---|
| Danube Park | 49 | 7 | 8 | 104 | 0.2 | 3 | |
| Futoška Street | 46 | 5 | 7 | 98 | 0.2 | 26 | |
| Jevrejska Street | 46 | 6 | 10 | 103 | 0.2 | 41 | |
| Zmaj Jovina Pedestrian Street | 49 | 7 | 8 | 1041 | 0.2 | 3 | |

To explore whether air pollution levels differ between weekdays and weekends, additional data were collected on a Sunday during the midday, using the same locations and methodology. The results, shown in Table 3, revealed a noticabe shift in overall air quality compaed to the weekdays. While resutls from Friday fell entirely within „Good"(AQI<50) category, all Sunday values were eleavnted into the „Moderate" (AQI 57-62) range. Interestingly, this increase occured despite relatevely low NO2 levels, suggesting that the chnage was not primarly driven by traffic emissions.

On weekends, restaurants often experience peak hours during luch hours which may lead to emissions that accumulate in surrounding areas, especially when the urban flow is llimited.

**Table 3:** Air Quality Measurements Near Dining Areas in Novi Sad 12 PM (Sunday).

| Location | AQI | PM 2.5 µg/m$^3$ | PM10 µg/m$^3$ | O3 µg/m$^3$ | CO mg/m$^3$ | NO2 µg/m$^3$ | Color Code |
|---|---|---|---|---|---|---|---|
| Danube Park | 57 | 5 | 5 | 111 | 0.2 | 1 | |
| Futoška Street | 62 | 5 | 4 | 114 | 0.2 | 9 | |
| Jevrejska Street | 62 | 6 | 4 | 114 | 0.2 | 9 | |
| Zmaj Jovina Pedestrian Street | 57 | 5 | 5 | 111 | 0.2 | 1 | |

### *3.2. 24-hour air quality changes*

The area shown in Figure 1 is also reviewed to determine if changes occur within a 24-hour time frame. For all locations in this area, results were similar as presented in Figure 2 for June 20, 2025.

Pollution levels were moderate from 6 PM to 6 AM, then improved to "Good" from approximately 8 AM to 6 PM. This pattern aligns with the daily restaurant rhythm, suggesting that evening periods may contribute to higher pollution levels.

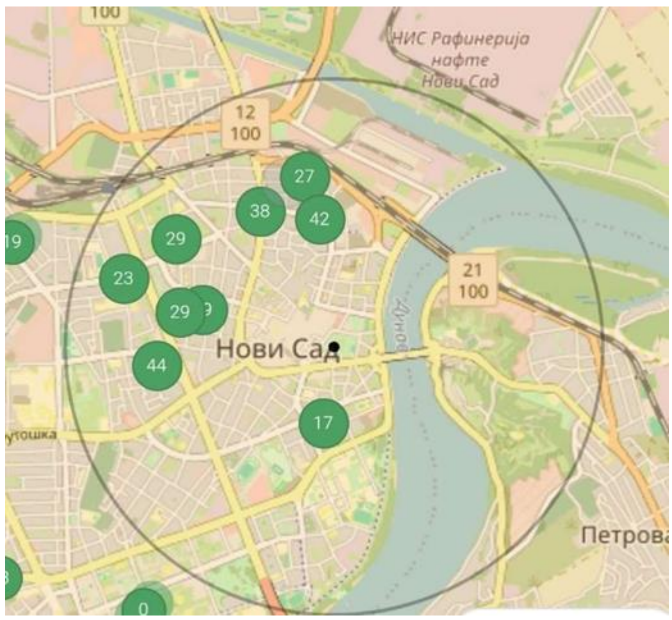

**Figure 2.** Covered areas.

**Figure 3.** Air Quality 7 PM- Jevrejska street Sunday.

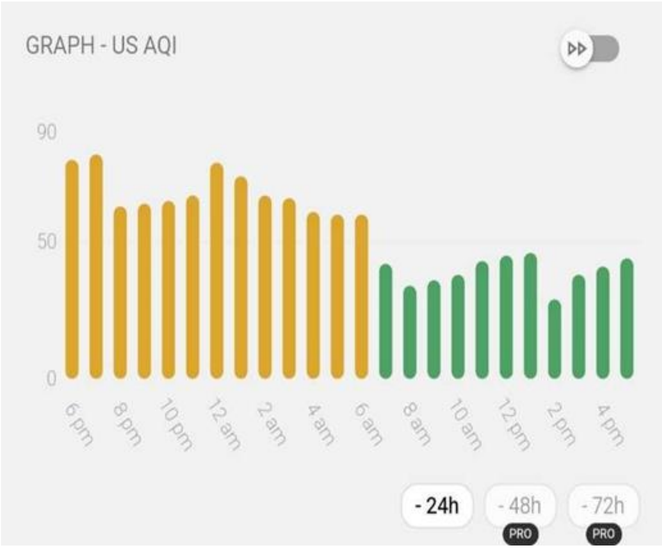


**Figure 4.** 24-hours overview.

## 4. Conclusion

This paper explores the relationship between restaurant activity and local air quality in Novi Sad. Through real-time air quality measurements collected during the midday and evening hours, significant variations are identified in pollutant levels, particularly nitrogen dioxide (NO2) in areas located near restaurant clusters.

While pedestrian-friendly areas (Danube Park and Zmaj Jovina) maintained low pollution levels, streets with heavier restaurant density (Jevrejska and Futoška) showed worse air quality, especially during evening hours.

Further analysis showed that high air pollution is associated with peak restaurant hours. Several factors can be associated with it – cooking emissions, delivery traffic and reduced atmospheric circulation.

Although this research is based on limited data and localized measurements, the findings suggest that restaurant zones may contribute to an increase in pollution.

These findings suggest that restaurants not only react to surrounding environmental conditions but may also play a role in shaping urban air quality over different periods.

These results can be explained in the following way: restaurants often operate at full capacity during evening hours. It includes increased use of grills, ovens, and fryers, which may release fine particles and gases into the surrounding air via ventilation systems. Higher human density in restaurant areas can influence micro-level air circulation and impact air quality. It additionally leads to more traffic in these areas.

Findings made by observing measurements collected for this research, show that more attention is needed to be directed towards the influence that restaurants have and it is important to investigate more the influence that restaurants have on air quality as this is the first step towards finding mechanisms for reducing negative impact and improve air quality in these areas.

## Acknowledgements

The results presented here are the result of research project "Problem of air pollution originating from restaurant facilities - characteristics, sources, proposed measures" supported by directorate of the city government of Novi Sad for environmental protection, Republic of Serbia (RS) according to Contract No. 2608 from 06.09.2024.

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# Uticaj restoranskih zona na kvalitet vazduha u urbanim sredinama: primer Novog Sada

**Ivana Stošić[1, *], Tatjana Kosić[1]**

[12] Fakultet za graditeljski menadžment, Univerzitet Union Nikola Tesla, Beograd, Srbija

[*]**Autor za dopisivanje: istosic@unionnikolatesla.edu.rs**

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**Apstrakt:** Ovo istraživanje ispituje kako bi aktivnost restorana mogla uticati na lokalni kvalitet vazduha u urbanom području Novog Sada. Studija je osmišljena da proceni nivoe zagađenja vazduha u blizini klastera restorana, sa fokusom na uticaj ovih objekata tokom kritičnih perioda dana. Podaci o zagađenju vazduha prikupljeni su na četiri centralne lokacije u blizini ovih klastera tokom dva dnevna perioda: podne (12:00 časova) i veče (19:00 časova). Rezultati pokazuju da su nivoi azot-dioksida ($NO_2$) bili značajno viši u područjima sa gustom aktivnošću restorana tokom večernjih sati. Ovo ističe vezu između povećane ljudske aktivnosti, emisija gasova iz kuvanja i saobraćaja dostave povezanog sa restoranima. Nasuprot tome, zelene površine i pešačke zone konstantno održavaju niže nivoe zagađenja, što sugeriše da urbani dizajn i planiranje mogu ublažiti neke od negativnih efekata zagađenja vazduha. Štaviše, uporedna analiza merenja radnim danima i vikendom, zajedno sa procenom 24-časovnog trenda kvaliteta vazduha u celom gradu, ukazuje da nivoi zagađivača imaju tendenciju rasta tokom špica restorana, posebno uveče. Ovi nalazi ističu značaj priznavanja da restorani mogu uticati na lokalizovane promene kvaliteta vazduha, posebno tokom špica rada. Iako je istraživanje zasnovano na ograničenim podacima, ono naglašava hitnu potrebu da se u urbanističkom planiranju i naporima za održivost uzme u obzir uticaj ugostiteljskih objekata na životnu sredinu, promovišući zdravije urbano okruženje za sve stanovnike.

**Ključne reči:** Kvalitet vazduha, restorani, Novi Sad, PM2.5, PM10, $NO_2$, $O_3$.

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**Global sustainability challenges**
2025; 3(1): 15-23
https://gsc.unionnikolatesla.edu.rs/index.php/gsc
UDC: 615.477:615.33
620.1:615.477
620.1:617.3-7
ISSN: 2956-1051 (Online)

# Gentamicin Release from Hydroxyapatite-based Bioceramic Coating on Titanium

**Vesna Mišković-Stanković[1, *], Marija Djošić[2], Ana Janković[3], Milena Stevanović[3], Teodor M. Atanackovic[4]**

[1]Faculty of Ecology and Environmental Protection, University Union - Nikola Tesla, 11000 Belgrade, Serbia
[2]Institute for Technology of Nuclear and Other Mineral Raw Materials, 11000 Belgrade, Serbia
[3]Innovation Center of the Faculty of Technology and Metallurgy, University of Belgrade, 11000 Belgrade, Serbia
[4]Faculty of Technical Sciences, University of Novi Sad, 21000 Novi Sad, Serbia

[*]**Corresponding author:** vesna.miskovicstankovic@unionnikolatesla.edu.rs

**To cite this article:**
Mišković-Stanković, V. et.al. (2025). Gentamicin Release from Hydroxyapatite-based Bioceramic Coating on Titanium. *Global sustainability challenges, 3*(1), pp. 15-23.

**Received**: Sep 15, 2025; **Accepted**: Nov 11, 2025; **Published**: Dec 22, 2025

**Abstract:** Novel antibacterial bioceramic hydroxyapatite/poly(vinyl alcohol)/chitosan/gentamicin (HAP/PVA/CS/Gent) coating on titanium substrate was successfully produced for bone tissues implants, to enable a drug delivery directly at the infection site and avoid the systemic antibiotic administration in the case of post-operative hospital infections. This study represents novel two compartmental model with General fractional derivative of distributed order used to investigate the release of gentamicin in surrounding tissue. The gentamicin release profile was represented as time dependence of ratio between mass of released gentamicin, determined by high-performance liquid chromatography (HPLC), and initial mass of gentamicin in the coating. It has been proved that proposed a two compartmental model with General fractional derivative of distributed order exhibited excellent agreement between experimental values and calculated values from the model, and enabled the determination of gentamicin diffusion coefficient in entire time period.

**Keywords:** Coatings, Bioceramics, Hydroxyapatite, Titanium, Gentamicin, Diffusion, Modeling

## 1. Introduction

Compartmental models are often used in pharmacokinetics to describe the response to drug bolus administration (Copot et al., 2017). Numerous works have proved their applicability for optimal drug delivery assist devices in different medical treatments, e.g. diabetes, cancer, anaesthesia, immune deficiency, leukaemia and hormonal treatment (Churilov et al., 2009; Copot & Ionescu, 2014; Drexler et al., 2011; C. M. Ionescu et al., 2017; Kiss et al., 2013; Kovács et al., 2011; Popović et al., 2015). Fractional-order models are found to be more adequate for compartmental analysis in many cases (Atanackovic et al., 2025; Dokoumetzidis et al., 2010; Dokoumetzidis & MacHeras, 2009; C. Ionescu et al., 2017; Miskovic-Stankovic et al., 2023; Mišković-Stanković et al., 2024, 2025; Mišković-Stanković & Atanackovic, 2024; Miskovic-Stankovic & Atanackovic, 2023; Popović et al., 2010, 2011, 2015; Rajšić et al., 2022; Sopasakis et al., 2018; Verotta, 2010) where fractional calculus (FC) was applied in pharmacokinetics and drug diffusion in biological systems.

The rapid aging of the world's population undoubtedly leads to a growing need for orthopaedic interventions. In order to be suitable for implantation, biomaterials have to meet numerous requirements, including biocompatibility, bioactivity, as well as good mechanical and antibacterial properties (Fiume et al., 2021). Titanium (Ti) is still the most commonly used metallic material in reconstruction surgery due to its good mechanical properties and biocompatibility, as well as its corrosion resistance (Kaur & Singh, 2019). In order to improve biocompatibility, bioactivity and to prevent bacterial biofilm formation, titanium surface should be modified (Chouirfa et al., 2019; Stepanovska et al., 2020). For metallic implants´ surface modification, hydroxyapatite (HAP) is very often the material of choice due to its similarity to the mineral part of the natural bone tissue. On the other side, HAP is brittle, having poor mechanical strength (Mahanty & Shikha, 2022). Synthetic and/or natural polymers, like poly(vinyl alcohol) (PVA), and chitosan (CS) are often used in production of HAP-based composites with the aim to provide good adhesion and improve the mechanical properties of the coatings (Abdulghani & Mitchell, 2019; Mahanty & Shikha, 2022; Raut et al., 2020).

In the field of orthopaedic and trauma surgery, possible infections of the surgical site can cause serious complications. With the aim to overcome this issue, a great number of antibiotics are applied in the medical treatment of bacterial infections. Sometimes, it is required to apply a high local concentration of antibiotics to prevent the biofilm formation, e.g. after orthopaedic surgery. Significant reduction of colonized bacteria on the bone and implant surfaces (methicillin-sensitive S. aureus (MSSA) and methicillin-resistant S. aureus (MRSA)) could be achieved by employing the antibiotic-coated implants (Masters et al., 2019) since the antibiotic-loaded implants' surface coatings enable a delivery of high concentrations drugs directly at the infection site, reducing the possibility of side effects, which may occur during systemic antibiotic administration.

Due to the numerous advantages, e.g. uniform composition and thickness of the deposited coatings, the possibility of deposition on substrates of complex geometries that can be found in orthopaedics, low degree of environmental pollution, as well as room temperature processing, which is crucial for deposition of bioceramic coatings containing thermo labile antibacterial agents, we have chosen electrophoretic deposition (EPD) for the production of biocomposite coatings (Stevanović, Djošić, Janković, Kojić, et al., 2020; Stevanović, Djošić, Janković, Nešović, et al., 2020; Stevanović et al., 2018, 2021). The drug release behaviour is a major parameter that could influence both antibacterial activity and biocompatibility, therefore antibiotic release measurements are an integral part of the in vitro characterizations of drug-loaded materials.

In this work we made attempt to incorporate gentamicin in hydroxyapatite/poly(vinyl alcohol)/chitosan/gentamicin (HAP/PVA/CS/Gent) coating on titanium aimed for bone tissues implant, in order to enable a drug delivery directly at the infection site and avoid the systemic antibiotic administration. The advantages of HAP/PVA/CS/Gent coating produced by EPD from four-component aqueous suspension are environmentally friendly product consisting of medical approved components deposited in one step without additional fabrication and uniform coating thickness, We employed novel FC model to study the release of gentamicin from HAP/PVA/CS/Gent coating..

# 2. Materials and Methods

### *2.1. Materials*

Hydroxyapatite powder (particles<200 nm particle size, Sigma-Aldrich), chitosan powder (medium molecular weight 190-310 kDa, deacetylation degree 75-85%, Sigma-Aldrich), poly(vinyl alcohol) (medium molecular weight 89-98 kDa, 99% hydrolyzed, Sigma-Aldrich), and aqueous gentamicin sulphate solution (concentration 50 mg/ml, Sigma-Aldrich) were used. Titanium plates, Ti (99.7% purity, Sigma-Aldrich), were mechanically polished before EPD (grit emery paper) and ultrasonicated (15 min in acetone and 15 min in ethanol).

### *2.2. Electrophoretic deposition*

EPD was performed in aqueous suspension consisting of hydroxyapatite (1.0 wt%), chitosan (0.05 wt%), poly(vinyl alcohol) (0.1 wt%) and gentamicin sulphate (0.1 wt%). Cathodic EPD process was performed on the titanium plate (dimensions 1 cm x 1 cm) using constant voltage method according to the procedure we have published earlier (Stevanović, Djošić, Janković, Nešović, et al., 2020). The coating thickness was 3.1 μm.

### *2.3. Gentamicin release*

For the gentamicin release measurements, the HAP/PVA/CS/Gent coating on titanium was immersed in deionized water and kept at 37 °C. The concentration of released gentamicin was determined using a high-performance liquid chromatography (HPLC) (Thermo Fisher Scientific, USA) coupled with ion trap (LCQ Advantage, Thermo Fisher Scientific) as a mass spectrometer (MS), according to procedure we have published earlier (Stevanović et al., 2021)[31].

# 3. Results and Discussion

### *3.1. Mathematical model*

We shall use General fractional calculus to formulate mathematical model in order to describe release of gentamicin in the experiments described in Section 2.3. We recall some basic notation of the general fractional calculus and then we define a distributed order general fractional derivative. It will be used in two compartmental system to describe the mass exchange.

The basic idea of the General fractional calculus is the definition of a General fractional integral $\boldsymbol{I}_{(\boldsymbol{M})}^{\boldsymbol{t}}$ and General fractional derivative $\boldsymbol{D}_{(\boldsymbol{K})}^{\boldsymbol{t}}$ as

$$I_{(M)}^{t}[\tau]f(\tau) = \int_0^t M(t-\tau)f(\tau)d\tau,$$
$$D_{(K)}^{t}[\tau]f(\tau) = \frac{d}{dt}\int_0^t K(t-\tau)f(\tau)d\tau, \quad (1)$$

where the kernels, $M$ and $K$, satisfy certain properties, i.e., they are associated in the sense of Sonin. The general fractional derivative of the Caputo type with the kernel $K$ follows the classical definition and reads

$${}_0^C D_{(K)}^t f(\tau) = \int_0^t K(t-\tau) f^{(1)}(\tau) d\tau, \quad (2)$$

The kernels in Eq. (1) and Eq. (2) satisfy

$$M(t), K(t) \in C_{-1,0}(0,\infty), \ \int_0^t M(t-\tau)K(\tau)d\tau = 1, \quad (3)$$

where

$$C_{a,b}(0,\infty) = \{f(t):\ f(t) = t^p Y(t), \quad t > 0,$$
$$a < p < b, \quad Y(t) \in C[0,\infty)\}. \quad (4)$$

Note that the Riemann-Liouville kernels (Atanackovic et al., 2014), (Podlubny, 1999)

$$M(t) = \frac{t^{\alpha-1}}{\Gamma(\alpha)}, \quad K(t) = \frac{t^{-\alpha}}{\Gamma(1-\alpha)}, \quad (5)$$

where $0 < \alpha < 1$ and $\Gamma$ is the Euler Gamma function, satisfy Eq. (1) and Eq. (3) and that, in this case Eq. $(1)_1$ and Eq. (2) become fractional integral and fractional Caputo derivative in the usual sense.

There are many kernels that satisfy Eq. (2) and Eq. (3) as shown in (Tarasov, 2021). To study the mass exchange in pharmacokinetics, in our earlier paper (Miskovic-Stankovic et al., 2023) we used Eq. (5), while in (Miskovic-Stankovic et al., 2023) the following kernels are used

$$M(s) = \lambda^\alpha + \frac{\alpha}{\Gamma(1-\alpha)} \int_t^\infty \frac{exp(-\lambda u)}{u^{1+\alpha}} du,$$
$$K(t) = \frac{t^{\alpha-1}}{\Gamma(\alpha)} exp(-\lambda t). \quad (6)$$

where $\lambda = const. \geq 0$ . Therefore, the general fractional derivative of the Caputo type that we use as a basis for our analysis is

$${}_0^C D^{\alpha,\lambda} f(t) = {}^C D_{(K)}^t f[\tau]$$
$$= \frac{1}{\Gamma(1-\alpha)} \frac{1}{\Gamma(1-\alpha)} \int_0^t \frac{exp(-\lambda\tau)}{\tau^\alpha} f^{(1)}(t-\tau) d\tau, \quad (7)$$

where $0 \leq \alpha \leq 1.$ The proof that $M$ and $K$ used in Eq. (6) satisfy Eq. (3) is given in (Samko & Cardoso, 2003). Using Eq. (7) we define *distributed* order General fractional derivative as

$${}_0^C\bar{D}C_t^{\alpha,\lambda} f(t) = \int_0^1 \varphi(\alpha)\, {}_0^C D_t^\alpha f(t) d\alpha. \quad (8)$$

In Eq. (8) the weight function $\varphi(\alpha),\ \alpha \in [0,1]$ denote a weighting function that has must have dimension $dim\, \varphi\,(\alpha) = [dim\, t]^\alpha$ to obtain dimensional homogeneity of Eq. (8). The simplest form of such function, that we shall use in Eq. (8) is $\varphi(\alpha) = \psi(\alpha) a^\alpha$ where $a$ is the characteristic time and $\psi(\alpha), \alpha \in [0,1]$ is a dimensionless function. In the analysis that follows we take $\psi(\alpha) = 1.$ Then Eq. (8) becomes

$${}_0^C\bar{D}_t^{\alpha,\lambda} f(t) = \int_0^1 a^\alpha\, {}_0^C D_t^\alpha f(t) d\alpha. \quad (9)$$

We shall use Eq. (9) to define kinetics of a two compartmental model of pharmacokinetics (Fig. 1). Recall that the classical two compartmental model of pharmacokinetics, with different volumes of compartments is described as, see (Rescigno, 2003)

$$\frac{1}{V_1}\frac{dm_1}{dt} = -k\left(\frac{m_1(t)}{V_1} - \frac{m_2(t)}{V_2}\right) + f_1(t),$$
$$\frac{1}{V_2}\frac{dm_2}{dt} = k\left(\frac{m_1(t)}{V_1} - \frac{m_2(t)}{V_2}\right) + f_2(t), \quad (10)$$

where $m_i, i = 1{,}2$ is the gentamicin mass in compartments **1** and **2**, respectively, $V_i, i = 1{,}2$ are volumes of compartments **1** and **2,** $k$ is a constant depending on the diffusion coefficient. The dimension of $k$ is [cm$^2$/s]. Also, we assume that in compartments **1** and **2** we have supply $f_i, i = 1{,}2$. The Eq. (10) may be written in the form when on the left and side we have $\frac{dm_1}{dt}$ and $\frac{dm_2}{dt}$ instead of $\frac{1}{V_1}\frac{dm_1}{dt}$ and $\frac{1}{V_2}\frac{dm_2}{dt}$, see (Rescigno, 2003). In this case coefficient $k$ may be different in each of Eq. (10) and they represent transport activity of the substances that can be approximated by concentration and the rate of change of concentration. We propose the generalization of Eq. (10) in which we replace first derivatives on the left-hand side by Distributed order general fractional derivative Eq. (9). Then we obtain

$$\frac{1}{V_1} b^\beta\, {}_0^C D_t^{\beta,\Lambda} m_1(t) + \frac{1}{V_1}\, {}_0^C\bar{D}_t^{\alpha,\lambda} m_1(t)$$
$$= -k\left(\frac{m_1(t)}{V_1} - \frac{m_2(t)}{V_2}\right) + f_1(t),$$
$$\frac{1}{V_2} b^\beta\, {}_0^C D_t^{\beta,\Lambda} m_2(t) + \frac{1}{V_2}\, {}_0^C\bar{D}_t^{\alpha,\lambda} m_2(t)$$
$$= k\left(\frac{m_1(t)}{V_1} - \frac{m_2(t)}{V_2}\right) + f_2(t), \quad (11)$$

where, $0 \leq \alpha, \beta \leq 1$ and $m_i, V_i, i = 1{,}2$ denote the mass of drug and volume of the compartment *i*, respectively. The derivatives ${}_0^C D_t^{\beta,\Lambda}(\cdot)$ and ${}_0^C\bar{D}_t^{\alpha,\lambda}(\cdot)$ is given by Eq. (7) and Eq. (9) and *a* and *b* are constants having the dimension of time to the exponent $-1+\alpha$ and $-1+\beta$ , respectively. Note that in (Miskovic-Stankovic et al., 2023) we used model of the type Eq. (11) with weighting functions in Eq. (8) taken as

$$\varphi(\alpha) = a\delta(\alpha - \alpha_1), \quad (12)$$

where $\alpha_1$is a constant, and $\delta$ denotes Dirac distribution.

We formulate now a mathematical model for the gentamicin release in antibacterial hydroxyapatite-based bioceramic coating on titanium surface. The physical system is shown in Fig. 1a, while the corresponding two compartmental model is shown in Fig. 1b.

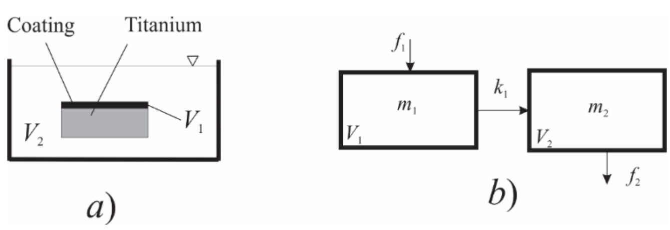


**Figure 1.** Two compartmental simplified model of gentamicin release: a) physical system, b) mathematical model.

We write the system Eq. (11) is in expanded form as

$$\frac{1}{V_1} b^{\beta} \frac{1}{\Gamma(1-\beta)} \int_0^t \frac{exp(-\Lambda\tau)}{\tau^{\beta}} m_1^{(1)}(t-\tau)d\tau + \frac{1}{V_1}\int_0^1 a^{\alpha}\left[\frac{1}{\Gamma(1-\alpha)}\int_0^t \frac{exp(-\lambda\tau)}{\tau^{\alpha}} m_1^{(1)}(t-\tau)d\tau\right]d\alpha = -k_1\left(\frac{m_1(t)}{V_1}-\frac{m_2(t)}{V_2}\right)+f_1(t),$$

$$\frac{1}{V_2} b^{\beta} \frac{1}{\Gamma(1-\beta)} \int_0^t \frac{exp(-\Lambda\tau)}{\tau^{\beta}} m_2^{(1)}(t-\tau)d\tau + \frac{1}{V_2}\int_0^1 a^{\alpha}\left[\frac{1}{\Gamma(1-\alpha)}\int_0^t \frac{exp(-\lambda\tau)}{\tau^{\alpha}} m_2^{(1)}(t-\tau)d\tau\right]d\alpha = k_2\left(\frac{m_1(t)}{V_1}-\frac{m_2(t)}{V_2}\right)+f_2(t).$$

In the analysis that follows we shall take $k_1V_1 = k_2V_2 = k$ to preserve the mass conservation equation that. Also we multiply Eq. (11)$_{1,2}$ with $V_1$ and $V_2$ respectively, to obtain the form of presented in (Rescigno, 2003).

$$b^{\beta} \frac{1}{\Gamma(1-\beta)} \int_0^t \frac{exp(-\Lambda\tau)}{\tau^{\beta}} m_1^{(1)}(t-\tau)d\tau + \frac{1}{V_1}\int_0^1 a^{\alpha}\left[\frac{1}{\Gamma(1-\alpha)}\int_0^t \frac{exp(-\lambda\tau)}{\tau^{\alpha}} m_1^{(1)}(t-\tau)d\tau\right]d\alpha = -k\left(\frac{m_1(t)}{V_1}-\frac{m_2(t)}{V_2}\right)+f_1(t),$$

$$\frac{1}{V_2} b^{\beta} \frac{1}{\Gamma(1-\beta)} \int_0^t \frac{exp(-\Lambda\tau)}{\tau^{\beta}} m_2^{(1)}(t-\tau)d\tau + \frac{1}{V_2}\int_0^1 a^{\alpha}\left[\frac{1}{\Gamma(1-\alpha)}\int_0^t \frac{exp(-\lambda\tau)}{\tau^{\alpha}} m_2^{(1)}(t-\tau)d\tau\right]d\alpha = k_2\left(\frac{m_1(t)}{V_1}-\frac{m_2(t)}{V_2}\right)+f_2(t). \quad (13)$$

To Eq. (13) we adjoin the following initial conditions that are used in our experiments

$$m_1(0) = m_0, \quad m_2(0) = 0. \quad (14)$$

System Eq. (13) represents the generalized two compartmental model with GFD that we shall use in this work.

### *3.2. Solution of the system Eq. (13) and Eq. (14)*

We use the Laplace transform method in solving Eq. (13) and Eq. (14). The Laplace transform of an exponentially bounded function $f$ is defined as

$$L[f(t)](s) = \hat{f}(s) = \int_0^{\infty} f(t)\, exp(-st)dt. \quad (15)$$

Where $s \in C$ is a complex number. Since

$$L\left[\frac{t^{-\alpha}}{\Gamma(1-\alpha)} exp(-\lambda t)\right](s) = \frac{1}{(s+\lambda)^{1-\alpha}}, \quad \lambda \geq 0,$$

where $0 \leq \alpha \leq 1$ and $L\left[m_1^{(1)}\right](s) = s\hat{m}_1(s) - m_1(0)$, we have

$$L\left[\frac{1}{\Gamma(1-\alpha)}\int_0^t \frac{exp(-\lambda u)}{u^{\alpha}} m_1^{(1)}(t-u)du\right] = \frac{s}{(s+\lambda)^{1-\alpha}}\hat{m}_1(s) - \frac{1}{(s+\lambda)^{1-\alpha}} m_1(0) \quad (16)$$

Applying the Laplace transform to Eq. (7) and using Eq. (8) it follows

$$L\left[{}_0^C\bar{D}_t^{\alpha,\lambda} m_1(t)\right](s) = a\int_0^1 \left[\frac{s}{[a(s+\lambda)]^{1-\alpha}}\hat{m}_1(s) - \frac{1}{[a(s+\lambda)]^{1-\alpha}} m_1(0)\right]d\alpha.$$

Let

$$K(s) = \int_0^1 \frac{d\alpha}{[a(s+\lambda)]^{1-\alpha}} = \frac{1-[a(s+\lambda)]^{-1}}{ln[a(s+\lambda)]} = \frac{a(s+\lambda)-1}{a(s+\lambda)\, ln[a(s+\lambda)]}, \quad (17)$$

so that

$$L\left[{}_0^C\bar{D}_t^{\alpha,\lambda} m_1(t)\right](s) = aK(s)\left(s\hat{m}_1(s) - m_1(0)\right). \quad (18)$$

We now apply Laplace transform to Eq. (13) and Eq. (14) and obtain

$$\left[\frac{b}{[b(s+\Lambda)]^{1-\beta}} + aK(s)\right][s\hat{m}_1(s) - m_1(0)] = -k\left(\frac{\hat{m}_1(s)}{V_1} - \frac{\hat{m}_2(s)}{V_2}\right) + \hat{f}_1(s),$$

$$\left[\frac{b}{[b(s+\Lambda)]^{1-\beta}} + aK(s)\right]s\hat{m}_2(s) = k\left(\frac{\hat{m}_1(s)}{V_1} - \frac{\hat{m}_2(s)}{V_2}\right) + \hat{f}_2(s), \quad (19)$$

By solving Eq. (19) we obtain the Laplace transform of $m_1$ and $m_2$ as

$$\hat{m}_2(s) = \frac{1}{V_1}\frac{k\left(m_1(0) + \frac{\hat{f}_1(s)+\hat{f}_2(s)}{\frac{b}{[b(s+\Lambda)]^{1-\beta}}+aK(s)}\right)}{s\left[\frac{bs}{[b(s+\Lambda)]^{1-\beta}} + asK(s) + k\left(\frac{1}{V_1}+\frac{1}{V_2}\right)\right]}, \quad (20)$$

and

$$\hat{m}_1(s) = \frac{m_1(0)}{s} - \frac{\hat{f}_1(s)+\hat{f}_2(s)}{s\left[\frac{b}{[b(s+\Lambda)]^{1-\beta}} + aK(s)\right]} - \frac{1}{V_1} \times \frac{k\left(m_1(0) + \frac{\hat{f}_1(s)+\hat{f}_2(s)}{aK(s)}\right)}{s\left[\frac{bs}{[b(s+\Lambda)]^{1-\beta}} + asK(s) + k\left(\frac{1}{V_1}+\frac{1}{V_2}\right)\right]}. \quad (21)$$

Note that from Eq. (19) we obtain the following conservation of mass law

$$m_1(t) + m_2(t) = m_1(0) + L^{-1}\left[\frac{\hat{f}_1(s)+\hat{f}_2(s)}{aK(s)}\right]. \quad (22)$$

In the special case when $f_1(t) = f_2(t) = 0$ i.e., there is no addition/loss of the mass in the compartments we have, as expected, conservation of mass law

$$m_1(t) + m_2(t) = m_1(0).$$

By using the Initial and Final Value Theorems (Brezinski, 2007), for the case $f_1(t) = f_2(t) = 0$ the following estimates are obtained from Eq. (20) and Eq. (21)

$$\lim_{s\to\infty} s\,\hat{m}_1(s) = m_1(0),$$

$$\lim_{s\to 0} s\,\hat{m}_1(s) = m(\infty) = m_1(0)\frac{V_1}{V_1+V_2},$$

$$\lim_{s\to 0} s\,\widehat{m}_2(s) = m_2(\infty) = m_1(0)\frac{V_2}{V_1+V_2}. \quad (23)$$

Therefore, limiting concentration in each compartment

$$c_i = \frac{m_i}{V_i}, i = 1,2,$$

are equal

$$c_1(\infty) = c_2(\infty) = \frac{m_1(\infty)}{V_1} = \frac{m_2(\infty)}{V_2} = \frac{m_1(0)}{V_1+V_2},$$

in accordance with Fick's model of diffusion.

### *3.3. Results*

In this Section we present the results of numerical inversion of Eq. (20). Since in our experiments we have

$$f_1(t) = f_2(t) = 0,$$

so that

$$\widehat{m}_2(s) = \frac{1}{V_1}\frac{k m_1(0)}{s\left[\frac{bs}{[b(s+\Lambda)]^{1-\beta}} + asK(s) + k\left(\frac{1}{V_1}+\frac{1}{V_2}\right)\right]}. \quad (24)$$

The *central equation of this work expressing the mass* of the released gentamicin is determined by Laplace transform inversion formula from the Eq. (24)

$$m_2(t) = m_1(0)\frac{k}{V_1}\frac{1}{2\pi}$$

$$\times \int_{x_0-i\infty}^{x_0+i\infty} exp(\,x_0+ip)t\,(x_0+ip)$$

$$\times \frac{b(x_0+ip)}{[b(x_0+ip+\lambda_1)]^{1-\beta}} + a(x_0+ip)K\big((x_0+ip)\big)$$

$$+k\left(\frac{1}{V_1}+\frac{1}{V_2}\right)]dp, \quad (25)$$

where $i = \sqrt{-1}$ is the imaginary unit and $x_0$ chosen so that all zeros in the denominator of Eq. (25) are with the real part less than $x_0$. In the equation Eq. (25) it is necessary that $x_0 > 0$.

Parameters in the model $a, k, \lambda, b, \beta, \Lambda$ are determined by least square method, i.e., the sum squared residuals $Z$ between experimental and calculated from the model values of $m_2$ at five measured points, is *minimized*, that is

$$Z(a,k,\lambda,b,\beta,\Lambda) = \sum_{j=1}^{5}(m_2(t_j) - m_{2,\text{experimental}}(t_j))^2, (26)$$

where $m_2(t_j)$ are the values determined from Eq. (25) and $m_{2,\text{experimentaal}}(t_j)$ are the measured values at time instant $t_j$. The measured values are given in the Table 1.

The experimental values of mass $m_2$ are divided by initial, total mass of gentamicin that in our experiments is 163.52 mg. Thus, we define relative mass of the gentamicin in hydrogel, $m_{1,\text{rel}}$ and relative mass of released gentamicin in deionized water surrounding coating, $m_{2,\text{rel}}$ as

$$m_{1,\text{rel}}(t) = \frac{m_1(t)}{m_1(0)}, \quad m_{2,\text{rel}}(t) = \frac{m_2(t)}{m_1(0)}.$$

The values of $m_{1,\text{rel}}$ and $m_{2,\text{rel}}$ are represented in Table 1.

**Table 1** Experimental values of $m_{2,\text{rel,exp}}$ and calculated according to Eq. (25) values of $m_{2,\text{rel}}$

| *t*, days | $m_{2,\text{rel,exp}}$ | $m_{2,\text{rel}}$ |
|---|---|---|
| 0 | 0 | 0.00 |
| 1 | 0.22 | 0.222 |
| 2 | 0.30 | 0.287 |
| 7 | 0.32 | 0.316 |
| 14 | 0.31 | 0.317 |
| 21 | 0.31 | 0.318 |

The parameters in the model $(a^*, k^*, \lambda^*, b^*, \beta^*, \Lambda^*)$ are determined from the condition

$$\min_{(a,k,\lambda,b,\beta,\Lambda)} Z(a,k,\lambda,b,\beta,\Lambda) = Z(a^*,k^*,\lambda^*,b^*,\beta^*,\Lambda^*). (27)$$

In the minimization process we considered restrictions

$$a > 0,\ b > 0,\ k > 0,$$

since $a$ and $b$ have meaning of relaxation times and $k$ is connected with diffusion coefficient. Also,

$$\lambda \geq 0, \Lambda \geq 0,$$

as this is required by the definition of General fractional derivative. Finally, since we are dealing with Fickian diffusion, the function $m_2(t), t \geq 0$ must be increasing. Since fractional derivative Eq. (7) for $\beta > 0$ has oscillatory, we must have

$$0 \leq \beta \leq 1.$$

Fitting parameters for GFD model of gentamicin release from HAP/PVA/CS/Gent coating are presented in Table 2.

**Table 2.** Fitting parameters for different models of gentamicin release from HAP/PVA/CS/Gent coating according to Eq. (27)

| Parametar | GFD model |
|---|---|
| a | 7.7x10$^{-5}$ |
| b | 0.1697 |
| $\lambda$ | 9.5x10$^{-4}$ |
| $\Lambda$ | 0.170 |
| $k$ (cm$^3$/day) | 2.04x10$^{-5}$ |
| $D$ (cm$^2$ s$^{-1}$) | 7.63x10$^{-7}$ |
| $\beta$ | 1 |
| $Z$ | 0.000300 |

Finally, we determined the diffusion coefficient of gentamicin, *D,* from coefficient *k.* In Eq. (13) on the left-hand side, for Fick's interpretation of coefficient *k,* we used $k_1 V_1 = k_2 V_2 = k$, so $\frac{k}{V_1} = k_1$. Diffusion coefficient *D,* may be then determined from $k_1$:

$$D = \frac{k/V_1}{A \times 24 \times 3600} = 7.634 \times 10^{-7}\ \mathrm{cm}^2/\mathrm{s}. \tag{28}$$

where $A$=1 cm$^2$ is the coating surface area. This value was calculated from our novel GFD model for entire time period of gentamicin release. The corresponding value of the square residual is $Z(a^*, k^*, \lambda^*, b^*, \beta^*, \Lambda^*) = 0.000300$.

# 4. Conclusion

The main results of our work are summarized as:

1. Novel antibacterial bioceramic HAP/PVA/CS/Gent coating on Ti substrate was successfully produced for bone tissues implants, in order to enable a drug delivery directly at the infection site and avoid the systemic antibiotic administration in the case of post-operative hospital infections.
2. Gentamicin release study indicated "burst" release effect in the first 48 h, with ~ 30% of total gentamicin released from the HAP/PVA/CS/Gent coating which is beneficial for the blockage of biofilm formation, followed by slow and steady release in the later time period.
3. We formulated novel two compartmental mathematical model to describe the release of gentamicin. It is based on General fractional derivative of distributed order and generalizes earlier models with fractional derivatives.
4. The experimental values corresponded very well with the model calculated values. In addition, we determined the value of the diffusion coefficient of gentamicin based on the model approximating the entire time period of the release.

# Acknowledgements

This research is supported by the Serbian Academy of Sciences and Arts, Contract No. F-52 (VMS), University Union - Nikola Tesla, Belgrade, Republic of Serbia, Contract No. 1318/1 (VMS), and the Ministry of Science, Technological Development and Innovation, Republic of Serbia, Contract No. 337-00-110/2023-05/13 and 451-03-136/2025-03/200287 (AJ, MS) and 451-03-136/2025-03/200023 (MDj).

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# Otpuštanje gentamicina iz biokeramičke prevlake na bazi hidroksiapatita na titanu

**Vesna Mišković-Stanković[1,*], Marija Djošić[2], Ana Janković[3], Milena Stevanović[3], Teodor M. Atanackovic[4]**

[1]Fakultet za ekologiju i zaštitu životne sredine, Univerzitet Union - Nikola Tesla, 11000 Beograd, Srbija
[2]Institut za tehnologiju nuklearnih i drugih mineralnih sirovina, 11000 Beograd, Srbija
[3]Inovacioni centar Tehnološko-metalurškog fakulteta Univerziteta u Beogradu, 11000 Beograd, Srbija
[4]Fakultet tehničkih nauka, Univerzitet u Novom Sadu, 21000 Novi Sad, Srbija

[*]**Autor za dopisivanje:** vesna.miskovicstankovic@unionnikolatesla.edu.rs

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**Apstrakt:** Nova antibakterijska biokeramička hidroksiapatit/poli(vinil-alkohol)/hitozan/gentamicin (HAP/PVA/CS/Gent) prevlaka na titanu je uspešno dobijena za primenu u implantatima koštanog tkiva, da bi omogućila isporuku lekova direktno na mestu infekcije i da bi se izbegla sistemska administracija antibiotika u slučajevima postoperativne bolničke infekcije. Ovaj rad predstavlja novi dvokompartmentski model sa Generalnim frakcionim izvodom raspoređenog reda koji je korišćen za ispitivanje otpuštanja gentamicina u okolinu. Profil otpuštanja gentamicina je prikazan kao vremenska zavisnost odnosa mase otpuštenog gentamicina, odredjenog tečnom hromatografijom visoke performancije (HPLC), i početne mase gentamicina u prevlaci. Dokazano je da predloženi dvokompartmentski model sa Generalnim frakcionim izvodom raspoređenog reda pokazuje odlično slaganje sa eksperimentalnim vrednostima, i omogućava određivanje koeficijenta difuzije gentamicina u celom vremenskom periodu.

**Ključne reči:** Prevlake, biokeramika, hidroksiapatit, titan, gentamicin, difuzija, modelovanje

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**Global sustainability challenges**
2025; 3(1): 24-30
https://gsc.unionnikolatesla.edu.rs/index.php/gsc
UDC: 628.477.6.036(497.113)
ISSN: 2956-1051 (Online)

# Construction and Demolition Waste and Recycling Opportunities: A Case Study of Novi Sad, Serbia

**Sanja Mrazovac Kurilić[1, *], Vladanka Presburger Ulniković[1]**

[1]Union-Nikola Tesla University, Belgrade, Serbia

[*]**Corresponding author:** smrazovac@unionnikolatesla.edu.rs

**To cite this article:**
Mrazovac Kurilić, S. & Presburger Ulniković, V. (2025). Construction and Demolition Waste and Recycling Opportunities: A Case Study of Novi Sad, Serbia. *Global sustainability challenges, 3*(1), pp. 24-30.

**Received**: July 10, 2024; **Accepted**: Nov 28, 2025; **Published**: Dec 22, 2025

**Abstract:** Construction and demolition waste (CDW) poses a significant environmental and economic challenge in urban areas, especially in rapidly developing cities. This study examines the types, quantities, and management practices of CDW in Novi Sad, Serbia, emphasizing recycling potential and sustainability. Drawing on data from local environmental authorities and recent waste generation reports (City of Novi Sad, 2024; SEPA, 2024), we identify key waste types and evaluate current recycling practices and infrastructure. The analysis reveals that soil and stones constitute the largest share of CDW in Novi Sad, with concrete, bricks, and metals also playing major roles. Although legal frameworks require selective collection and recycling, actual recycling rates are low. The paper proposes strategies to enhance recycling efficiency, such as investing in material recovery facilities, enforcing regulations more rigorously, and fostering public-private partnerships. These findings aim to guide local policy and advance circular economy goals and environmental protection.

**Keywords:** Construction waste, Demolition waste, Recycling, Novi Sad, Circular economy, Serbia, Waste management

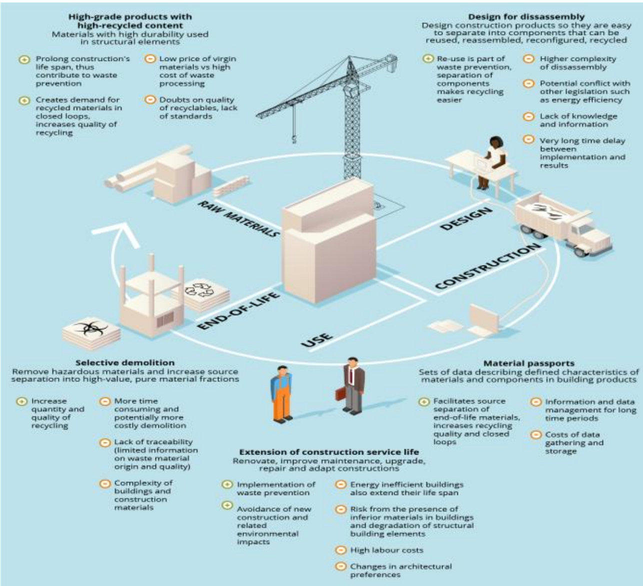
## 1. Introduction

Construction and demolition waste (CDW) is one of the heaviest and most voluminous waste streams generated in the European Union and globally (Fig. 1). It comprises a wide range of materials including concrete, bricks, wood, glass, metals, plastic, and excavated soil and stones. The mismanagement of this type of waste can result in significant environmental degradation, inefficient resource use, and increased pressure on landfills.

It is a rapidly growing waste stream worldwide, closely linked to urban development, population growth, and infrastructure expansion. According to the European Commission, CDW accounts for approximately 25%–30% of all waste generated in the European Union, making it the single largest waste stream by volume (European Commission, 2020). This trend is not limited to Europe; countries around the world are facing similar challenges in managing the environmental impact of construction activities (Fig. 2).

In high-income countries, significant attention has been given to reducing, reusing, and recycling CDW. For example, in the Netherlands, approximately 98% of CDW is recycled or reused, primarily as secondary raw materials in road base layers or new construction. This success is attributed to strong regulatory frameworks, market incentives for recycled materials, and the integration of circular economy principles into national waste strategies (Coelho and de Brito, 2011).

**Figure 1.** EU challenges and opportunities diagram – illustrates CDW flows,




issues, and strategic solutions in Europe.

Germany also demonstrates a robust system, where over 90% of mineral-based CDW is recycled. The country benefits from well-developed infrastructure for sorting and processing, as well as legal mandates for selective demolition and material recovery. In contrast, the United States still struggles with inconsistent CDW management practices across states. While some states like California have implemented stringent recycling targets and green building codes, others continue to rely heavily on landfilling due to low tipping fees and limited policy enforcement.

Emerging economies face even greater challenges. In rapidly urbanizing countries such as India and China, the volume of CDW has surged dramatically over the past decade. In China, it is estimated that the annual generation of CDW exceeds 3 billion tons, yet only a small percentage—less than 10%—is effectively recycled (Zhao et al., 2020). The lack of infrastructure, public awareness, and economic incentives contributes to low recycling rates and widespread illegal dumping.

India presents a similar case. With rapid urban sprawl and infrastructure development, CDW generation is expected to rise sharply. Despite the launch of the Construction and Demolition Waste Management Rules in 2016, implementation remains weak, especially at the municipal level. Studies indicate that over 50% of CDW in Indian cities remains uncollected or is dumped in open areas, leading to air and water pollution, encroachment on natural habitats, and public health risks.

In Latin America and Africa, data on CDW generation and treatment is often scarce. However, anecdotal evidence and case studies suggest that informal recycling practices are common, often carried out by unregulated workers who recover valuable materials such as metals and wood. While these activities provide income opportunities, they also expose workers to hazardous conditions and contribute to environmental degradation due to lack of safety measures and pollution control.

On a global scale, the push toward sustainable construction practices and circular economy models has sparked interest in improving CDW management. Innovations such as modular construction, prefabrication, and design-for-disassembly are being explored to reduce waste generation at the source. Furthermore, international initiatives like the UN's Sustainable Development Goal 11 (Sustainable Cities and Communities) emphasize the importance of resource-efficient construction and responsible waste management (Shao et al., 2022).

Despite these efforts, major obstacles remain, including the high cost of recycling infrastructure, inconsistent legislation, lack of standardized classification systems for waste, and limited market demand for recycled construction materials. Addressing these barriers requires coordinated action among policymakers, industry stakeholders, and the public (Yu et al., 2025).

In conclusion, while some countries have made significant progress in managing CDW sustainably, many others lag behind due to financial, institutional, and technical constraints. Lessons from global best practices can inform the development of more effective policies and systems in countries like Serbia, where urban centers such as Novi Sad are experiencing growth and increased pressure on waste management infrastructure.

Recycling construction and demolition waste (CDW) has emerged as a central strategy in the transition toward a circular economy in the construction sector. Successful recycling not only conserves natural resources and reduces landfill usage but also decreases greenhouse gas emissions and energy consumption associated with the production of virgin construction materials. However, recycling practices vary widely across regions due to differences in regulatory frameworks, economic incentives, infrastructure availability, and technological development (European Environment Agency, 2020).


**Figure 2.** Global CDW management market infographic

European countries are among the global leaders in CDW recycling. The European Union's Waste Framework Directive (2008/98/EC) mandates a minimum 70% recovery rate (by weight) for non-hazardous CDW. Several countries have exceeded this target through coordinated efforts involving regulation, incentives, and infrastructure investment (European Commission, 2016).

In many developing countries, formal recycling systems are underdeveloped, but informal practices play a significant role. In Brazil, for example, a large portion of CDW is recycled by small-scale enterprises that process debris into handmade bricks, pavers, and fill material. Municipalities such as Belo Horizonte have piloted public CDW collection and recycling centers, with some success in diverting materials from illegal dumping sites (Tseng, 2021).

South Africa has launched initiatives such as the Waste Economy Master Plan to increase CDW recovery through extended producer responsibility and green job creation. Pilot projects in Cape Town have demonstrated the viability of crushing concrete and masonry into secondary materials for use in low-cost housing developments.

Several technological innovations are advancing the global capacity to recycle CDW more efficiently. Mobile crushers and screening units now allow on-site processing of concrete and masonry waste, reducing transportation emissions and costs (Ragossnig, 2020). Artificial intelligence (AI) and robotics are increasingly being used for automated sorting and deconstruction, improving accuracy and material purity (Fig. 3). (Saka et al., 2024)

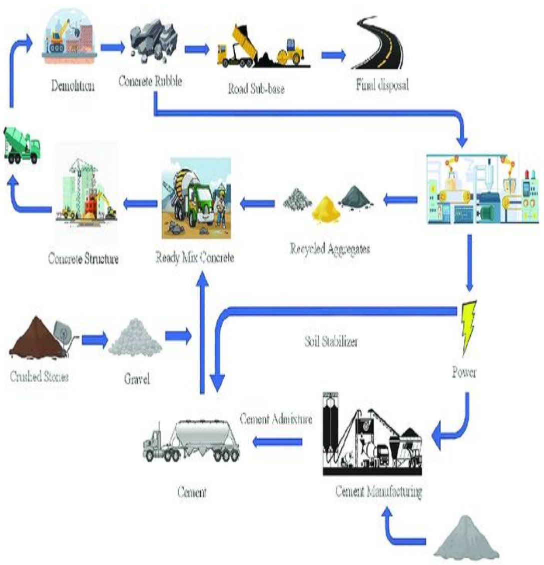



**Figure 3.** Production and recycling process schematic – detailed flow of CDW materials to recycled aggregates.

Materials science research has also expanded the potential applications of recycled CDW. For example, fine recycled aggregates are now being integrated into prefabricated concrete panels and non-structural building elements. Carbon capture techniques are being explored in the curing process of recycled concrete blocks to improve environmental performance (Papamichael et al, 2023).

Despite the progress in many parts of the world, CDW recycling still faces significant challenges, including the lack of standardized quality specifications, low demand for recycled products, contamination of materials, and weak enforcement of waste regulations. Financial incentives, public procurement standards, and urban planning policies that prioritize reuse and recycling are critical to overcoming these barriers (Bajwa et al., 2025).

Governments, construction companies, and civil society must work collaboratively to scale up successful models and integrate circular thinking into the life cycle of buildings. As global demand for raw materials continues to rise, the role of CDW recycling will become even more central to achieving sustainability goal (Cook and Velis, 2022).

As global demand for raw materials continues to rise, the role of CDW recycling will become even more central to achieving sustainability goals (Cook and Velis, 2022). Governments, construction companies, and civil society must work collaboratively to scale up successful models and integrate circular thinking into the life cycle of buildings.

In Serbia, and particularly in the city of Novi Sad, urban expansion and infrastructure development have led to increasing amounts of CDW. Although Serbian legislation aligns with EU directives to some extent, the implementation and efficiency of recycling practices vary significantly across municipalities. Novi Sad, as the second-largest city in Serbia, provides a representative case for examining the challenges and opportunities in CDW recycling (SEPA 2024; Statistical Office of Republic of Serbia, 2024).

An important recent development in the Serbian regulatory framework is the new Regulation on the Management of Construction Waste (Regulation, 2024). This Regulation introduces the obligation to prepare and approve a Construction Waste Management Plan for construction, demolition, and removal works. Importantly, the Plan must be prepared already at the building permit project stage, which strengthens the responsibility of the investor/owner and enables earlier and more systematic control of CDW generation, sorting, storage, and final treatment. This measure provides a concrete opportunity for improving construction waste management in cities such as Novi Sad in the near future.

This paper aims to analyze the quantities and types of CDW generated in Novi Sad, assess current waste management practices, and propose sustainable solutions to enhance recycling rates. Using data collected from local environmental reports and statistical analyses, this research contributes to the understanding of urban waste dynamics in the Western Balkans and offers practical policy recommendations.

## 2. Materials and Methods

This study employs a descriptive and analytical methodology based on the review and processing of official data on construction and demolition waste generated in the territory of Novi Sad. The municipal dataset used in this study is based on several key city-level documents and reports, including: Local Waste Management Plan For the City of Novi Sad for the Period 2023-2032. ("Official Gazette of the City of Novi Sad", No. 21/2023) 2023–2032 (City of Novi Sad), the Annual Report on Generated and Processed Waste for the City of Novi Sad, reports from licensed construction and demolition waste operators active in the Novi Sad administrative area, and relevant chapters of the

Environmental Protection Programme of the City of Novi Sad. These documents provide detailed information on CDW quantities, composition, and current management practices at the local level. Primary data were sourced from the official reports on generated waste quantities, which presents detailed information on the types and volumes of CDW collected and categorized by composition.

The analysis includes the classification of waste types according to standard categories such as concrete, bricks, ceramics, wood, glass, plastic, metals, cables, insulation materials, gypsum-based materials, and soil and stones. Quantitative data were analyzed to determine the relative proportions of each waste type and to evaluate trends in waste generation.

Supplementary data on legal frameworks, infrastructure availability, and recycling practices in Serbia and the city of Novi Sad were obtained from local municipal sources, academic literature, and international guidelines on construction waste management.

# 3. Results

The main source of data used in this study includes data collected from construction sites and waste management operators in Novi Sad for a recent one-year period. These data form the empirical basis for evaluating current waste management practices and estimating the potential for material recovery and recycling in Novi Sad's construction sector (City of Novi Sad, 2024).

The data analysis reveals that soil and stones constitute by far the largest portion of CDW in Novi Sad, accounting for over 90% of the total volume. This category, often associated with excavation and earthworks, poses specific challenges for reuse and recycling due to contamination and variability in composition.

Following soil and stones, bricks and concrete are the most significant contributors to the CDW stream. These materials have well-established recycling methods and are often used as secondary aggregates in road construction or as base materials in new building projects. However, their actual recovery rates remain modest due to lack of separation at source, insufficient infrastructure, and limited market demand for recycled materials.

Metals, particularly iron and steel, represent a valuable waste stream with high recycling potential and existing markets. Despite their relatively low volume compared to inert materials, they offer economic incentives for recovery.

Other waste types such as ceramics, wood, glass, plastics, and insulation materials appear in much smaller quantities. Their recycling potential is currently underutilized, mostly due to technological and economic constraints. These materials require specialized treatment facilities that are not yet sufficiently developed in Novi Sad or the broader region.

The quantitative analysis of CDW composition in Novi Sad is presented in Figure 4. A horizontal bar chart was used to effectively visualize the significant disparity in the proportions of different waste types, particularly to highlight the very small but potentially valuable fractions.

The analysis reveals the extreme dominance of soil and stones, which constitute the vast majority of the waste stream at 93.22%. The second and third most prevalent materials are bricks (2.80%) and concrete (2.53%), which are clearly visible and comparable on the chart. All other materials each account for less than 1.0% of the total CDW. Among these, gypsum-based materials (1.00%) and metals, specifically iron and steel (0.25%), are the most significant. The remaining fractions (wood, cables, insulation, ceramics, glass, and plastic)

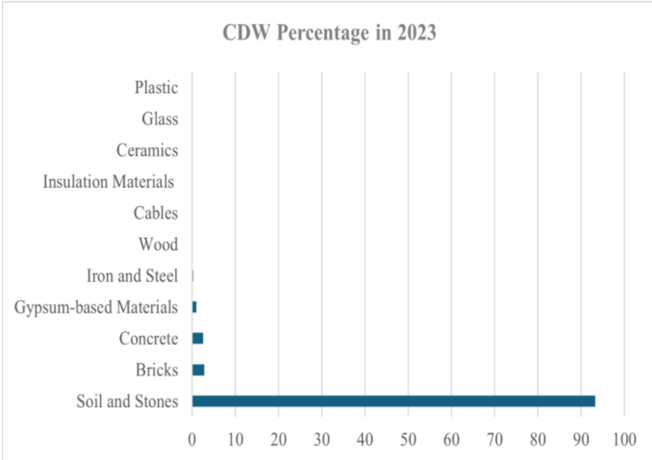



**Figure 4.** Horizontajl bar chart showing the composition of CDW in Novi Sad by material type.

collectively represent less than 0.20% and are all easily identifiable on the horizontal bar chart, which allows for a clear comparison of their minimal but non-zero values.

This composition is typical for urban construction sites and underscores the critical need for targeted management strategies for the mineral fraction (soil, stones, bricks, concrete) and the development of specialized recycling channels for the smaller, yet valuable, fractions like metals.

This composition illustrates the dominance of inert and mineral-based waste, which is typical for urban construction sites. It also underscores the need for systematic sorting and targeted investments in recycling infrastructure.

In the current context, CDW management in Novi Sad is primarily reliant on disposal, with limited instances of material recovery. Factors contributing to this situation include inadequate enforcement of construction waste regulations, lack of incentives for recycling, and the absence of well-equipped facilities. Public awareness regarding the benefits of recycling and circular construction practices also remains low.

To improve CDW recycling in Novi Sad, strategic interventions are needed. These may include the introduction of mandatory waste separation on construction sites, subsidies for recyclers, development of local markets for secondary materials, and stronger cooperation between municipalities and private companies. Moreover, incorporating circular economy principles into urban planning and public procurement processes can provide long-term benefits for both the environment and the local economy.

# 4. Conclusion

The findings of this study, visually emphasized by the horizontal bar chart analysis, unequivocally demonstrate the overwhelming dominance of soil and stones (93.22%) in the CDW stream of Novi Sad. This composition presents both a significant challenge and a clear opportunity. While the recycling potential for inert mineral fractions (bricks, concrete) and valuable metals exists, the current infrastructure, regulatory enforcement, and economic incentives remain insufficient to support a transition to sustainable waste management practices.

Improving the CDW recycling system in Novi Sad requires a multi-faceted and modern approach, drawing on successful global practices:

Infrastructure Investment: The establishment of a modern, regional CDW recycling center equipped with mechanical screening and crushing technology is paramount. This facility should specifically handle the large volume of soil and stones, focusing on screening for contamination and processing for reuse in earthworks and construction backfill, following the examples set by Western European countries.

Regulatory Strengthening and Enforcement: Moving beyond existing mandates, stricter enforcement of waste separation at source on construction sites is needed. This should be complemented by the introduction of digital waste tracking tickets to monitor CDW flows from generation to final disposal or recycling, ensuring transparency and accountability.

Economic and Market Incentives: To stimulate demand, public procurement policies must be updated to mandate the use of recycled CDW materials (e.g., recycled concrete aggregate, processed soil) in municipal infrastructure projects. Additionally, the introduction of a reduced VAT rate for products containing recycled content could boost market competitiveness, mirroring successful incentives in the EU.

Targeted Material Recovery: While managing the mineral fraction is crucial, strategies must also create pathways for high-value, low-volume streams. This includes promoting on-site separation of metals (which have a ready market) and exploring innovative solutions for gypsum recycling, thus embracing the principle of material-specific valorization.

Data-Driven Policy and Awareness: Enhancing the quality and transparency of CDW data is fundamental for informed policy-making. Concurrently, professional training programs for construction managers and architects on circular economy principles and deconstruction techniques are essential to reduce waste generation at the source.

By adopting these measures, which combine infrastructure modernization, regulatory diligence, economic incentives, and targeted material recovery, Novi Sad can transform its CDW management from a linear disposal model to a circular, resource-efficient system. This transition is not only critical for achieving local and national environmental objectives but also for aligning with broader European Green Deal goals and building a more resilient and sustainable construction sector.


# Acknowledgements

This work was supported by City Administration for Environmental Protection, City of Novi Sad , NP 2609/24 (VI-501-2/2024-14в-15).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# Otpad od građenja i rušenja i mogućnosti njegove reciklaže: Studija slučaja Novog Sada, Srbija

**Sanja Mrazovac Kurilić[1, *], Vladanka Presburger Ulniković[1]**

[1]Fakultet za ekologiju i zaštitu životne sredine, Univerzitet Union-Nikola Tesla, Beograd, Srbija

[*]**Autor za dopisivanje: smrazovac@unionnikolatesla.edu.rs**

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**Apstrakt:** Otpad od građenja i rušenja predstavlja sve veći ekološki i ekonomski izazov u urbanim područjima, posebno u gradovima koji se brzo razvijaju. Ova studija ispituje vrste, količine i prakse upravljanja otpadom od građenja i rušenja u Novom Sadu, Srbija, sa fokusom na potencijal recikliranja i održivost. Koristeći podatke od lokalne samouprave i iz nedavnih izveštaja o generisanju otpada (Grad Novi Sad, 2024; SEPA, 2024), identifikovane su ključne vrste otpada i procenjene trenutne prakse recikliranja i infrastrukturu. Analiza pokazuje da zemlja i kamen čine najveći deo otpada od građenja i rušenja u Novom Sadu, dok materijali poput betona, cigle i metala takođe igraju značajnu ulogu. Iako pravni okvir zahteva selektivno sakupljanje i recikliranje, stvarne stope reciklaže su niske. Rad predlaže strategije za poboljšanje efikasnosti reciklaže, uključujući ulaganja u objekte za oporavak materijala, strožiju primenu propisa i javno-privatna partnerstva. Ovi nalazi imaju za cilj da informišu lokalnu politiku i doprinesu širim ciljevima cirkularne ekonomije i zaštite životne sredine.

**Ključne reči:** Građevinski otpad, Otpad od rušenja, Reciklaža, Novi Sad, Cirkularna ekonomija, Srbija, Upravljanje otpadom

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**Global sustainability challenges**
2025; 3(1): 31-37
https://gsc.unionnikolatesla.edu.rs/index.php/gsc
UDC: 340.137:349.6(4-672EU:497.11)
551.583(497.11)
ISSN: 2956-1051 (Online)

# Serbia’s Path to Climate Resilience: A Critical Assessment of the Climate Change Law and Its Implications

**Vladanka Presburger Ulniković[1*], Anđelka Radosavljević[2], Bojana Božilović[1], Ana Ćirišan[1]**

[1]Faculty of Ecology and Environmental Protection, University Union-Nikola Tesla, Cara Dušana 62-64, Belgrade11000, Serbia
[2] Serbian Environmental Protection Agency, Ruže Jovanovića 27a, Belgrade11000, Serbia

[*]**Corresponding author:** vladanka.gsc@unionnikolatesla.edu.rs

**To cite this article:**
Presburger Ulniković, V. *et.al.* (2025). Serbia’s Path to Climate Resilience: A Critical Assessment of the Climate Change Law and Its Implications. *Global sustainability challenges, 3*(1): 31-37.

**Received**: Nov 3, 2025; **Accepted**: Nov 12, 2025; **Published**: Dec 22, 2025

**Abstract:** Serbia's Climate Change Act (2021) represents a key element in developing a modern national climate governance system, aligned with the Paris Agreement and European Union policies. This paper provides an analytical overview of its potential to contribute to Serbia's climate resilience through examination of the institutional architecture, monitoring mechanisms, and compliance with contemporary climate governance approaches. By introducing comprehensive frameworks for mitigation, adaptation, and reporting, the Act establishes a solid foundation for further development of climate policies and marks an important step toward long-term transformation of the environmental protection system. At the same time, the analysis identifies certain areas where further strengthening of the integration of scientifically grounded methodologies and enhancement of participatory processes is possible, which can be viewed as opportunities for further development and alignment with international practices. Drawing on contemporary literature on climate governance (Braithwaite et al., 2007; Bulkeley, 2021; Triyanti et al., 2023), the paper indicates that the Act provides a stable foundation upon which, with consistent institutional support and continued intersectoral collaboration, an effective and sustainable climate policy system can be built. In this sense, the continued implementation of the Act is expected to contribute to the gradual strengthening of Serbia's climate resilience and progress toward long-term development goals.

**Keywords:** Climate Change Law, greenhouse-gas emissions, MRV, CBAM, EU ETS, energy transition, climate policy

## 1. Introduction

The escalating impacts of climate change underscore the imperative for robust national governance frameworks. Serbia's adoption of the Climate Change Law in 2021 marked a pivotal transition from ad-hoc measures to a structured policy approach, intended to align with the Paris Agreement and the EU acquis. The law establishes a comprehensive system for mitigation, adaptation, monitoring, reporting, and verification (MRV), targeting a sectoral transformation in line with Serbia's pledge to reduce greenhouse gas (GHG) emissions, as detailed in its Third Nationally Determined Contribution (Republika Srbija, 2025). This goal is further underscored in the national Low-Carbon Development Strategy (Republika Srbija, 2023) and recent assessments (UNDP Serbia, 2025).

Serbia’s updated NDC (submitted December 2022, accepted by UNFCCC) commits the country to reducing greenhouse gas emissions by 33.3 % by 2030 compared to 1990 levels — a significantly more ambitious baseline than the previous 9.8 % reduction against 2010 (Republika Srbija, 2025).

However, as seminal scholarship on regulation and governance asserts, the mere existence of a legal instrument is insufficient to guarantee its effectiveness (Braithwaite et al., 2007). Achieving transformative climate action requires institutional capacity, cross-sectoral coordination, science-driven planning, and inclusive participatory processes

(Bulkeley, 2021; Bosselmann, 2016). This aligns with broader European assessments of climate progress (European Environment Agency, 2024) and global scenario analyses (UNEP, 2024; IEA, 2023).

This paper critically examines Serbia's Climate Change Law through this conceptual lens, assessing its institutional design, operational mechanisms, and practical implementation through illustrative case studies. The analysis aims to identify key governance gaps and offer evidence-based recommendations for enhancing the law's contribution to Serbia's climate resilience, a goal further underscored in the national Low-Carbon Development Strategy (Republika Srbija, 2023). The analysis aims to identify key governance gaps and offer evidence-based recommendations for enhancing the law's contribution to Serbia's climate resilience, a goal further underscored in the national Low-Carbon Development Strategy (Republika Srbija, 2023) and recent assessments (UNDP Serbia, 2025).

# 2. Methodological Approach

The methodology includes a review of Serbia's Climate Change Law (2021), its Nationally Determined Contribution (NDC), and relevant EU legislation, including the EU Climate Law and the Carbon Border Adjustment Mechanism (CBAM) (European Commission, 2022). This assessment employs a qualitative analytical framework that synthesizes legal, institutional, and policy dimensions to evaluate the nascent climate governance system in Serbia. The methodology is structured around four interconnected pillars:

(1) **Legal and Policy Analysis:** A review of the Climate Change Law (2021), Serbia's Nationally Determined Contribution (NDC), and relevant EU legislation, including the EU Climate Law and the CBAM (European Commission, 2022).

(2) **Scientific and Governance Literature Review:** Engagement with contemporary scholarship on climate governance effectiveness (Bulkeley, 2021), the role of law in sustainability transitions (Bosselmann, 2016), the critical function of scenario frameworks (Triyanti et al., 2023), and the behavioral dimensions of institutional change (Alavosius & Houmanfar, 2020). Participatory governance practices are also considered, drawing on ongoing efforts to improve policy planning (EU za tebe, 2025).

(3) **Institutional Mapping:** Analysis of the roles and responsibilities assigned to various state and sub-national bodies to identify potential coordination challenges and fragmentation.

(4) **Illustrative Case Study Examination:** Exploration of high-profile projects, such as the Vinča Waste-to-Energy facility and the modernization of the TENT power plant, to ground the analysis in practical implementation contexts, using publicly available official documents and reports.

This multi-faceted approach facilitates a holistic evaluation of both the law's structural provisions and its initial real-world impacts.

# 3. National Context and Institutional Architecture

Serbia's climate policy is shaped by its international commitments and economic structure, which is characterized by a significant reliance on fossil fuels. The energy sector remains the dominant source of GHG emissions, with official inventories reporting emissions of approximately 63.7 $MtCO_2e$ in 2022 (SEPA, 2025), as also reflected in the First Biennial Transparency Report (Republika Srbija, 2024).

The Climate Change Law creates a multi-level institutional framework to address these challenges. However, this distribution of responsibilities, detailed in Table 1, inherently presents risks of coordination failures and policy incoherence, a well-documented challenge in multi-level governance systems (Scown et al., 2023; Bulkeley, 2021) that continues to be a significant hurdle, as noted in the most recent report.

***Table 1.*** Institutional Responsibilities under the Climate Change Law

| Institution | Key Responsibilities |
|---|---|
| Ministry of Environmental Protection | Overall coordination, national planning, UNFCCC reporting |
| Environmental Protection Agency (SEPA) | National GHG inventory, e-GHG platform, MRV system management |
| Hydrometeorological Service of Serbia (RHMZ) | Climate data collection, modelling, early warning systems |
| Sectoral ministries (energy, agriculture, transport, etc.) | Sector-specific mitigation and adaptation plans |
| Local self-governments | Local climate action plans, vulnerability assessments, public engagement |
| Inter-ministerial Council for Climate Change (established March 2021) | Cross-sectoral coordination (currently with limited executive power) |
| Institution | Key Responsibilities |

# 4. Core Implementation Mechanisms

The cornerstone of the law is the establishment of a Monitoring, Reporting, and Verification (MRV) system for industrial emissions, mirroring the structure of the EU Emissions Trading System. This system obliges operators of large installations to monitor their GHG emissions, submit annual reports, and have these reports verified by accredited entities. The operationalization of this system has been supported by the development of a digital platform, e-GHG, which streamlines data submission and enhances transparency (UNDP Serbia, 2023). A critical implementation milestone was the deadline of 30 June 2024 for existing operators to apply for GHG emission permits, signaling a tangible shift towards a regulated carbon management regime and supported by the launch of the e-GHG digital platform (e-GHG, 2025).

As noted above, the following are the core implementation milestones (2021–2025):

• March 2021 – Law adopted and Inter-ministerial Council formally established

• 1 March 2024 – e-GHG digital platform officially launched (SEPA, 2025)

• 30 June 2024 – Legal deadline for existing installations to apply for GHG emission permits

• 2023–2025 – First Continuous Emission Monitoring Systems (CEMS) installed at TENT A/B, Kostolac, and Vinča WtE facility. The introduction of a CEMS is a direct response to the requirements of the Climate Change Act regarding MRV (EPS, 2023).

• Ongoing – Preparation of integrated National Energy and Climate Plan (NECP) and Long-Term Strategy (LTS) — both significantly delayed (expected adoption 2026 at earliest)

# 5. Case Studies: Bridging Law and Practice

### *5.1. The Vinča Waste-to-Energy Project*

The Vinča WtE plant represents a significant shift in urban metabolism and waste management for Belgrade. By processing municipal waste to generate energy, the project directly contributes to mitigating methane emissions from landfills, a potent greenhouse gas. Project documentation highlights its role in reducing overall GHG emissions from the waste sector and advancing the circular economy (Beo Čista Energija, 2022). This case illustrates the law's objective to drive decarbonization in key sectors through large-scale infrastructure modernization.

### *5.2. Emission Monitoring in the Energy Sector*

The introduction of Continuous Emission Monitoring Systems (CEMS) at facilities like the TENT thermal power plant is a direct response to the MRV requirements of the Climate Change Law. The implementation of CEMS is a foundational step for accurate data collection, which is a prerequisite for identifying emission reduction opportunities and informing decarbonization strategies (EPS, 2023). This underscores the law's role in catalyzing the adoption of essential monitoring technologies in high-emission industries.

# 6. Synthesis: Visualizing the Governance Pathway

The interplay between the Law's foundational framework and its practical implementation challenges reveal a dynamic transition period in Serbia's climate policy. To crystallize this analysis, the pathway from legislative adoption to envisioned resilience is mapped below (Fig. 1), synthesizing key milestones, current crossroads, and future imperatives. This schematic synthesizes the transition from legislative foundation through operational implementation to the current critical juncture, where addressing governance gaps will determine the achievement of long-term climate resilience targets.

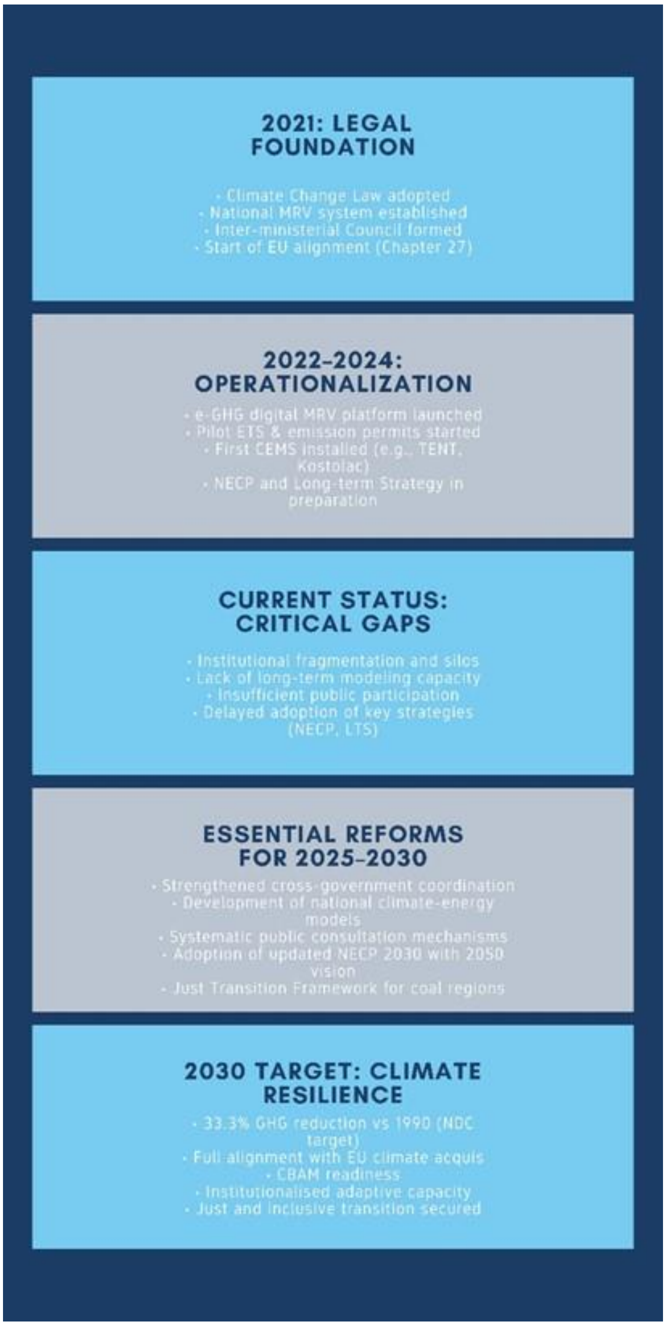


**Figure 1.** Serbia's Climate Governance Pathway. *

**Abbreviations: MRV = Monitoring, Reporting & Verification; e-GHG = national digital MRV platform; CEMS = Continuous Emissions Monitoring Systems; WtE= Waste-to-Energy, a process that converts waste materials into usable forms of energy, such as electricity or heat; NECP National Energy and Climate Plan; ETS = Emission Trading System; LTS = Long-Term Strategy; NECP&LTS = National Energy and Climate Plan and the Long-Term Strategy for climate action.*

The e-GHG digital platform represents the central technical infrastructure of the Serbian climate system: the national MRV architecture and its digital platform, e-GHG. This platform represents the main data channel for monitoring, reporting and verification, supporting transparency and evidence-based policy in line with international best practices (Alavosius & Houmanfar, 2020; European Climate Advisory

Board, 2025). Through this structure, Serbia is institutionalizing a climate monitoring regime that reflects the methodologies of the EU ETS and the IPCC Emissions Guidelines (IPCC, 2022). Accredited verifiers (who are accredited exclusively by the Accreditation Body of Serbia - ATS) have an independent oversight role in the system, ensuring data integrity through compliance assessments, audits and methodological checks . This aligns with global experience showing that verification bodies significantly improve the credibility and accountability of environmental governance systems (Bulkeley, 2021).

# 7. Strengths and Limitations of the Climate Change Law

This structured visualization offers a comparative lens to the law's advantages and vulnerabilities. Strengths shine in foundational elements: a comprehensive framework aligned with EU acquis like the EU-ETS Directive and Paris Agreement obligations, successful MRV system deployment for GHG inventory and projections, and emerging pilots such as the Just Energy Transition Plan. These enable cost-effective emission limits, adaptation programs, and public data transparency on vehicle emissions, positioning Serbia toward European Green Deal compatibility.

Limitations, however, crystallize at the crossroads, demanding urgent reforms. Without binding science-driven modeling (e.g., for 1.5°C pathways), projections lack rigor (Triyanti et al., 2023; UNEP, 2024; IEA, 2023; siloed ministries exacerbate bottlenecks in by-law enforcement and sectoral roadmaps (Scown et al., 2023; European Commission, 2025); and limited stakeholder engagement hampers ownership, as seen in ongoing gaps highlighted by civil society (Koalicija 27, 2025). Limitations, however, crystallize at the crossroads, demanding urgent reforms. Without binding science-driven modeling (e.g., for 1.5°C pathways), projections lack rigor (Triyanti et al., 2023); siloed ministries exacerbate bottlenecks in by-law enforcement and sectoral roadmaps (Scown et al., 2023; European Commission, 2025); and limited stakeholder engagement hampers ownership, as seen in ongoing gaps highlighted by civil society (Koalicija 27, 2025). The law's promising advisory roles and penalty regimes remain unrealized without deliberate governance upgrades in coordination, science integration, and participation to unlock the upper pathway toward resilient, decarbonized outcomes by 2030. These strengths position Serbia toward European Green Deal compatibility, though progress must be benchmarked against EU-wide trends (European Environment Agency, 2024). Project will contribute to a better environmental and climate change status and quality of life for citizens in the Republic of Serbia and support the implementation of the EU Green Agenda. As a candidate country, Serbia is already making efforts to align with EU policies and actions and achieve climate neutrality by 2050. (EU za tebe, 2025).

### *7.1. Policy Recommendations*

To translate the legislative framework into tangible climate outcomes, targeted enhancements are required across several governance domains. The following recommendations are proposed:

(1) **Institutional Strengthening:** Develop formal inter-ministerial coordination bodies with clear mandates and resources to overcome sectoral silos.

(2) **Embedding Scientific Robustness:** Legally mandate the development and use of national climate scenarios in line with IPCC methodologies to inform policy planning and track progress against long-term goals.

(3) **Enhancing Accountability:** Introduce clear performance indicators and reporting requirements for sectoral ministries and local governments to ensure the implementation of planned measures.

(4) **Fostering Inclusive Governance**: Establish legally defined channels for stakeholders and public participation in the development and revision of climate plans, drawing on best practices for participatory governance and ongoing efforts to improve policy planning. (EU za tebe, 2025).

(5) **Implementing a Just Transition**: Accelerate the adoption and funding of the Plan for Just Energy Transition to ensure a fair and structured phase-out of coal-dependent economies (Ministarstvo rudarstva i energetike, 2025).

# 8. Conclusion

Serbia's Climate Change Law undeniably provides the indispensable legal foundation for a coordinated national response to climate change, marking a decisive break from previous ad-hoc approaches. This analysis unequivocally demonstrates that the law represents a starting point rather than a complete solution, a point emphasized in the latest national strategic documents (Republika Srbija, 2023; Republika Srbija, 2025). It has successfully initiated crucial processes for monitoring emissions and planning for a low-carbon future, with the MRV system and illustrative projects like Vinča and TENT serving as tangible proof-of-concept. However, this analysis unequivocally demonstrates that the law in its current form represents a starting point rather than a complete solution. Its architectural scope, while commendable, is undermined by foundational weaknesses that risk rendering it a symbolic rather than a transformative instrument. The European Commission's 2025 Country Report for Serbia explicitly highlights the continued delay in adopting the integrated NECP and the insufficient empowerment of the Inter-ministerial Council as the two most critical obstacles to Chapter 27 progress.

The ultimate success of Serbia's climate policy will not be measured by the law's adoption, but by its capacity to drive tangible emission reductions and build systemic resilience. This hinges entirely on subsequent regulatory and policy efforts to address its core weaknesses, a point emphasized in the latest national strategic documents (RoS, 2025) and international assessments (European Commission, 2025).

Second, building cohesive institutional capacity and mandating coordination is critical to overcome the pervasive fragmentation that currently threatens implementation. Third, establishing clear accountability mechanisms and performance indicators is essential to translate plans into actionable results and ensure that institutions are answerable for their climate commitments. Finally, embracing participatory democracy is not merely about fairness; it is about harnessing societal knowledge and building the public mandate necessary for difficult transitions.

The external pressures, most notably the EU's CBAM and the escalating physical impacts of climate change, make inaction a costly and increasingly unviable option. External pressures are reinforced by global findings on emissions gaps and energy transitions (UNEP, 2024; IEA, 2023).

The European Commission's 2025 Country Report for Serbia explicitly highlights the continued delay in adopting the integrated NECP and the insufficient empowerment of the Inter-ministerial Council as the two most critical obstacles to Chapter 27 progress (European Commission, 2025).

By embarking on these essential reforms, Serbia has the opportunity to solidify its climate governance framework, protect its economic interests, and navigate a more secure, sustainable, and equitable developmental path. The journey from a foundational legal text to a transformative governance system is complex and demands sustained political will, but it is the only path toward genuine climate resilience.

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# Put Srbije ka otpornosti na klimatske promene: Kritička procena Zakona o klimatskim promenama i njegovih implikacija

**Vladanka Presburger Ulniković[1*], Anđelka Radosavljević[2], Bojana Božilović[1], Ana Ćirišan[1]**

[1]Fakultet za ekologiju i zaštitu životne sredine, Univerzitet „Union" Cara Dušana 62-64, Beograd 11000, Srbija

[3]Agencija za zaštitu životne sredine Srbije, Ruže Jovanovića 27a, Beograd 11000, Srbija*

**Autor za dopisivanje:** vladanka.gsc@unionnikolatesla.edu.rs

**Apstrakt:** Zakon o klimatskim promenama Srbije (2021) predstavlja ključni element u razvoju modernog nacionalnog sistema klimatskog upravljanja, usklađenog sa Pariskim sporazumom i politikama Evropske unije. Ovaj rad daje analitički pregled njegovog potencijala da doprinese klimatskoj otpornosti Srbije kroz razmatranje institucionalne arhitekture, mehanizama monitoringa i usklađenosti sa savremenim pristupima klimatskom upravljanju. Uvođenjem sveobuhvatnih okvira za mitigaciju, adaptaciju i izveštavanje, zakon uspostavlja čvrstu osnovu za dalji razvoj klimatskih politika i predstavlja važan korak ka dugoročnoj transformaciji sistema zaštite životne sredine.Istovremeno, analiza prepoznaje određene oblasti u kojima je moguće dodatno ojačati integraciju naučno utemeljenih metodologija i unaprediti participativne procese, što se može posmatrati kao prilika za dalji razvoj i usklađivanje sa međunarodnim praksama. Oslanjajući se na savremenu literaturu o klimatskom upravljanju (Braithwaite et al., 2007; Bulkeley, 2021; Triyanti et al., 2023), rad ukazuje da zakon predstavlja stabilan temelj na kojem se, uz doslednu institucionalnu podršku i nastavak međusektorske saradnje, može graditi efikasan i održiv sistem klimatskih politika. U tom smislu, očekuje se da će dalja primena zakona doprineti postepenom jačanju klimatske otpornosti Srbije i napretku ka dugoročnim razvojnim ciljevima.

**Ključne reči:** Zakon o klimatskim promenama, emisije gasova staklene bašte, MRV, CBAM, EU ETS, energetska tranzicija, klimatska politika