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ENVIRONMENTAL AND HEALTH IMPACTS OF AGRICULTURAL WASTE COMBUSTION FOR BIOENERGY: A TOXICITY AND EMISSION REVIEW

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Abstract

This study examines the environmental and health impacts caused by the release of polycyclic aromatic hydrocarbons (PAHs) from the combustion of biomass and agricultural waste. Today, bioenergy plays a crucial role in global energy systems, accounting for 70 % of renewable energy consumption, 9.5 % of total primary energy supply, and 13 % of global gross final energy consumption. However, environmental pollution remains one of the greatest challenges of the 21st century, with serious implications for human health, biodiversity, and climate change. PAHs, released during the incomplete combustion of organic fuels, are particularly concerning due to their carcinogenic and mutagenic properties.

This review aims to evaluate the emissions of PAHs during biomass combustion, with a focus on fuel types and combustion conditions. It synthesizes data from over 30 contemporary scientific sources, comprehensively analysing PAH formation and distribution in flue gases, and identifies the key factors influencing these emissions.

The research reveals that PAH emissions vary significantly depending on the type of biomass, combustion conditions, and the control measures employed. Open burning of agricultural residues generates much higher PAH concentrations compared to controlled combustion in stoves or furnaces. The analysis assumes consistent data reporting across studies and acknowledges that real-world conditions may differ from laboratory settings, potentially affecting emission levels.

The findings underscore the importance of implementing effective emission control strategies to reduce environmental and health risks, particularly in regions like Ukraine that rely heavily on biomass as an energy source. By addressing a critical gap in the literature, this review enhances understanding of the long-term impacts of bioenergy on environmental health and sustainability and advocates for updating Ukrainian regulatory legislation with modern methodological procedures.

Key words: agricultural waste combustion, polycyclic aromatic hydrocarbons, emission profiles, bioenergy, environmental health.

Problem statement

Open biomass burning is the largest global atmospheric source of climate-effective black carbon (BC), accounting for 40 % of global emissions [1, 2]. Furthermore, organic aerosols (OA) are a primary component of particulate matter (PM) released during biomass burning [3], and together with BC, they are commonly referred to as carbonaceous aerosols. Biomass burning organic aerosols (BBOA) adversely affect the climate [4], the carbon cycle [5, 6], and human health [7, 8].

Polyaromatic hydrocarbons (PAHs) are a class of persistent organic pollutants characterized by multiple fused aromatic rings. These compounds are primarily released into the environment through anthropogenic activities, especially the combustion of organic materials, such as fossil fuels, biomass, and agricultural waste. Due to their harmful effects on human health, particularly their carcinogenicity, controlling PAH emissions from combustion processes has become a priority for environmental and public health agencies [9].

Agricultural waste, such as crop residues, is increasingly used as a renewable energy source. However, burning these materials generates significant amounts of PAHs. This article provides a detailed review of PAH formation during the combustion of organic fuels and agricultural waste, discussing emission profiles as well as influencing factors.

Search strategy and selection of data sources

To conduct the review, a thorough search of scientific publications was performed focusing on the toxicity and emission profiles of agricultural residues used as renewable sources. The search was limited to publications published between 2000 and 2023, as this period has seen a significant increase in research on agricultural residues as renewable energy sources and their environmental and health impacts.

The search was conducted using databases such as Scopus, Web of Science, Google Scholar, and relevant journals in the fields of ecology, bioenergy, and public health. Keywords used in the search included "agricultural waste combustion", "PAHs emissions", "toxicity of biomass burning", "bioenergy and environmental health", "sustainable energy sources", among others relevant to the topic. A total of over 100 publications were initially reviewed, from which 30 studies were selected based on the defined criteria. The selection process took into account the quality of the studies, the level of detail on toxicity and emissions, and their relevance to bioenergy from agricultural residues (see Table 1). In addition to the relevance of the studies, citation count was considered as an indicator of their scientific impact and recognition within the research community. Therefore, preference was given to studies with higher citation counts, ensuring the inclusion of well-regarded and influential research in the field.

Table 1 – Inclusion and exclusion criteria

Inclusion criteria	Exclusion criteria
1. Studies addressing the toxicity and emissions associated with the combustion of agricultural residues. 2. Publications providing quantitative and/or qualitative data on pollution levels and their impact on the environment and human health. 3. Research examining both bioenergy technologies and PAHs emissions.	1. Studies that do not provide results on toxicity or emission profiles of agricultural residues. 2. Articles focusing only on general bioenergy issues without specific data or experimental results on emissions and toxicity. 3. Review papers that do not present original data or research.

Analysis of the recent researches and publications

PAHs are formed under conditions of incomplete combustion, where organic material breaks down at high temperatures and subsequently reforms into larger, more complex molecules. During the combustion of organic fuel, factors such as oxygen availability, combustion temperature, and fuel characteristics significantly influence the formation of PAHs [10]. It is important to differentiate between two primary modes of biomass combustion: smoldering and flaming. Both can occur simultaneously during a fire and alternate depending on a complex interplay of air availability, mixing of pyrolysis gases, temperature conditions, and fuel properties. Flaming combustion is characterized by a high-temperature pyrolysis process with relatively high combustion efficiency. As a fire progresses, smoldering combustion, which exhibits lower combustion efficiency and produces high emissions of biomass burning organic aerosols (BBOA), becomes more prevalent. This phase involves surface oxidation and pyrolysis of both aboveground and underground biomass [11].

The highest PAH emissions typically occur during low-temperature combustion with oxygen deficiency, as these conditions favor the recombination of smaller organic fragments into PAH structures [12]. In the combustion of agricultural waste, PAHs tend to form from the breakdown of lignin, cellulose, and hemicellulose present in biomass. Studies show that the concentration of PAHs increases in the presence of lignocellulosic materials, which are abundant in agricultural residues such as straw, husks, and stalks [13]. The composition of waste and the combustion method used can significantly influence the level of PAHs in the resulting flue gases.

During the combustion of solid fuels (either fossil or biomass), PAHs are reported to form at the initial stage of the process following the devolatilization of fuel particles. At this stage, methane, acetylene, and other organic volatile compounds are partially cracked into smaller (unstable) free radicals. In the next stage, these radicals recombine into various PAHs with two or more aromatic rings [14]. Some PAHs with a greater number of aromatic rings (four to six), such as benzo[a]anthracene, chrysene, benzo[b,k]fluoranthene, benzo[a]pyrene, indeno[1,2,3-cd]pyrene, and dibenz[a,h]anthracene, are recognized as strong carcinogens and mutagens [15].

PAHs with low molecular weights (or with 2 and 3 aromatic rings), such as naphthalene, acenaphthylene, phenanthrene, and fluoranthene, are generally associated with gaseous combustion products, whereas the more hazardous PAHs with higher molecular weights (or with 4, 5, and 6 aromatic rings) are primarily emitted via fly ash and soot particles, commonly referred to as particulate matter [16].

A large number of research studies have quantified PAH emissions from various combustion systems co-fired with coal and biomass fuels. The ash-borne PAH emissions are reported to depend on-and can be controlled by-operating conditions (particularly excess air) and apparently correlate with the ash particle size [17]. Moreover, PAH toxicity increases with particulate aging, as demonstrated in studies on soot particle toxicity in lung cell models [18].

Statement of the problem and its solution

More than 100 PAH compounds have been identified in flue gases from combustion processes. Sixteen of these PAHs, recognized as priority pollutants by the U.S. Environmental Protection Agency (EPA), are frequently studied due to their high toxicity. Among them, the most harmful are considered to be benzo[a]pyrene, benzo[b]fluoranthene, and dibenzo[a,h]anthracene, particularly due to their carcinogenic properties [19].

During the combustion of agricultural waste, higher molecular weight PAHs (HMW-PAHs), which consist of four or more aromatic rings, are commonly formed. These compounds are more stable, resistant to environmental degradation, and pose long-term risks [20]. Studies using gas chromatography-mass spectrometry (GC-MS) have shown that the burning of agricultural waste, such as rice straw and corn husks, produces significant levels of HMW-PAHs [21].

One notable practical finding comes from the study *«Chemical fingerprinting of biomass burning organic aerosols from sugar cane combustion: complementary findings from field and laboratory studies»* [22]. The authors were able to identify specific volatile organic compounds (VOCs) with a detailed breakdown of compounds detected via chromatography, showing positive fold changes at a significance level of $p < 0.01$. Each compound is classified into broader chemical classes such as Methoxyphenols, PAHs (Polycyclic Aromatic Hydrocarbons), and n-Alkanes, with subclasses specifying the structure or chemical nature, such as Aromatic, Cyclic, or Heterocyclic (see Figure 1).

An additional outcome of this study is the review and description of over 60 target pollutants, whose formation has been confirmed by actual experiments during the combustion of various fuel types (see Table 2).

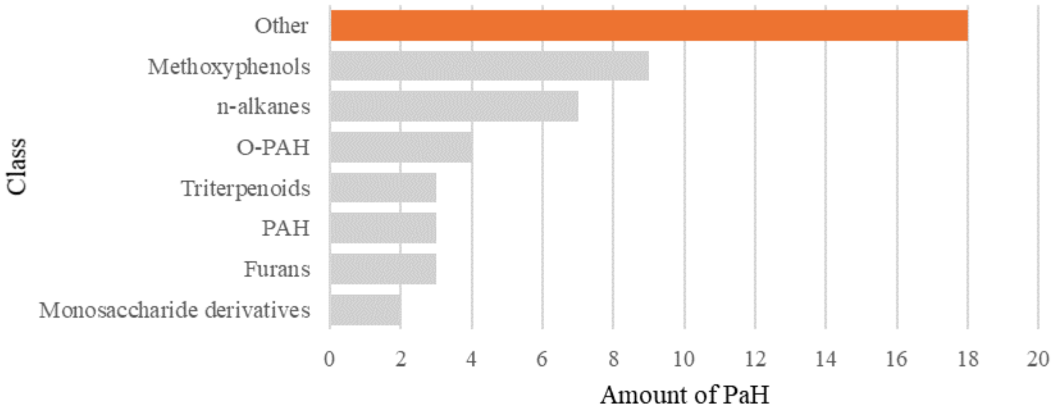

Figure 1 – The composition of polyaromatic compounds obtained during the study of burning sugar cane [22]

Table 2 – Key classes and number of polyaromatic compounds [22]

No.	Class	Amount of PaH
1.	Alkanes	20
2.	Furan derivatives	2
3.	Methoxyphenols	9
4.	Monosaccharide derivatives	4
5.	M-PAH	2
6.	O-PAH	3
7.	Other	2
8.	PAH	18
9.	Phytosterols	2
10.	Triterpenoids	2

Emission Factors for Organic Fuels and Agricultural Waste

Emission factors for polycyclic aromatic hydrocarbons (PAHs) from burning different types of organic fuels vary significantly depending on the type of fuel and combustion conditions. For example, coal tends to produce higher PAH emissions compared to natural gas due to its complex organic structure and tendency for incomplete combustion [23]. Biomass, including agricultural residues, can produce comparable or even higher levels of PAHs depending on moisture content, combustion temperature, and air-to-fuel ratio [24].

Studies have shown that open burning of agricultural residues results in significantly higher PAH concentrations compared to controlled burning in stoves or furnaces. In open burning, PAH emissions can reach up to 100 μg/m^3, whereas controlled burning can reduce these emissions to less than 10 μg/m^3 [25]. Properly designed combustion systems with appropriate air supply and temperature control are crucial for minimizing PAH formation.

A recent study by Väätäinen et al. [26] investigated the impact of air staging and combustion air control on black carbon and other particulate and gaseous emissions from a sauna stove. The study analyzed the concentrations of selected gaseous compounds such as carbon dioxide (CO_2), carbon monoxide (CO), methane (CH_4), acetylene (C_2H_2), propene (C_3H_6), benzene (C_6H_6), and organic gaseous carbon (OGC), revealing significant variability across different combustion settings. The findings showed that blocking secondary air supply led to increased gaseous emissions, particularly CO_2, CO, and OGC, indicating incomplete combustion. CO emissions were 30 % higher, while OGC concentrations increased by 72 % compared to the control. Similarly, using an air-tight firebox door resulted in elevated gaseous emissions, though to a lesser extent than the blocked secondary air setup. Limiting primary air supply resulted in the lowest average CO emissions, while other gaseous emissions showed minimal reduction.

Rinta-Kiikka et al. [27] further explored the effect of wood species on emissions from a modern wood stove (see Table 3). The study found that wood burning in residential spaces significantly contributes to fine particle and gaseous emissions. Scandinavian wood species such as birch (A and B), spruce, dry spruce, pine, and alder were evaluated. Birch A had the lowest emissions, while spruce and alder had the highest. Fine particulate matter ($PM_{2.5}$) was predominantly composed of elemental carbon, typical for modern appliances. The lowest PAH concentrations were observed in birch and pine, with total PAH levels reaching 107 μg/m^3 and 250 μg/m^3, respectively.

Shen et al. [28] investigated emissions of parent, nitrated, and oxygenated polycyclic aromatic hydrocarbons (PAHs) from indoor corn straw burning under different combustion conditions. The study found that oxygen-deficient conditions in the stove chamber led to significantly higher emission factors (EFs) for PAHs. The primary factors influencing these emissions were fuel burning rate, air supply, and combustion efficiency, which accounted for 72…85 % of the total variation in emissions.

Janvijitsakul and Kuprianov [29] examined PAH and gaseous emissions from a fluidized-bed combustor firing rice husk. Their results indicated that excess air (EA) levels significantly influenced CO, NOx, and PAH emissions, with the highest PAH concentrations associated with the largest ash particles.

Fakinle et al. [30] quantified PAH emissions from the combustion of crop residues such as maize cobs, maize husk, rice husk, and bean chaff (see Table 4). The study identified 16 PAHs, including benzo[ghi]perylene, naphthalene, acenaphthene, and benzo[a]pyrene, with concentrations ranging from 1.47 to 0.01 μg/mg across samples. The composition of PAHs varied significantly between different residues, highlighting the influence of fuel type on emissions.

Table 3 – Polyaromatic compounds detected during wood fuel combustion, µg/m³ [27]

Detected Pollutants	Birch A1	Alder	Pine	Spruce	Spruce Dry
Methane	56.7 ± 25.1	56.1 ± 22.2	46.7 ± 18.4	69.6 ± 14.2	64.4 ± 23.3
Pentane	32.8 ± 7.8	11.9 ± 3.5	14.7 ± 6.2	21.2 ± 5.4	14.7 ± 8.7
Acetylene	14.2 ± 10.7	20.5 ± 10.6	7.9 ± 6.1	8.8 ± 0.1	15.9 ± 11.6
Ethylene	22.5 ± 13.2	24.7 ± 9.3	16.7 ± 8.4	21.2 ± 3.9	22.1 ± 12.0
Propene	29.4 ± 12.9	25.6 ± 7.4	18.1 ± 7.5	25.4 ± 4.6	25.8 ± 9.1
1,3-Butadiene	13.4 ± 8.5	14.6 ± 6.7	15.8 ± 9.4	7.8 ± 0.3	6.3 ± 2.3
Benzene	30.1 ± 13.5	36.8 ± 12.8	28.8 ± 10.4	30.3 ± 2.0	38.3 ± 22.0
Formic Acid	4.7 ± 1.6	1.9 ± 1.1	2.4 ± 1.3	2.3 ± 1.0	2.4 ± 1.5
Acetic Acid	75.4 ± 26.5	13.9 ± 10.0	10.7 ± 7.5	14.9 ± 6.2	15.4 ± 10.2
Formaldehyde	29.8 ± 10.2	14.2 ± 4.6	15.4 ± 7.5	23.6 ± 6.7	18.0 ± 7.7
Acetaldehyde	13.7 ± 7.3	4.3 ± 2.1	6.3 ± 3.5	8.9 ± 3.8	7.3 ± 4.0
Methanol	15.7 ± 9.6	1.5 ± 0.3	2.0 ± 2.2	2.2 ± 1.8	1.9 ± 1.4

Table 4 – Polyaromatic compounds detected during agricultural residues fuel combustion, µg/m³ [30]

Detected Pollutants	Maize Cobs	Maize Husks	Rice Husk	Bean Chaff
Naphthalene	1.05 ± 0.42	0.01 ± 0.08	1.02 ± 0.43	0.01 ± 0.11
Acenaphthylene	1.02 ± 0.31	0.09 ± 0.10	1.00 ± 0.26	ND
Acenaphthene	0.03 ± 0.11	0.31 ± 0.16	0.03 ± 0.10	0.03 ± 0.15
Phenanthrene	1.00 ± 0.25	1.00 ± 0.20	0.26 ± 0.09	ND
Anthracene	0.04 ± 0.10	1.21 ± 0.43	0.32 ± 0.12	0.02 ± 0.10
Fluorene	0.02 ± 0.10	0.11 ± 0.13	0.03 ± 0.12	0.49 ± 0.23
Fluoranthene	0.04 ± 0.13	0.15 ± 0.23	0.04 ± 0.10	0.61 ± 0.28
Pyrene	0.13 ± 0.26	0.13 ± 0.10	0.63 ± 0.35	0.83 ± 0.30
Benzo[a]anthracene	0.02 ± 0.14	1.02 ± 0.37	0.67 ± 0.31	0.82 ± 0.30
Benzo[b]fluoranthene	1.32 ± 0.37	1.36 ± 0.34	1.40 ± 0.41	1.32 ± 0.38
Chrysene	0.96 ± 0.46	0.56 ± 0.10	1.37 ± 0.46	0.82 ± 0.19
Benzo[a]pyrene	0.02 ± 0.15	0.02 ± 0.11	0.03 ± 0.21	0.74 ± 0.20
Indene[1,2,3-cd]pyrene	0.01 ± 0.12	0.02 ± 0.10	0.01 ± 0.06	1.18 ± 0.37
Benzo[k]fluoranthene	1.06 ± 0.31	0.03 ± 0.20	0.01 ± 0.02	0.54 ± 0.22
Benzo[ghi]perylene	1.47 ± 0.18	0.02 ± 0.13	ND	0.58 ± 0.26
Dibenzo[ah]anthracene	ND	ND	ND	0.01 ± 0.03

These studies collectively highlight the significance of combustion conditions and fuel type in determining the emission profiles of PAHs and other gaseous compounds. They provide critical insights into how different biomass burning practices can impact air quality and environmental health.

Impact of PAHs on the Environment and Health

Polycyclic aromatic hydrocarbons (PAHs) raise serious concerns due to their persistence in the environment, potential for bioaccumulation, and toxicity. They can adhere to airborne particles, facilitating their transport over long distances and deposition in soils and water bodies [31]. Studies have shown that PAHs in soil and water can enter the food chain, with long-term exposure posing risks to both wildlife and human health [32].

The impact of PAHs on human health is associated with various issues, including respiratory diseases, skin conditions, and cancer. Occupational exposure to PAH-rich smoke, particularly in agricultural settings where biomass is often burned, is a growing concern [33]. Efforts to reduce PAH emissions in these environments could have a significant impact on public health.

Long-term exposure to even low levels of certain PAHs, including benzo(a)pyrene, has been linked to cancer in laboratory animals [34]. Naphthalene exposure through inhalation or ingestion can lead to the destructtion of blood cells [35]. Research has documented that the risk of acute respiratory infections, after adjustting for socio-economic and lifestyle factors, more than triples in areas with high agricultural residue burning, with children being the most vulnerable group [36].

According to Gurjar et al. (2016), farmers burn crop residue to dispose of agricultural waste, releasing volatile organic compounds (VOCs), carbon monoxide, hydrocarbons, nitrogen oxides, and PAHs. In addition to greenhouse gas emissions (CH_4, N_2O, CO_2), air contaminants (non-methane hydrocarbons, smoke, VOCs, CO, SO_2, PAHs, NOx, particulate matter, NH_3), agricultural waste burning also causes severe land and water contamination at both local and national levels, posing a significant threat to public health. Ravindra et al. (2019) [37] reported annual estimates of air pollutant emissions from open-field burning of rice straw in three different countries: India (16253012, 779, 144719 and 207 µg of CO_2, CO, Total Particulate Matter (TPM) and PAHs, respectively), Thailand (12206603, 290116, 108689 and 156 µg of CO_2, CO, TPM and PAHs, respectively), and the Philippines (11850034, 281641, 105514 and 151 µg of CO_2, CO, TPM and PAHs, respectively). These emissions contribute to increased atmospheric pollution and have severe impacts on both human health and the environment.

The effects of burning crop residues can be detrimental to both humans and the environment. Short-term/acute health effects include eye irritation, nausea, vomiting, skin irritation, and inflammation [39]. Long-term/chronic health effects include decreased immune function, cataracts, kidney and liver damage, asthma-like symptoms, and lung function abnormalities [31]. Additionally, black soot contributes to increased particulate concentrations in the air, leading to poor visibility [40]. The generation of these vapor pollutants also indirectly leads to high ozone gas concentrations, a major contributor to air pollution. Furthermore, the destruction of soil texture and the eventual loss of soil minerals, which subsequently affect productivity in future cultivation years, are also dangers of burning agricultural residues.

Conclusion

The comprehensive review of studies highlights the significant environmental and health challenges associated with the combustion of agricultural residues, particularly regarding emissions of PAHs. Biomass combustion, especially of crop residues like corn straw, rice husk, and maize cobs, produces a complex mixture of harmful pollutants, including VOCs, carbon monoxide, and particulate matter. These emissions vary depending on fuel types, combustion conditions, and the overall combustion efficiency.

The persistence of PAHs in the environment is particularly concerning due to their ability to bioaccumulate, leading to long-term risks for both ecosystems and human health. The ability of PAHs to attach to airborne particles facilitates their wide dispersal, causing deposition in soils and water bodies where they can enter the food chain. This poses serious health risks, including respiratory diseases, skin disorders, and cancer, especially in regions where open burning of biomass is common.

Future research should focus on developing cost-effective, scalable emission control technologies and further investigating the long-term impacts of low-level PAH exposure on human health. It is also critical to explore the socioeconomic aspects of transitioning to cleaner energy practices in regions where biomass combustion is a primary energy source as Ukraine. Finally, advancing policy frameworks will be essential to drive the adoption of cleaner technologies and protect public health. This integrated approach – combining technological innovation, regulatory efforts, and public health initiatives – will be essential for mitigating the environmental and health challenges associated with biomass burning and will be important within the Ukrainian post-war reconstruction period.

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ВПЛИВ СПАЛЮВАННЯ СІЛЬСЬКОГОСПОДАРСЬКИХ ВІДХОДІВ НА НАВКОЛИШНЄ СЕРЕДОВИЩЕ ТА ЗДОРОВ'Я ДЛЯ БІОЕНЕРГЕТИКИ: ОГЛЯД ТОКСИЧНОСТІ ТА ВИКИДІВ

У дослідженні розглядається вплив на довкілля та здоров'я людини, зумовлений вивільненням поліциклічних ароматичних вуглеводнів (ПАВ) під час спалювання біомаси та сільськогосподарських відходів. Біоенергетика відіграє важливу роль у глобальних енергетичних системах, забезпечуючи 70% споживання відновлюваної енергії, 9,5% загального постачання первинної енергії та 13% світового кінцевого енергоспоживання. Однак забруднення довкілля залишається однією з головних проблем 21 століття, яка має серйозні наслідки для здоров'я людей, біорізноманіття та зміни клімату. ПАВ, що виділяються при неповному згорянні органічного палива, викликають особливе занепокоєння через їхні канцерогенні та мутагенні властивості.

Метою цього огляду є оцінка викидів ПАВ під час спалювання біомаси з акцентом на типи палива та умови згоряння. У дослідженні узагальнено дані з понад 30 сучасних наукових джерел, проведено всебічний аналіз утворення та розподілу ПАВ і визначено ключові фактори, що впливають на ці викиди.

Дослідження демонструє, що викиди ПАВ значно залежать від типу біомаси та умов спалювання. При відкритому спалюванні сільськогосподарських відходів концентрація ПАВ суттєво вища, порівняно з контрольованим спалюванням у котлах або печах. Аналіз підкреслює необхідність узгодженої звітності даних між різними дослідженнями та визнає, що реальні умови можуть значно відрізнятися від лабораторних, що може впливати на рівень викидів.

Результати підкреслюють важливість впровадження ефективних стратегій контролю викидів для зменшення ризиків для довкілля та здоров'я, особливо в таких країнах, як Україна, які суттєво залежать від біомаси як джерела енергії. Заповнюючи важливу прогалину в літературі, цей огляд покращує розуміння довгострокового впливу біоенергетики на здоров'я та сталий розвиток довкілля, а також підкреслює необхідність оновлення українського регуляторного законодавства із впровадженням сучасних методологічних процедур.

Ключові слова: спалювання сільськогосподарських відходів, поліциклічні ароматичні вуглеводні, профілі викидів, біоенергетика, екологічна безпека.

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