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Data Article

Dataset for the assessment of NO_x emissions from the combustion of various nitrogen-rich agricultural residues

Julie Sobotková[a], Tereza Zlevorová[b], Jakub Lachman[b], Antonín Kintl[a], Marek Baláš[b], Martin Lisý[b], Jakub Elbl[a,*]

[a] Agricultural Research, Ltd., Zahradní 1, 664 41 Troubsko, Czech Republic
[b] Department of Power Engineering, Faculty of Mechanical Engineering, Brno University of Technology, Czech Republic

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Dataset link: Data for the assessment of NOx emissions from firing various nitrogen-rich agricultural residues (Original data)

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Solid biofuels
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Herbaceous biomass
Pellet boiler

ABSTRACT

The presented set of data contains experimental results from the combustion of various solid biofuels in a small-scale boiler. The biofuels were prepared from agricultural plant residues that included: 4 samples of *Melilotus albus*, 3 samples of *Papaver somniferum*, 1 sample of *Medicago lupulina*, *Medicago sativa* and *Sinapis alba*. The residues were processed into 8 mm pellets. Standardized spruce pellets were used as a reference material. The dataset includes basic fuel properties (moisture, ash and volatile matter content and LHV) and elemental composition (C, H, N, S, O). Compared to spruce pellets, the agricultural residues contain considerable amounts of nitrogen, and their combustion thus presents a potential environmental hazard. The combustion tests were carried out on an automatic pellet boiler with a bottom-feed retort burner. The emissions of NO_x were closely monitored and evaluated. The dataset serves primarily for the assessment of NO_x emissions from burning nitrogen-rich biofuels; however, other important parameters are included as well: CO, TOC emissions, O_2 content, flue gas temperature and boiler power output.

* Corresponding author.
E-mail address: jakub.elbl@mendelu.cz (J. Elbl).

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Specifications Table

Subject	Earth & Environmental Sciences
Specific subject area	Environmental impact of solid biofuel combustion, emission assessment
Type of data	Table, Graph, Figure Raw and processed data
Data collection	The solid biofuels were analysed through standard laboratory procedures (in accordance with EN ISO). The combustion conditions were measured with a series of Pt100 RTD sensors, K-type thermocouples and Flomag 3000 magnetic flow meter and recorded with NI Labview software. The gaseous emissions were measured with a Horiba VA-5000 series multicomponent gas analyser and recorded with the manufacturer's custom software.
Data source location	Brno University of Technology, Faculty of Mechanical Engineering, Dept. of Power Engineering, Technická 2896/2, Královo Pole, 61,669, Brno, Czech Republic
Data accessibility	Repository name: Mendeley Data Data identification number: doi:10.17632/hhz98tncwg.2 Direct URL to data: https://data.mendeley.com/datasets/hhz98tncwg/3 Instructions for accessing the data: The data are freely available without additional conditions
Related research article	None

1. Value of the Data

- Residues from agricultural processing are a promising source of renewable energy, due to their abundance and availability. Their fuel properties are often similar to those of woody biomass, and their ash tends to be rich in nutrients.
- The wide use of nitrogen-based fertilizers coupled with the relatively short lifespan of many plants, however, causes high nitrogen presence in the feedstock. Fuel-bound nitrogen is among the main originators of nitrogen oxide (NO_x) emissions. The deployment of biofuels made from agricultural residues thus needs to be critically evaluated.
- The presented dataset serves primarily to indicate the dramatic increase in fuel-originated NO_x emissions when firing feedstock rich in nitrogen and includes elemental fuel analysis and the corresponding emissions of NO_x from their combustion in a residential heating boiler.
- The presented dataset will allow researchers, boiler operators, emission control agencies and users to preliminary determine the NO_x emissions based on the nitrogen content in the feedstock and thus to evaluate the environmental impact of thermally utilizing individual biofuels.
- A graphical representation of the relation between NO_x emissions and the nitrogen content in the feedstock was derived from the dataset and is presented in Fig. 2. A strong positive correlation can be observed between the two variables.

2. Background

The demand for available renewable energy sources, waste utilization and circular economy brings attention to various herbaceous residues from agricultural processing. Clippings, prunings, husks, shells, straws etc. of fodder crops are often left unused. Recently, efforts have been made to valorize these residues by using them as solid biofuels in residential heating. While the deployment of such fuels is commendable, a careful evaluation of their environmental impact is necessary. Most fertilizers used in agriculture are rich in nitrogen, which in turn increases the

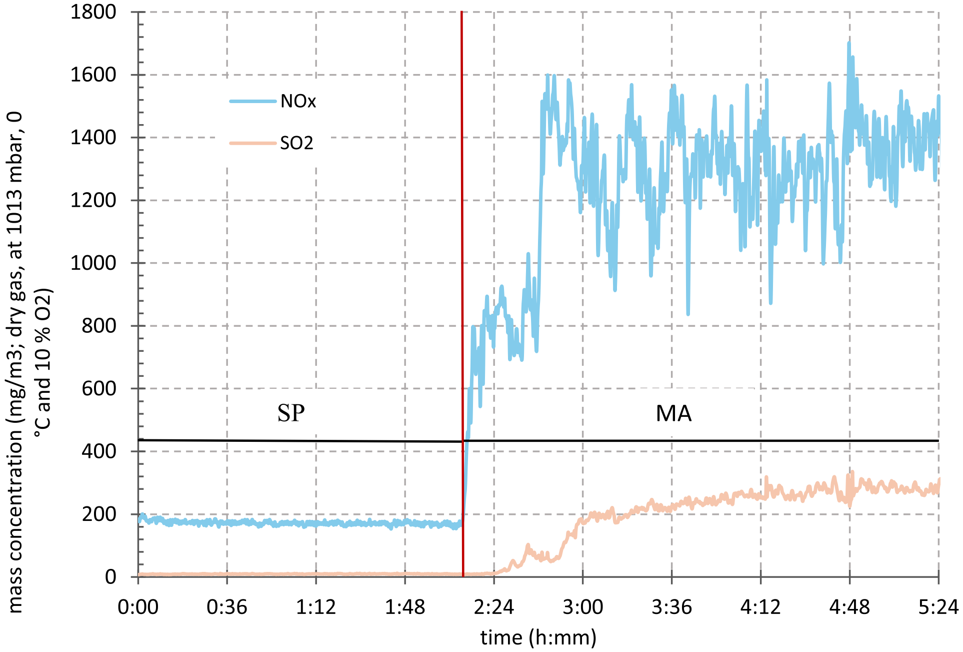

Fig. 1. Real time fuel transition from spruce (SP) to Melilotus albus (MA) showing a sharp increase in NO_x and SO_2 emissions.

likelihood of excessive NO_x emissions during combustion. The present research shows cases of NO_x emissions from a variety of agricultural residues combusted in a 25 kW boiler for residential heating. A typical example of real time fuel switch is shown in Fig. 1. The fuel base was gradually switched from spruce (SP) to *Melilotus albus* (MA) pellets. A sharp increase in NO_x and SO_2 emissions was observed. Since the combustion conditions (temperatures, power output etc.) were almost identical, the increase in NO_x concentrations can be solely attributed to the fuel-bound nitrogen. To further investigate this phenomenon, an extensive dataset of identical combustion tests on various agricultural residues was collected and is presented in this study.

3. Data Description

The dataset includes fuel characteristics, boiler operating conditions and gaseous emissions from a variety of solid biofuels labelled as: SP – spruce pellets (reference biofuel), MA – *Melilotus albus* (4 different samples), PS – *Papaver somniferum* (3 different samples), MS – *Medicago sativa*, ML – *Medicago lupulina* and SA – *Sinapis alba*.

3.1. Proximate and ultimate analysis

The file contains measured sample mass and parameters established in accordance with the appropriate standards (see below). Two or three measurements are presented, based on the guidelines of the corresponding standard. Repeatability was verified for the determination of moisture content, volatiles and calorific value in accordance with listed standards.

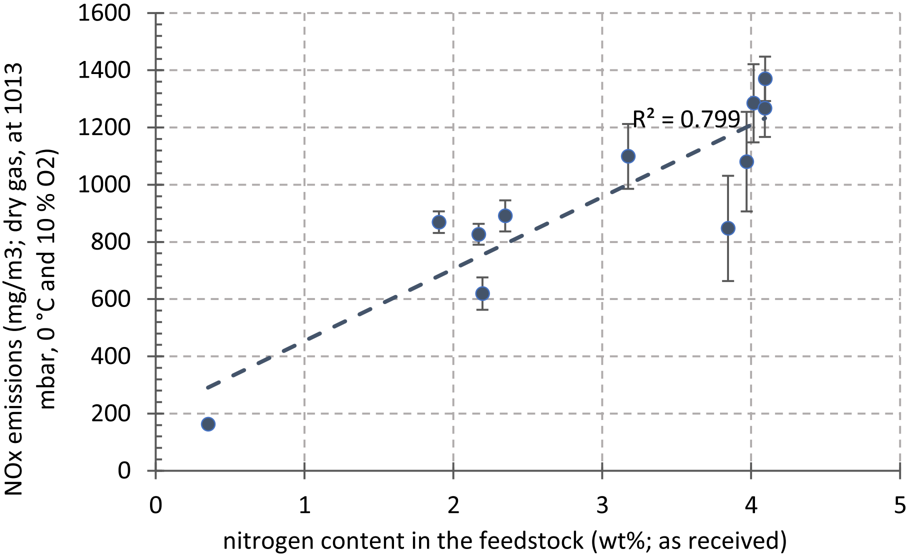

Fig. 2. Graphical representation of NO_x dependence on the nitrogen content in the feedstock.

3.2. Boiler operating conditions

The file contains recorded values of exhaust temperature and boiler power output for the duration of the experiment. The values were recorded every 3 s and the average value along with standard deviation is included as well.

3.3. Gaseous emissions

The file contains recorded values of O_2, NO_x, SO_2, CO and TOC concentrations measured at the stack sampling point for the duration of the experiment. Average values and standard deviations are included as well. The values were recorded every 5 s and are presented as 1-minute averages. Summary results of the average NO_x and SO_2 values along with standard deviations are presented in Fig. 3 and Fig. 4, respectively.

4. Experimental Design, Materials and Methods

A total of 10 different biofuels were combusted in a residential heating boiler, and their gaseous emissions were recorded. The fuels were prepared from various leftover agricultural residues in the form of 8 mm pellets. Spruce pellets were used to establish comparative reference values. A simplified scheme of the experimental procedure is shown in Fig. 5.

4.1. Feedstock composition

Prior to the combustion tests the herbaceous materials were characterized by proximate and ultimate analyses, shown in Table 1. Sampling and homogenization of the materials were carried out in accordance with ISO 18,135:2017 [5]. Proximate analysis consists in the determination of moisture content (ISO 18134-3:2023 [6]), determination of ash content (ISO 18122:2022 [7]) and

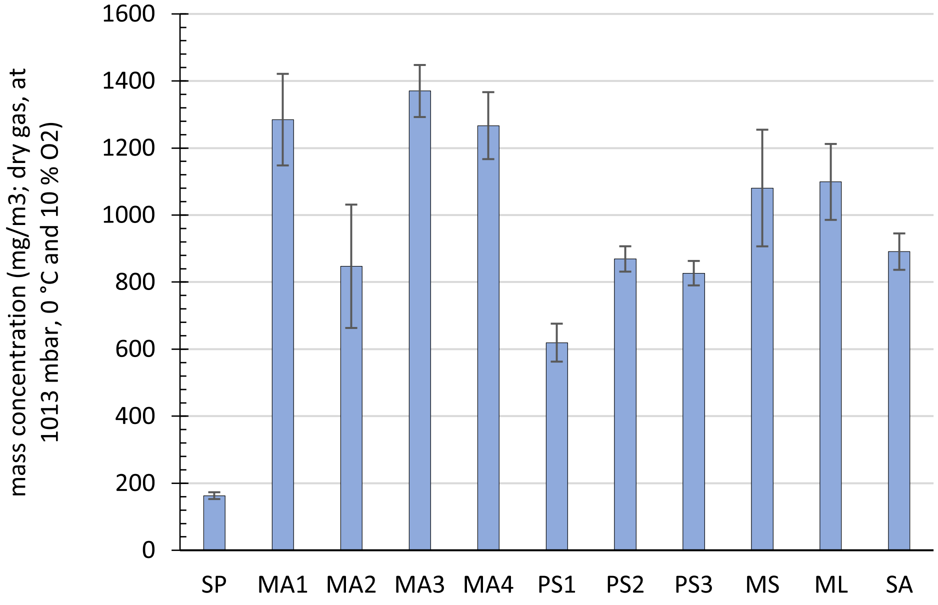

Fig. 3. Average NO_x concentrations with standard deviations.

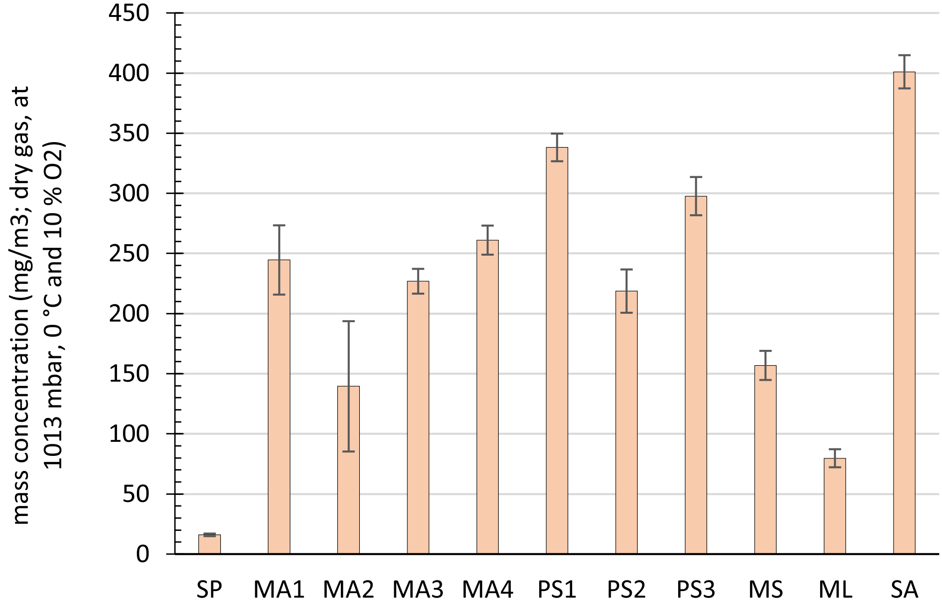

Fig. 4. Average SO_2 concentrations with standard deviations.

determination of volatile matter (ISO 18123:2023 [8]). Mentioned fuel properties are marked as M_{ad}, A_d, V_d respectively and are expressed in wt % relative to dry basis (index d). Next, calorific value (LHV) was calculated from the measured higher heating value (HHV). Determination was conducted using the Parr 6200 Calorimeter in accordance with ISO 18125:2017 [9]. Finally, the elemental composition of combustibles was measured using the certified CHNS Elemental ana-

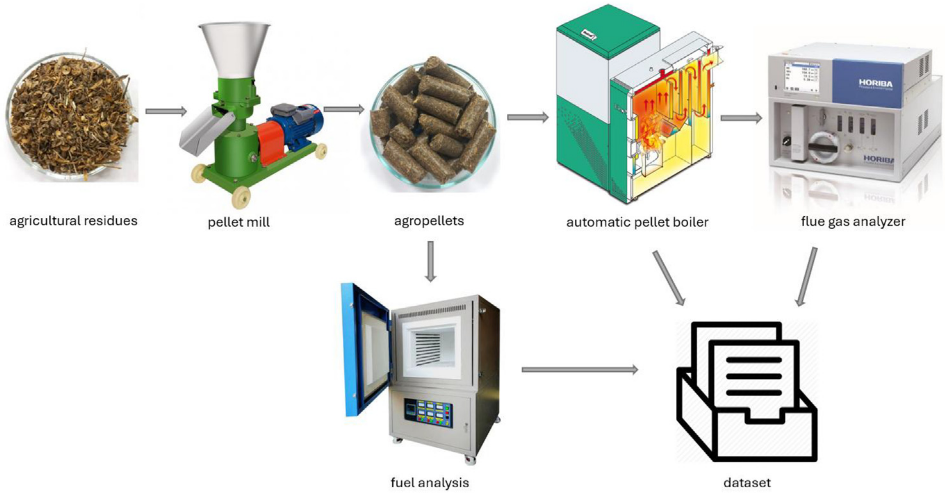

Fig. 5. Simplified diagram of the experimental procedure and data acquisition (custom made with pictures from [1–4]).

Table 1
Proximate and ultimate analyses of tested biofuels.

	M_{ad} wt %	A_d wt %	V_d wt %	LHV MJ/kg	C (daf, wt %)	H	N	O	S
SP	7.0	0.6	82.9	18.10	51.98	6.46	0.38	41.18	0.00
MA1	8.3	7.8	76.2	16.42	51.96	7.43	4.75	33.71	0.26
MA2	9.8	6.5	77.4	16.95	51.86	7.35	4.56	36.11	0.12
MA3	9.7	6.4	77.3	16.98	52.07	7.35	4.84	35.59	0.04
MA4	7.8	7.0	76.9	16.83	50.21	7.47	4.77	37.40	0.31
PS1	9.9	28.2	60.8	12.08	47.74	7.28	3.39	41.24	0.39
PS2	7.5	36.3	53.5	11.21	54.85	9.06	3.23	32.67	0.25
PS3	7.4	36.2	53.9	11.11	52.14	8.22	3.67	35.61	0.34
MS	7.6	6.8	76.7	17.25	50.99	7.60	4.61	36.49	0.18
ML	7.2	9.3	76.3	16.02	49.78	7.34	3.77	39.02	0.10
SA	7.9	6.6	77.8	16.57	50.32	7.55	2.73	38.91	0.46

lyzer, sulfur content was determined in accord with ISO 16994:2017 [10] while the oxygen content was calculated from difference. The elemental composition is reported on a dry ash-free (daf) basis. The average values of the fuel properties are summarized in Table 1, while all the supporting data is presented in the dataset.

4.2. Boiler specifications

The combustion tests were carried out on an automatic pellet boiler (Ekoscroll Alfa Pellet) equipped with a 25 kW bottom-feed retort burner. The boiler is rated for Ecodesign in accordance with the EU Directive 2009/125/EC. The retort burner is commonly used for firing lump coal. For spruce pellets, more efficient burners are available on the market. However, for pellets with the high ash content, i.e. made from herbaceous biomass, agricultural residues etc., the retort burner is generally the best choice. The boiler consists of five passes: the first pass (combustion chamber) is equipped with firebrick cladding and the third and fourth passes are equipped with turbulators. The boiler was run at commonly used operating conditions, i.e. inlet water temperature of 60 °C and outlet water temperature of 80 °C, at its rated power output or as close to it as possible. The draft at the stack was kept at 12 Pa.

Table 2
Optimal average boiler operating conditions for each of the tested biofuels.

	Power output	Flue gas temperature	O_2 content	CO	TOC
	kW	°C	vol %	mg/m^3	mg/m^3
SP	21.6	166	9.22	128	1.31
MA1	15.5	134	8.85	376	4.03
MA2	21.1	165	10.19	1722	16.99
MA3	14.9	140	10.56	1241	7.10
MA4	20.6	158	8.46	178	1.03
PS1	17.4	133	9.71	144	1.74
PS2	11.6	122	13.63	1462	17.54
PS3	11.5	123	13.85	1596	22.50
MS	21.1	154	7.71	344	1.93
ML	19.1	152	8.22	403	0.55
SA	20.5	159	8.67	106	0.34

4.3. Combustion conditions

The combustion conditions under which the biofuels were fired (Table 2) were optimal for each fuel. These values were established through an extensive series of pilot tests and represent the right balance between the highest possible power output and minimal unburnt carbon content in the ash. As such, the average power output is different for each fuel. The power output was measured calorimetrically in real time and was regulated by the auger work/pause cycle. The combustion efficiency was determined from the O_2, CO and TOC values measured in real time and was regulated by the air supply fan RPM. The process conditions listed in Table 2 include the average power output, the flue gas temperature measured at the stack sampling point, oxygen concentration in the flue gas, CO and TOC emissions.

4.4. Emission measurements

The emission measurements were carried out in accordance with the standard EN 303–5 [11] using a multicomponent gas analyzer Horiba VA-5000 series (model VA-5116 for NO_x and SO_2, VA-5111 for CO, PMA 10 for O_2 and SK-Elektronik Thermo FID for TOC). Flue gas was sampled from an insulated stack with the sampling point located 1100 mm above the boiler outlet. Nitrogen oxides were measured with a dual-beam non-dispersive infrared absorption (NDIR) method and are reported collectively as NO_x (NO_2 being the referential oxide). The analyzer has two ranges for NO_x measurement: 0–700 and 0–2000 mg/m^3. The deviation from linearity is 0.3 %FS (of full scale) for the lower range and 0.4 %FS for the higher range. The repeatability for both zero and span is within 0.5 %FS and the 95 % response is below 25 s. The reported drift of the analyzer is below 1 %FS/week and the analyzer is being calibrated in monthly intervals. The calibration gases contain 363.3mg/m^3 and 1759.1 mg/m^3 of NO for the low and high range, respectively. The estimated expanded uncertainty of the NO_x measurement ($k = 2$) is below 15 mg/m^3. CO and SO_2 concentrations were measured in a similar manner as NO_x. To determine TOC concentrations, a flame ionization detector (FID) was deployed. The O_2 concentrations were measured paramagnetically. Prior to the analysis, the flue gas sample undergoes conditioning (moisture removal and cooling), so that the measured sampled gas volume is recorded at normal conditions. The emissions are measured in volume concentrations (ppm) and then converted to mass concentrations (mg/m^3). The values are recorded in one-minute averaging windows and referenced to oxygen concentration of 10 %, so that the varying dilution by air is eliminated. The final concentrations presented in the dataset are thus reported at normal conditions (1013 mbar and 0 °C), in dry gas and referenced to 10 % O_2, as is the common practice. The conversion from ppm to mg/m^3 and referencing to 10 % O_2 content for NO_x was done using the following equation:

$$NO_x(ref.) = NO_x(ppm) \cdot f_{NO2} \cdot \frac{21 - O_2(ref.\%)}{21 - O_2(meas.\%)}\left(mg/m^3\right) \quad (1)$$

where NO_x (ref.) is the value reported in the dataset, NO_x (ppm) is the concentration measured and recorded by the analyzer, f_{NO2} (2.053) is the conversion factor for NO_x (ppm) to NO_2 (mg/m^3), O_2 (ref.) is the reference oxygen concentration of 10 % and O_2 (meas.) is the recorded O_2 concentration corresponding to the individual NO_x measurement. The conversion factors for the other gases were 2.858 for SO_2, 1.25 for CO and 1.64 for TOC (with propane as the calibration gas). The referencing to 10 % O_2 content was done according to Eq. 1.

Limitations

The dataset and its acquisition have certain limitations that may affect the reproducibility of results. The gas analyzer and thermocouples were frequently calibrated to reduce drift; however, minor measurement errors could still occur. Boiler operation was fine-tuned by a series of pilot tests; however, the same results under the same conditions may not be achievable on another heating appliance, due to the fact that nitrogen oxides originate through a variety of pathways. Nonetheless, the data presented in this study clearly demonstrates a dramatic increase in fuel originated NO_x emissions when firing nitrogen-rich agricultural residues in local heating appliances. To maintain a high degree of reproducibility, future experiments should be carried out on automatic pellet boilers equipped with a bottom-feed retort burner and rated power output around 25 kW. No air staging should be present in the combustion chamber. The combustion chamber should be water-cooled and equipped with sufficient firebrick cladding to prevent flame quenching and to allow complete burnout of CO and volatile combustibles. The temperature at the combustion chamber outlet should be below 500 °C. The flue gas sampling should be carried out in accordance with EN 303–5 [11] on a certified NO_x and O_2 gas analyzer.

Ethics Statement

The authors confirm to have been informed about ethical requirements for publication in the journal Data in Brief and follow them. They further confirm that this research does not include experiments on humans, animals or data obtained from the platforms of social media.

CRediT Author Statement

Julie Sobotková: Conceptualization, Investigation, Formal analysis, Supervision. **Tereza Zlevorová**: Conceptualization, Investigation, Data Curation, Writing – Original Draft, Visualization. **Jakub Lachman**: Conceptualization, Methodology, Investigation, Writing – Original Draft. **Antonín Kintl**: Conceptualization, Investigation, Project administration, Funding acquisition, Resources. **Marek Baláš**: Supervision, Validation. **Martin Lisý**: Project administration, Funding acquisition, Resources. **Jakub Elbl:** Supervision, Validation, Writing – review & editing.

Data Availability

Data for the assessment of NOx emissions from firing various nitrogen-rich agricultural residues (Original data) (Mendeley Data).

Acknowledgements

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Declaration of Competing Interest

The authors declare there are no competing financial interests or personal relationships known to them that could have appeared to influence the work reported in this paper.

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Glossary

d: dry basis
daf: dry ash-free
FID: flame ionization detector
HHV: higher heating value
LHV: calorific value
MA: *Melilotus albus*
ML: *Medicago lupulina*
MS: *Medicago sativa*
NDIR: non-dispersive infrared absorption
PS: *Papaver somniferum*
SA: *Sinapis alba*
SP: spruce pellets
TOC: total organic carbon