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SCIENTIFIC JUSTIFICATION OF APPROACHES TO ENHANCE THE ENVIRONMENTAL SAFETY OF THERMAL POWER PLANTS WHEN USING AGRICULTURAL WASTE AS A FUEL

Introduction

Thermal power plants (TPPs) remain one of the major contributors to anthropogenic air pollution due to their predominant reliance on fossil fuels such as coal, oil, and natural gas. Their emissions are associated with greenhouse gas accumulation, acidifying compounds, particulate matter, and other hazardous pollutants that undermine both environmental quality and human health (IPCC, 2018). In the context of energy transition, the gradual substitution of fossil fuels with renewable energy sources (RES) is considered a key strategy for decarbonisation and for achieving higher levels of ecological safety in the energy sector (IEA, 2021). Among the available renewable alternatives, agricultural residues - particularly sunflower husks, press cake, and meal generated during sunflower processing - represent a resource of high potential. Ukraine, as one of the world’s leading sunflower producers, accumulates significant annual volumes of such residues, creating favourable conditions for their energy utilisation in boilers and thermal power plants. The advantages of sunflower residues include relatively high calorific value and low sulphur content, which make them attractive as biofuel substitutes (Demirbas, 2005; Werther et al., 2000).

At the same time, the combustion of sunflower residues poses several ecological and technological challenges. Their relatively high ash content (3–5% in husks), variable moisture levels, and unstable granulometric composition may result in slagging, fouling, and reduced boiler efficiency. More critically, experimental studies indicate that flue gases from sunflower residue combustion can contain hazardous pollutants such as polycyclic aromatic hydrocarbons (PAHs), volatile organic compounds (VOCs), and odour-forming substances, including acrolein and benzene. These pollutants are known for their toxicity, carcinogenic potential, and long-term ecological impact (Nussbaumer, 2003; Valverde & Medina, 2018).

Yet, the current Ukrainian regulatory framework does not explicitly include these compounds in the list of controlled emissions for biomass combustion facilities, creating a gap in air quality monitoring and risk assessment. Given these challenges, there is a growing need for scientifically justified methods to enhance the ecological safety of TPPs operating on sunflower residues. This requires not only technological improvements in fuel preparation, combustion, and gas cleaning systems, but also the development of modernised monitoring and regulatory approaches aligned with international best practices (European Commission, 2017; EEA, 2019).

The objective of this study is to propose and substantiate methods aimed at reducing the environmental risks associated with sunflower residue combustion at TPPs. To achieve this, the research applies a hierarchical decomposition approach to assess risks, prioritise ecological safety measures, and identify practical solutions for implementation at different territorial levels. The approach integrates expert-analytical methods and multi-criteria decision-making techniques, providing a comprehensive framework for evidence-based environmental management.

Environmental risks of sunflower residue combustion

The use of sunflower processing residues as fuel at thermal power plants provides a viable alternative to fossil energy sources, yet it also introduces a complex set of environmental risks. These risks arise from the specific physical and chemical properties of the residues, as well as from the incomplete adaptation of existing combustion and flue-gas treatment technologies to such fuels.

One of the key challenges is the high ash content of sunflower husks (3–5%), which promotes slagging and fouling in boilers. These processes reduce operational efficiency and increase the need for maintenance, while also intensifying the release of fine particulate matter. Another important factor is the variability of fuel quality, including moisture content and particle size distribution, which leads to fluctuations in combustion stability and emissions.

More critical, however, are the toxic organic compounds generated during combustion. Experimental studies and practical trials have demonstrated that flue gases from sunflower husks and press cake may contain:

- **Polycyclic aromatic hydrocarbons (PAHs)** – persistent organic pollutants with mutagenic and carcinogenic properties, known to accumulate in ecosystems and pose long-term risks to human health (Seinfeld & Pandis, 2016).

• **Volatile organic compounds (VOCs)** such as **acrolein** (CH_2=CHCHO), a highly toxic aldehyde capable of causing acute respiratory irritation and odour nuisances near emission sources (Jenkins et al., 1998; Demirbas, 2005).

• **Benzene**, recognised as a Group 1 carcinogen (IARC, 2018), which is especially concerning given its potential emission even at low combustion temperatures.

These substances are not currently included in the Ukrainian emission inventory methodology for biomass combustion. As a result, official air quality data may underestimate the actual ecological risks of sunflower residue-based energy production. This regulatory gap complicates the design of effective mitigation technologies and hinders the alignment of Ukraine's air quality management system with European standards (European Commission, 2017; EEA, 2019).

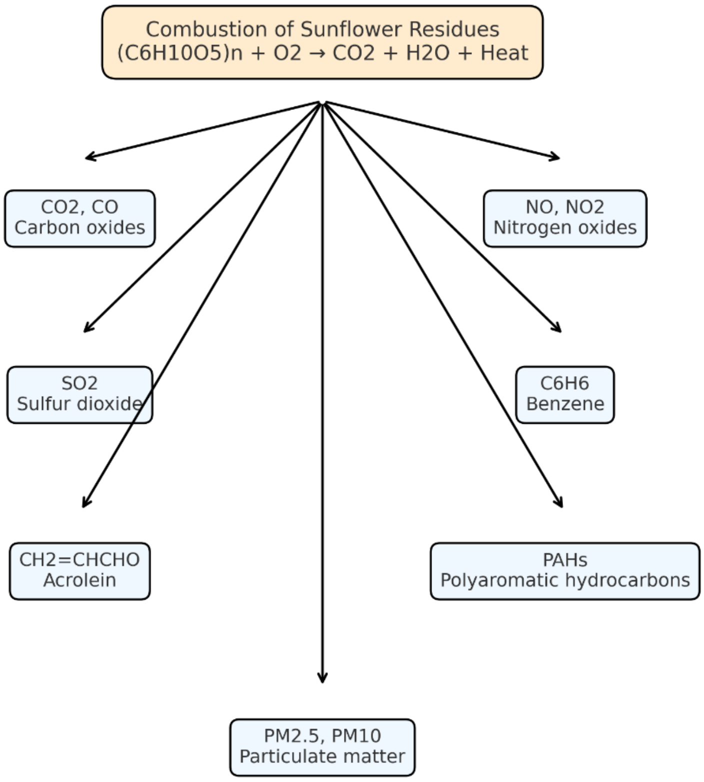

Figure 1 – Pollutant flows from sunflower residue combustion

To illustrate these issues, Figure 1 can present a schematic diagram of pollutant flows during sunflower residue combustion, highlighting both conventional pollutants (SO_2, NO_x, particulate matter) and unregulated compounds (PAHs, acrolein, benzene). Such a figure will help visualise the complexity of emissions and emphasise the need for updated monitoring and control strategies.

In summary, while sunflower residues hold significant promise for bioenergy applications, their combustion introduces environmental hazards that must be systematically addressed. A targeted combination of advanced combustion technologies, efficient gas-cleaning systems, and improved monitoring approaches is necessary to minimise the release of hazardous pollutants and to ensure the ecological safety of power generation facilities.

Methodological approach - hierarchical decomposition

The methodological framework is based on the AHP, which enables decomposition of the ecological safety management task into hierarchical levels. The objective is to justify and prioritize measures that reduce atmospheric pollution from thermal power plants (TPPs) using sunflower processing residues as fuel. Logic of the model could be present as followed:

1. Objective (ObJ): Ensure ecological safety of atmospheric air in the zone of influence of TPP emissions.
2. Criteria (C): Environmental components exposed to pollutants (air, soil, water, human health, flora, fauna).
3. Characterization of factors (ChF): Complex pollution factors (volume, toxicity, persistence, accumulation).
4. Object groups (Go): Groups of measures (technological, organizational, monitoring).
5. Territorial level of implementation (TLI)**:** Object-level (plant), local (hromada), regional.
6. Security measures (SM): Concrete interventions – fuel preparation optimization, emission control (filters, scrubbers, catalytic afterburners), continuous monitoring (CEMS), risk modelling.

Table 1 – Example of links between hierarchy levels

Hierarchy level	Element	Example of expert question
ObJ	Ecological safety of air	Which intervention most reduces the overall risk of air pollution?
C	Human health	Which pollutant (SO_2, NO_x, PAHs, VOCs) has the greatest impact on health?
ChF	Toxicity	How significant is the carcinogenic risk of benzene vs acrolein compared to CO or NO_x?
Go	Gas cleaning	Which technology (ESP, scrubber, catalyst) is most effective for VOC reduction?

TLI	Local hromada	Should monitoring and response measures be decentralized to communities?
SM	Continuous monitoring	How important is real-time CEMS compared to periodic laboratory testing?

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Objective (ObJ): Air ecological safety near TPPs
|
├── Criteria (C)
|     ├── Air pollution (SO2, NOx, CO, PAHs, VOCs: acrolein, benzene)
|     ├── Soil contamination (ash, heavy metals)
|     ├── Water quality (surface & groundwater impacts)
|     ├── Human health (respiratory, carcinogenic risks)
|     └── Biota (flora & fauna sensitivity)
|
├── Characterization of Factors (ChF)
|     ├── Volume of emissions (t/year)
|     ├── Toxicity coefficients (LD50, LC50, IARC classes)
|     ├── Persistence & accumulation potential
|     └── Odor nuisance index (OAV)
|
├── Object Groups (Go)
|     ├── Fuel-related methods (drying, pelletizing, additive dosing: CaCO3, MgO)
|     ├── Combustion technologies (fluidized bed, staged combustion)
|     ├── Gas cleaning systems (cyclones, electrostatic precipitators, scrubbers, catalytic
|     ├── Monitoring tools (CEMS, UAV sampling, dispersion models)
|     └── Organizational measures (regulations, training, emergency response)
|
├── Territorial Level of Implementation (TLI)
|     ├── TPP-level (plant operators)
|     ├── Local hromada (community monitoring, volunteer fire brigades)
|     └── Regional/national level (legislation, policy, subsidies)
|
└── Security Measures (SM)
      ├── Optimized fuel preparation to stabilize moisture & particle size
      ├── Advanced cleaning (ESP + scrubber combo for PAHs & VOCs)
      ├── Monitoring with Luenberger observer-based models
      ├── Risk-based zoning & emergency planning
      └── Normative framework update (inclusion of acrolein, benzene in standards)
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Figure 2 – Scheme of hierarchical decomposition (AHP-based model)

Results and conclusions

The hierarchical decomposition (Figure 2) structured the problem of ecological safety into logically connected levels – from the overarching objective of reducing air pollution to specific technical and organizational measures. This approach ensured that both quantitative emission factors and qualitative risk characteristics were incorporated into decision-making.

The analysis showed that the combustion of phytomass-based fuels (sunflower residues) results not only in conventional pollutants such as CO_2, SO_2, and NO_x, but also in toxic volatile organic compounds (VOCs) such as acrolein (CH_2=CH–CHO) and benzene (C_6H_6), along with polycyclic aromatic hydrocarbons (PAHs). These pollutants are not currently regulated in Ukrainian environmental standards, which creates a significant gap in air quality management.

Using AHP were identified the highest-priority criteria of groups of measures (Go) and security measures (SM). The highest-priority groups of measures included:

- Advanced gas cleaning systems (e.g., scrubbers, catalytic converters).
- Continuous monitoring technologies (CEMS).
- Organizational measures such as updating emission standards to include VOCs and PAHs.

At the most practical level, security measures (SM) were defined as:

- Optimization of fuel preparation and pre-treatment to reduce instability of residues.
- Application of best available technologies (BAT) for VOC and PAH control.
- Integration of real-time monitoring and early-warning tools into local risk management systems.

This hierarchical approach is particularly relevant for conflict-affected regions of Ukraine, where experimental datasets are limited, and decision-making relies on expert knowledge and structured evaluation methodologies.

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