



UNIVERSITÀ DI PARMA

ARCHIVIO DELLA RICERCA

University of Parma Research Repository

An overview of nitrogen oxides emissions from biomass combustion for domestic heat production

This is the peer reviewed version of the following article:

Original

An overview of nitrogen oxides emissions from biomass combustion for domestic heat production / Ozgen, S.; Cernuschi, S.; Caserini, S.. - In: RENEWABLE & SUSTAINABLE ENERGY REVIEWS. - ISSN 1364-0321. - 135:110113(2021), pp. 110113.1-110113.9. [10.1016/j.rser.2020.110113]

Availability:

This version is available at: 11381/2961387 since:

Publisher:

Published

DOI:10.1016/j.rser.2020.110113

Terms of use:

Anyone can freely access the full text of works made available as "Open Access". Works made available

Publisher copyright

note finali coverpage

(Article begins on next page)

02 May 2026

An overview of nitrogen oxides emissions from biomass combustion for domestic heat production

Ozgen S*
Laboratory of Energy and Environment Piacenza (LEAP), Italy
e-mail: senem.ozgen@polimi.it

Cernuschi S, Caserini S
Department of Civil and Environmental Engineering (DICA)
Politecnico di Milano, Milano, Italy
email: stefano.cernuschi@polimi.it; stefano.caserini@polimi.it

* corresponding author

Abstract

In order to fulfill the EU's climate and energy goals, the heating and cooling sector must cut its use of fossil fuels. Solid biomass can constitute an alternative to fossil fuels as a renewable and carbon-neutral source of energy but there are some aspects to biomass combustion in small scale domestic appliances that can compromise the environmental sustainability of this renewable energy source in terms of burden on air quality. The priority pollutants in this respect are particulate matter (PM) and nitrogen oxides (NO_x). While PM emissions are often discussed, NO_x emissions from domestic heating appliances are relatively less in the center of attention. The aim of the present study is to review the literature regarding the NO_x emissions from this emission source discussing the main formation mechanisms and the state-of-the-art control techniques, as well as the influence of fuel composition (especially fuel bound nitrogen), heating appliance type and operating conditions with the help of the gathered experimental emission factors data. The review crosslinks several aspects usually treated separately in scientific papers (e.g., only laboratory tests with basic theory or only field tests on emission levels etc.), providing thus a quick reference tool to the state-of-the-art knowledge on this topic.

Highlights

- NO_x emissions from biomass combustion mainly from the fuel bound nitrogen
- Average emission factors in the range of 67-79 mg/MJ for woody biomass combustion
- Hard times for the introduction in the market of N-rich alternative solid biofuels
- Research on NO_x abatement technologies in small scale heating appliances is needed

Keywords

Nitrogen oxides; emission factors; domestic heating; fuel bound nitrogen; char oxidation; air-staging; NO_x control; biomass combustion.

Word Count: 6135

1. Introduction

1
2
3 EU adopted the binding renewable energy target of at least 32% by 2030 which requires
4 member states to increase their proportion of renewable heat. In order to fulfil the EU's
5 climate and energy goals, the heating and cooling sector must cut its use of fossil fuels.
6 Biofuel use gains thus a crucial importance in the EU strategy for heating and cooling
7 together with other renewable heating and cooling technologies.
8

9
10 Solid biomass is potentially interesting given the high share (82%) in renewable heat
11 production and the advantage of the lower energy price with respect to fossil fuels. It can play
12 an important role in CO₂ emissions mitigation and be an alternative to fossil fuels as a
13 renewable and carbon-neutral source of energy but there are some aspects to biomass
14 combustion for domestic heat production that can compromise the environmental
15 sustainability of this renewable energy source in terms of burden on air quality. The priority
16 pollutants in this respect are particulate matter (PM) and nitrogen oxides (NO_x).
17

18
19 PM emissions are often discussed and pointed out as a major contributor to the air pollution in
20 lower atmosphere [1]. Since there are frequent exceedances of the PM air quality limit values,
21 more and more restrictions are in act including ban of less efficient biomass heating
22 appliances. NO_x emissions on the other hand are relatively less in the centre of attention even
23 though life cycle assessment studies indicate that a great part (40%) of the environmental
24 impact of a modern automatic wood furnace may be associated with NO_x emissions [2].
25

26
27
28 The present review aims to address key issues regarding NO_x emissions from domestic
29 heating appliances (indicatively <50 kW) fed with solid biomass in different forms (e.g.,
30 densified biomass such as pellets, firewood). First, various studies investigating the NO_x
31 formation from biomass combustion are synthesized to prospect the main aspects regarding
32 the formation and reduction of NO_x since a correct understanding of the parameters
33 regulating NO_x release contribute to the development of combustion technologies with
34 reduced emissions. Second, primary control mechanisms applied to domestic heating
35 appliances are presented and discussed with particular attention to air-staging as it is the main
36 control method applied to non-industrial appliances. Given the dominant influence of fuel
37 bound nitrogen (fuel-N) on NO_x emissions, this aspect is specifically addressed. The effect of
38 other fuel components is also discussed. Finally, given the important role that emission
39 factors play in the quantitative estimations of the emission source contributions to the
40 atmospheric levels, a review of literature experimental emission factors is reported and the
41 results are discussed in terms of the influence of heating appliance type and operating
42 conditions. The paper is concluded with a quick a comparison of biomass combustion for
43 domestic heat production with major fossil fuel alternatives and the assessment of the
44 gathered emission factors in the framework of national and European regulatory framework.
45
46
47
48

49
50 To the authors' knowledge this is the first review paper on NO_x emissions from small scale
51 (50 kW) domestic heating appliances burning solid biomass which crosslinks several aspects
52 usually treated separately in scientific papers (e.g., only laboratory tests with basic theory or
53 only field tests on emission levels etc.), providing thus a quick reference tool to the state-of-
54 the-art knowledge on this topic.
55
56
57
58
59
60
61
62
63
64
65

2. Methodology

72 scientific articles (predominantly from peer-reviewed journals, few from conference papers) and 15 other type of documents (i.e., web pages, databases etc.) were consulted in order to give an overview of NO_x emissions from small scale biomass combustion appliances. Table 1 summarizes the consulted scientific papers in terms of research area.

Table 1. Summary of the consulted scientific papers and the breakdown for the research area

Main research area	Total number of articles	References
NO _x formation mechanisms	13	[12-24]
NO _x control techniques	19	[2, 20, 25-41]
Fuel characterization	10	[2-11]
Fuel indexes and NO _x prediction from fuel-bound nitrogen	5	[28, 42-49]
Experimental NO _x emission factors	41	[6, 7, 9, 39, 41, 47, 50, 52-69, 71-86]

The papers were basically representative of European residential heating appliances (indicatively <50 kW). Few laboratory combustor studies discussing the fuel effects, or the influence of combustion air control were also included. The investigated appliances included automatically fed pellet boilers, multi-fuel boilers, wood log boilers, automatic or batch-fired room heaters (i.e., local space heaters), heat accumulating and slow heat release appliances, fireplace inserts, open fireplaces. Greater part of automatic boilers was equipped with air-staging solutions. Some were combined with heat storage buffer tanks. Most of the room heaters resulted characterised by a single common chamber for the thermal decomposition and combustion of formed gaseous flammable products (single stage combustion). Very few were equipped with specific secondary air inlets (diverse from window flush air). The biomass used comprehended wood and woody biomass, agriculture residues (husks, pits, shells, grains, pruning residues etc.), herbaceous biomass (grasses and straws), treated wood and wood industry residues, and food industry residues. The fuel was fed either as firewood (with and without bark) or in a densified form such as pellets or briquettes.

The collected emission factors were categorized in terms of heating appliance type (automatic vs. manually fed (i.e., batch working) appliances) and the origin of the biomass fuel (woody vs. non-woody biomass). Data analysis mainly consisted of the summary of experimental emission factors through descriptive statistics of the grouped data (i.e., per appliance and fuel type) and the graphical representation in the form of boxplots. Bootstrap confidence intervals (95%CI) were also calculated for group averages to have an idea whether there could be a significant difference between the investigated groups: largely overlapping confidence intervals would suggest a lack of statistical significance in the observed differences.

The main parameters of interest were the experimental NO_x emission factors, biomass fuel characterization (e.g., fuel-bound nitrogen, ash content, heating value), heating appliance characteristics and operational details. The gathered data, where necessary, was pre-processed as follows prior to statistical analyses to summarize the results or to investigate the fuel-N to NO_x relationship:

1 the fuel [18] and it is important because while the conversion of volatile-N can be reduced by
2 air control, char-N conversion into NO_x emissions is more difficult to overcome [19].

3 The volatile-N are converted into NH_i radicals through gas phase combustion (Reaction R3).
4 These radicals can either be oxidized (Reaction R3) to NO in oxygen rich conditions or can
5 work as a reduction agent and reduce the already formed NO to N₂O (Reaction R7); thus, they
6 are the driving force in NO_x reduction [20]. The presence of NO promotes the production of
7 N₂ which leads to a reduction in the conversion rate of fuel-N to NO for fuels with a higher
8 fuel-N because the concentration of gaseous N-species (including NO) increases [21].
9

10
11 The char-N on the other hand is oxidized to NO in the presence of oxygen (Reaction R4).
12 The initially formed NO is partly reduced (Reaction R5) inside the pore of the char particles
13 by heterogeneous or homogeneous reactions in the presence of CO catalyzed by char surface
14 and inorganic components [22, 23]. During char oxidation (Reaction R4) N₂O is also formed
15 to a much lower degree through homogeneous mechanism involving the release of HCN and
16 HNCO (Reaction R6) and the following reaction of NH and NCO radicals with NO (Reaction
17 R7), or through heterogeneous oxidation of the char-N (Reaction R4). The formed N₂O can
18 be, in turn, reduced to elementary nitrogen in presence of H₂O vapor and CO (Reaction R8)
19 [24].
20
21
22
23

24 **4. NO_x control in small scale biomass combustion**

25
26 Advanced understanding of the fuel-N mechanism contributes to the development of
27 combustion technologies with reduced NO_x emissions. Several methods used in large
28 combustion plants to control NO_x emissions such as air staging, fuel staging, flue gas
29 recirculation, selective catalytic reduction (SCR) and selective non-catalytic reduction
30 (SNCR). While the first three methods are primary measures (i.e., applied directly in the
31 region where the fuel is burned), the latter two are secondary measures applied downstream
32 the combustion area. The detailed description of the methods can be found in [2, 20, 25]. The
33 application of these measures to small scale heating appliances (<35 kW) is frequently not
34 equally efficient or feasible because of technological/operational aspects (e.g., too small
35 combustion chambers) and excessive costs of the abatement with respect to the heating
36 appliance cost.
37
38
39
40

41 Nonetheless, many authors experimentally investigated the application of some of the NO_x
42 control strategies on medium scale (35 kW – 500 kW) biomass boilers and laboratory-scale
43 combustors. Especially the application of air staging drew attention for its relative simplicity.
44
45

46 **4.1 Air staging applied to small heating appliances**

47
48 In air staging the combustion air is introduced into the furnace in stages, creating a fuel-rich
49 zone in the primary combustion zone where reduction conditions prevail due to lack of
50 oxygen, and a burnout zone where more air is injected to complete the fuel combustion. Air
51 staging applied to biomass combustion in small scale combustion appliances was studied in
52 literature through tests on real-scale plants or in laboratory furnaces, as well as with
53 computational fluid dynamics (CFD) studies.
54
55
56

57 Different air staging configurations have been experimented on an underfeed stoker biomass
58 pellet boiler (50 kW) including varying primary to secondary air ratios and different heights
59 of the secondary air inlets above the fuel bed [26]. Their results showed that air staging lead
60
61
62
63
64
65

1 to an effective NO_x reduction especially during combustion of fuels with higher fuel bound
2 nitrogen. The height of the secondary air inlets above the bed was found to have important
3 impacts on both NO_x and CO emissions. They suggest the adoption of bigger/taller
4 combustion chambers in the design. The lowest NO_x emissions were achieved under ‘strong
5 staging’ conditions corresponding to a stoichiometric ratio of the primary combustion zone of
6 about 1.25, while maintaining good combustion conditions and ‘acceptable’ CO emissions.
7 They however point out the need to carefully consider the trade-off between NO_x and CO
8 emissions since air staging may cause an increase in CO and unburnt hydrocarbons.
9

10 The parameters influencing NO_x control in various techniques can be further investigated
11 with laboratory reactors. Primary excess air ratios similar to boiler tests were found also in
12 these studies. For example, NO_x emission control by air-staging has been studied through
13 experiments with a grate-combustion multifuel reactor fed with different pelletized biomass
14 feedstocks and their mixtures [27, 28]. The experiments revealed that air-staging can be
15 effectively used for the NO_x emission reduction from grate biomass combustion. The primary
16 excess air ratio was found to be the most important parameter and an optimum value of 0.9
17 (fuel rich condition) was defined for the experimental conditions investigated. It was observed
18 that the optimum value may be influenced by low ash melting characteristics of the fuels if
19 sintering occurring on the fuel grate lowers the actual available oxygen with respect to the
20 amount fed to the reactor [28]. Experimental results for both staged and non-staged air
21 combustion have shown that NO_x emission levels are not affected significantly by
22 temperature for temperatures lower than 1000°C [27]. A similar lack of influence for the
23 temperature was shown burning woody biomass in a pellet boiler (35 kW) with air staging
24 and flue gas circulation [29]. This study concluded that the optimum primary air ratio is
25 independent of the fuel used for any given technology whereas the actual primary air ratio at
26 which NO_x emissions are minimized is a characteristic of the technology/boiler design. It was
27 also highlighted that high NO_x emissions of energy grasses can be reduced by up to 30% by
28 air staging. Discussing the effect of residence time on NO_x reduction efficiency with inherent
29 literature data [30, 31] it is concluded that residence times greater than 0.3-0.7s are required to
30 optimize NO_x reduction and primary combustion chambers in residential heating boilers are
31 often too small (short residence time) for efficient NO_x reduction.
32
33
34
35
36
37
38

39 Regarding small wood log burning room heaters, NO_x emissions from wood stoves were
40 studied through computational fluid dynamics (CFD) modelling of a 5 kW natural draft wood
41 log stove with primary air injected through slots at the bottom, secondary air through holes at
42 the back wall of the stove and flushing air injected vertically through a slot above the front
43 glass window [32, 33]. This configuration is different than the classic air staging in boilers
44 since the mixing of fuel gas and primary air is far from complete before the secondary air is
45 injected. The results have shown a significant NO_x reduction at a primary excess air ratio of
46 0.8, indicating the potential of NO_x reduction by staged air combustion also in these small
47 domestic appliances. Air staging was proposed also by other authors as an efficient way of
48 reducing emissions for chimney stoves without specific reference to NO_x emissions [34].
49
50
51

52 The performance of a lambda-sensor-controlled pellet boiler (15 kW) fired with agricultural
53 fuels was tested [35] and lambda control was discussed as an efficient way to reduce NO_x
54 emissions especially for non-woody biomass fuels without compromising complete
55 combustion. Another study investigated the influence of excess air and air distribution on the
56 emissions of domestic top-fed pellet stoves (12 kW) with various combustion chamber
57 heights (i.e., base model, shorter, taller), and burner pot configurations, these latter differing
58 in the total area, the primary air inlet area, and the ratio between the inlet area for primary and
59
60
61
62
63
64
65

secondary air [36]. The excess air was identified as the main parameter influencing NOx emissions, with no striking effect either of pot design or of the combustion chamber height. While NOx emissions showed an increasing linear relationship with flue gas O₂ when burning wood pellets (usually fuel-N<0.1%w) [36], NOx emissions were relatively insensitive to excess oxygen in the flue gas during combustion of grass pellets or grade 3 wood pellets (fuel-N=0.19%w) [37].

The effect of air staging ratios on the burning rate and emissions of a low-scale biomass combustor with an underfeed fixed-bed (5-12 kW) was studied [38] exploring the influence of using lower air staging ratios (15%-30%) with respect to regular ratios used for commercial boilers and burners (30%-50%, [26]). It was shown that an increase in the total airflow rate generates a higher fuel devolatilization in the bed and a greater availability of air in the secondary zone to burn the volatilized matter. Increased NOx emissions corresponding to increased primary airflow suggested associations with the increase in the burning rate.

The emissions from a modern wood pellet boiler (25 kW) for residential heating was studied with different air-staging settings and under different load operations (full load, half load, minimum load) [39]. Air-staging was experimented with alternatively reduced primary (71-82% decrease) and secondary air (17-33% decrease) simultaneously keeping constant the total air/fuel ratios. No striking differences in the emissions were observed for various experimental conditions.

4.2 Alternative methods

Given the direct relationship of NOx emissions with the fuel-N content some authors have also investigated fuel pre-treatment as a way of reducing NOx emissions. For example, wood washing was experimented as a pre-treatment on beech, oak, and fir woods, all with fuel-N content lower than 0.1 %_w [40]. The combustion of pelletized washed-biomass in a domestic pellet stove showed that the washing procedure did not affect the emissions of NOx in the exhaust (Fig. 2).

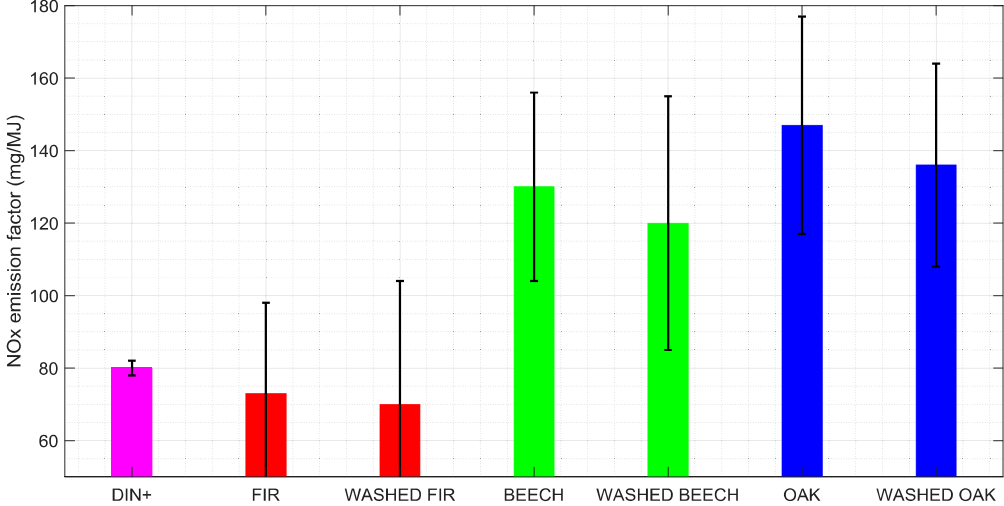


Fig. 2. Average and standard deviations of NOx emission factors from combustion of washed and non-washed biomass [40]

Another study [41] observed co-benefit in NOx reduction of fuel additives while investigating assortments to produce bench-scale agricultural biomass test fuels compliant with local boiler

1 tests criteria. The effect of fuel additives on the emissions was tested on a pellet boiler (49
2 kW) with separately controllable primary and secondary air firing herbaceous biomass,
3 namely wheat straw pellets (WSP, fuel-N=0.9%_{daf}) and wheat grain pellets (WGP, fuel-
4 N=1.6%_{daf}) as base case. No notable difference was observed between base case WSP and test
5 fuel with additives containing various mixtures of KCl+CaCl₂ (test fuel-N=0.8%_{daf}), or
6 K₂CO₃+CaCl₂ (test fuel-N=1.3%_{daf}). Interestingly, the addition to WGP of some bottom ash
7 from the combustion of the very same wheat grain assortment (test fuel-N=2.5%_{daf}) decreased
8 NOx concentrations of about 23% with respect to the base case (from 505±19 mg/m³ to
9 388±38 mg/m³).

11 12 13 **5. NOx emission factors in the literature**

14 15 **5.1 Influence of fuel bound nitrogen on NOx emissions**

16 Many authors have highlighted the relationship between fuel-N and NOx emissions explained
17 in section 3. For example, relevant combustion properties of fuels obtained from woody and
18 herbaceous biomass, as well as some agricultural and industrial residues were studied in order
19 to propose fuel indexes applicable to predict combustion related problems in fixed-bed
20 biomass combustion systems [42]. Fuel-N was used as an indicator for NOx emission
21 potential and increasing NOx concentrations were observed with increasing fuel bound
22 nitrogen [42, 43]. This finding is congruent with many other studies on domestic biomass
23 appliances fired with fuels with different fuel-N content [37, 44, 45, 46, 47]. An opposite
24 trend is obtained for the conversion rate of fuel-N to N in NOx emissions which decreases for
25 higher fuel-N content. It is concluded that for state-of-the-art grate-fired combustion units
26 with air-staging technology burning medium- (0.4-1 %_{w,db}, e.g., short rotation crops, straw) to
27 high-N fuels (1-10 %_{w,db}, e.g., cereals, waste wood) NOx concentrations higher than 200
28 mg/m³ (NTP, dry gas, 13% O₂) are to be expected [42].

29
30
31
32
33
34 In the present study, the relationship between the fuel-N content and NOx emissions is
35 explored based on the reviewed experimental emission factor data. Fig. 3 shows the literature
36 NOx emission factors lumped into groups in function of the fuel bound nitrogen content.
37 Except few data points scattered outside the ±2.7σ region, for fuel-Ns lower than 0.4%_w
38 average emission factor is about 64 mg/MJ (roughly 94 mg/m³ NTP, 13%O₂). The 75th
39 percentile value for fuel-Ns lower than 0.8%_w is 142 mg/MJ (roughly 209 mg/m³ NTP,
40 13%O₂). This fuel-N range (fuel-N < 0.4%_w) covers most of the woody biomass frequently
41 used in room heaters as well as some non-woody or residual biomass (e.g., wheat, walnut
42 shell) tested in domestic boilers. Ample variability in NOx emission factors is present for
43 fuel-Ns within the range 1.1%_w-2.3%_w with an average value of 187 mg/MJ (roughly 275
44 mg/m³) and 90th percentile of 433 mg/MJ (roughly 637 mg/m³). Higher nitrogen content in
45 the fuel (> 2.3 %_w) surely requires advanced NOx control measures since average emission
46 factors are placed around 513 mg/MJ (roughly 755 mg/m³) and 90th percentile of 679 mg/MJ
47 (roughly 998 mg/m³).

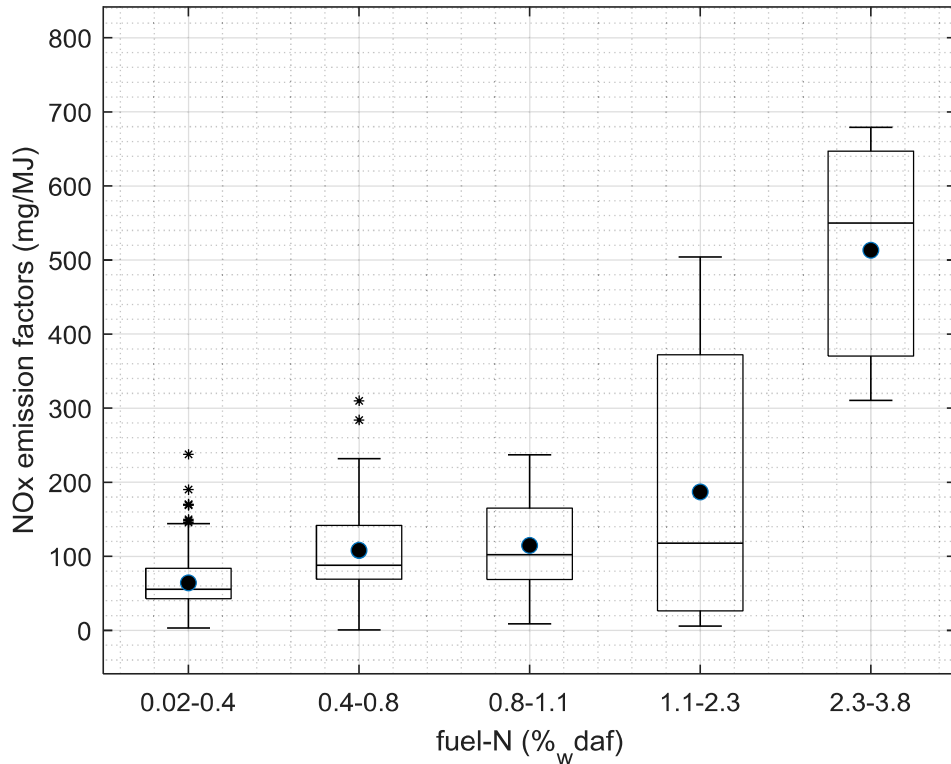


Fig. 3. Literature NOx emission factors grouped by fuel-N. (daf: dry ash free)

Regarding the conversion of fuel bound nitrogen into nitrogen in NOx emissions ($X_{\text{NOx-N}/\text{fuel-N}}$) Fig. 4 shows an exponential decline ($X_{\text{NOx-N}/\text{fuel-N}} = 1.014 e^{-101.97 N} + 0.1541 e^{-0.2796 N}$) in the conversion with increasing fuel-N, confirming the trend mentioned by [42]. The same dependency expressed in the form of a power function ($X_{\text{NOx-N}/\text{fuel-N}} = 0.08124 N^{-0.7405}$) was very similar to observations made for industrial chip boilers (300-2500 kW) [48] and for a laboratory combustor fed with several woody/non-woody fuels and fuel mixtures [49], despite the smaller scale of the heating appliances and the greater heterogeneity of appliances, fuels and operating modes considered in the present review study. The minimum conversion potential representative of the combustion at the optimum condition (i.e., primary excess air ratio of 0.9–0.95) is also graphically of a similar in shape [28]. The reduction in the conversion rate with increasing fuel-N is explained by the promoting effect of the presence of NO on the production of N₂ because the concentration of nitrogen species in the gas phase, including NO, increases when burning high-N fuels [21].

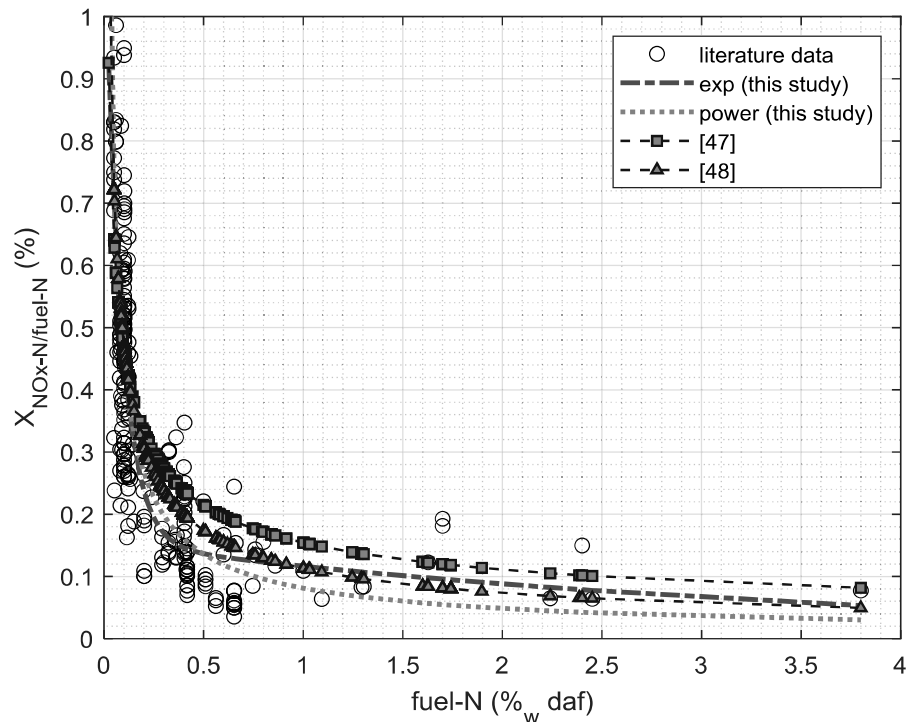


Fig. 4. Conversion of fuel bound nitrogen into nitrogen in NO_x emissions ($X_{\text{NO}_x\text{-N}/\text{fuel-N}}$) (daf: dry ash free)

5.2 Influence of other fuel constituents on NO_x emissions

The NO_x release in biomass combustion is regulated by a combined effect of fuel-N, fuel carbon (fuel-C) and fuel-ash content. As seen in Fig. 1, fuels with lower fixed carbon are expected to have lower emissions associated with char oxidation and net NO_x formation from fuel-N is influenced also by char-surface catalyzed reduction reactions.

The char/ash-effect on the formation and destruction of NO_x was observed during tests on a multi-fuel domestic boiler (40 kW) firing the appliance with several different woody and non-woody biomass pellets (e.g., herbaceous biomass, agriculture wastes) with fuel-Ns ranging from 0.4%_w for wood pellets to 1.7%_w for food industry residues [9, 50]. Distinct behavior in NO_x emissions was observed for different type of pellets and the importance of considering the catalytic effects of char and ash on the formation and reduction of NO_x was highlighted when dealing with high-ash fuels such as agro-pellets. The authors report a 7-fold increase in NO_x emissions for straw pellets (fuel-ash=10.7%_w, fuel-N=0.9%_w) with respect to wood pellets (fuel-ash=0.41%_w, fuel-N=0.1%_w). Ref. [18] discuss that most solid biofuels obtained from agricultural residual biomass have high contents of volatile matter and low contents of fixed carbon with reduced effect of char on the formation of NO_x, nonetheless the catalytic effect of the ash could be important for some residual biomass such as cotton husks, mustard husk, soya husks and groundnut husks which have high CaO contents that can lead to active surfaces capable of catalyzing the reduction of NO and N₂O.

Higher amounts of carbon is reported [51] to correspond to a higher net conversion of fuel-N to NO because as the carbon content increases, nitrogen is preferably bound in heterocyclic structures leading to the formation of HCN, rather than being present in the form of amines or quaternary-N structures, leading to the formation of NH₃ which is a stronger reductant of NO

1 than HCN. This latter on the other hand tends to reduce NO to N₂O, rather than to N₂, and
2 N₂O can degrade again to NO in fuel lean conditions and at low temperature.
3

4 **5.3 Influence of appliance type and operating conditions**

5
6 41 scientific papers [6, 7, 9, 39, 41, 47, 50, 52-69,71-86] were consulted in order to give an
7 overview of NO_x emission factors from small scale biomass combustion appliances (Table 1).
8 The highest NO_x emission factors were observed for automatic boilers and stoves burning
9 non-woody biomass (average: 286 mg/MJ; 95%CI: 224 mg/MJ-398 mg/MJ) and the lowest
10 for manually fed stoves and boilers burning firewood (average: 67 mg/MJ; 95%CI: 63
11 mg/MJ-72 mg/MJ). Feeding the automatic appliances with woody biomass and the usage of
12 non-woody biomass in manually fed appliances give comparable emissions factors with an
13 average of 79 mg/MJ (95%CI: 74 mg/MJ-86 mg/MJ) for the former and 98 mg/MJ (95%CI:
14 50 mg/MJ-180 mg/MJ).
15
16

17
18 Varying operating conditions and transitory periods have been shown to have a limited effect
19 on NO_x emissions for automatic boilers. For example, tests on a domestic wood pellet boiler
20 (22 kW) have shown that NO_x emissions have a marginal dependence of the boiler operating
21 conditions (excess air range around 2.6-4.6) [44]. Comparable emission factors for the steady
22 operation and transitory periods were obtained testing the emissions of residential combined
23 solar-wood pellet heating systems (12-20) under a realistic operation sequence including start-
24 up and stop phases [55]. Reducing the number of start and stops by modulating the appliance
25 power and using buffer stores had no visible effect on NO_x emissions. Since NO_x release
26 depends strictly on the fuel bound nitrogen, hence the fuel consumption, the start and stop
27 phases accounted only for the 10%-20% of accumulated NO_x emissions throughout the
28 operating sequence. A lack of marked differences between low to high power operation was
29 also obtained during tests on 12 kW – 20 kW boilers and a stove fired with woody pellets
30 [56]. Tests on a top-feed wood pellet boiler (25 kW) with controlled secondary air have
31 shown that average NO_x emission factors were almost equal for the boiler start phase and the
32 optimal operating conditions [57]. The optimal operation entailed only less variability in the
33 data. Reduced secondary air and the associated reduced oxygen supply slightly decreased
34 (about 10%) the emission factors. Similar observations were made on further studies on the
35 same boiler [58]. However, switching to a fuel with twice as much fuel-N almost doubled the
36 emission factor for the same boiler operating under optimal conditions stressing the
37 importance of fuel-N mechanism on NO_x formation [57]. Slightly decreased NO_x emission
38 factors (about 15%) were observed by closing the secondary combustion air inlet of a two-
39 stage up-draft pellet boiler [59]. Tests on 3 room heaters fed manually with different woody
40 biomass has shown that inclusion in the simulated real-life combustion cycles of final batches
41 with limited combustion air supply did not have a significant effect on NO_x emissions [60].
42
43
44
45
46
47

48
49 The influence of operating conditions seems to be more marked for automatic room heaters
50 with respect to boilers. In fact, for wood pellet stoves operated under full load an increase of
51 about 30%-35% in the emission factor was observed with respect to the operation under
52 partial load [59, 61]. An even higher emission factor was observed during operation with
53 higher burn rate (1.4-fold increase with respect to nominal load) [61]. Other tests with woody
54 biomass on a pellet stove (6 kW) and a multi-fuel chip boiler (40 kW) indicated higher
55 influence of the full load operation with respect to partial load operation when testing the
56 wood chip boiler rather than the pellet stove [62]. Limited effects of stove load on NO_x
57 emission factors between high and low loads were also reported for other stoves [63]; only a
58
59
60
61
62
63
64
65

1 small a decrease (around 10%) in NO_x emissions under low load conditions were noted with
2 lower excess oxygen in one of the tested stoves.

3 The user behavior influence (i.e., fuel charging, combustion air control, fuel quality) and
4 burning cycle (standard vs. real-life) shown to be of crucial importance for incomplete
5 combustion product emissions such as particulate matter from manually fed room heaters
6 results to have limited effect on NO_x emissions. Ref.60 compared real-life and standard
7 burning cycles (EN 13240:2001) and observed only about a 40% increase as a consequence of
8 the non-optimal operating conditions on NO_x emissions. No differences in NO_x emission
9 factors were observed between good operational practice and non-optimal operation (i.e.,
10 restricted combustion air supply and slight overload of the firebox) of a conventional masonry
11 heater (no staged-air, only minor window flush air) [64]. Similarly, the results of the
12 maloperation tests (i.e., minimum air level and high fuel load) on a logwood stove with
13 secondary air inlet (6 kW) have shown no striking differences with the standard operation,
14 interestingly the same tests on a conventional 6.5 kW stove (only primary air) caused a 30%-
15 40% decrease in NO_x concentrations during maloperation [61]. Slow ignition of a modern
16 masonry heater equipped with air staging technology did not show any particular effect on
17 NO_x emission factors [65].

18 With regard to combustion phases, some authors reported higher emission factors for the
19 flaming phase with respect to ignition and smoldering phases [59, 66] this is consistent with
20 the fuel bound nitrogen release mechanisms reviewed previously, since during smoldering the
21 dominant feature is the char-N conversion [67] with less NO_x formation with respect to
22 volatile-fuel-N conversion pathway.

23 Regarding the fuel quality, investigation of the influence of using fuels with relatively high
24 moisture content in manually fed appliances has pointed out that similar emission factors
25 were obtained both feeding dry (16.4%_w moisture) and wet (23.5%_w moisture) wood logs to a
26 conventional single-stage logwood stove (6 kW), except for a 3-fold increase during the burn-
27 out phase of one of the wet-log tests [59]. The same authors report about a 30% decrease in
28 the flaming phase emission factor when using wet logs (42.4%_w moisture) instead of dry logs
29 (13.3 %_w moisture) in a two-stage batch operated downdraft automatic wood boiler. The
30 emission performance of a residential stove (5.7 kW) burning high moisture woody biomass
31 was studied and it was concluded that NO_x emissions were more affected by the fuel-N
32 content rather than the fuel moisture [68]. Nonetheless, the study suggested that for the tested
33 hard wood species the fuel moisture may influence the nature of the emission of the nitrogen
34 species (i.e., partitioning between NO_x and NH₃). On the contrary, increased emission factors
35 were observed in another research study on the combustion of wet branches in a wood stove
36 (30 kW) for domestic hot water and space heating [69]. Similar findings were obtained on a
37 domestic heating wood chip boiler (50 kW) fed with logs of the same wood type but with
38 different moisture levels (<25%, 26-39%, >40%) with almost tripling concentrations for the
39 moist fuel (>40%) during the full load operation [70]. Moisture is reported to potentially
40 affect the quality of the combustion by greatly delaying the release of the volatiles [18].

53 **5.4 Comparison with fossil fuel alternatives**

54 The comparison of the literature residential heating experimental emission factors for biomass
55 combustion and common fossil fuels is shown in Fig. 5. Average emission factor for
56 automatic biomass appliances fed with woody biomass (79 mg/MJ) is 1.3 times the average
57 emission factor reported for light oil boilers (61 mg/MJ) under various operating conditions
58
59
60
61

[47, 52, 53, 54]. About a two-fold increase is observed when compared with the natural gas boilers (41 mg/MJ) studied in literature [53, 54].

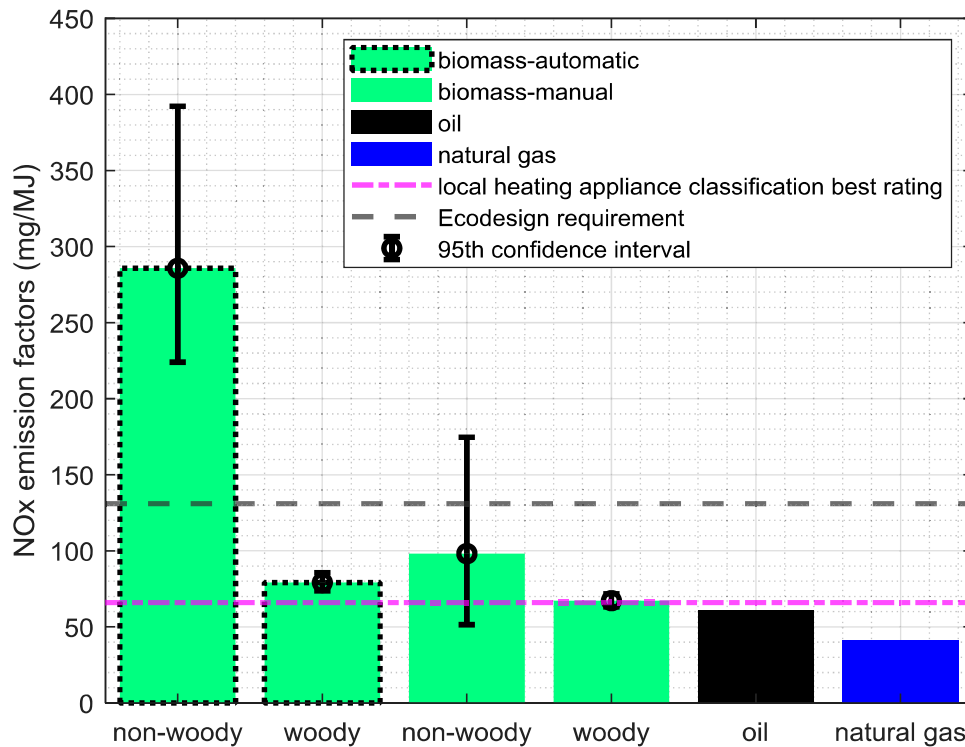


Fig. 5. Comparison of experimental emission factors for biomass and fossil fuels (grey and magenta dashed lines indicate the regulatory standards)

5.5 Regulatory frame implications

Source-specific emission standards are set within EU Clean Air Policy Framework to reduce the emissions from domestic combustion. Eco-design Directive through the Commission Regulations (EU) 2015/1185 and (EU) 2015/1189 provide minimum requirements to this effect, and state that, mandatory from 2020 (1st January 2022 for local space heaters), emissions of NOx by biomass burning local space heaters and boilers shall not exceed 200 mg/m³_{@13%O₂} (roughly 131 mg/MJ). Some local authorities take a further step and introduce appliance classifications to regulate the market introduction and use of biomass heating appliances to contrast the air quality problems related to this emission source. One such example is the Italian Decree n. 186 (2017) which establishes since 2018 the requirements, procedures and competences for the environmental certifications of heat generators fed with firewood, charcoal and biomass fuels. This decree introduces a limit of 100 mg/m³_{@13%O₂} (roughly 66 mg/MJ) for best performing appliances.

Considering that most of the collected NOx emission factors refer to literature data of the last ten years, the appliances are inclusive of relatively newer and older installations that would reflect many territorial realities where the gradual replacement of the stock of appliances by cleaner ones is still ongoing. The comparison of these emission factors (Fig. 5) with the appliance classification in the above-mentioned Decree n.186 points out that the wood burning stoves

1 and boilers though complying with Eco-design requirements are placed at the limit if not
2 below the best rating. On the other hand, none of the reviewed automatic boilers burning non-
3 woody biomass is compliant with Eco-design requirements indicating hard times for the
4 introduction in the market of alternative solid biofuels. Research conducted to this end [87]
5 though giving hopeful results for the fulfilling of the emission limits of other pollutants,
6 points out that the utilization of primary measures would not be enough to reduce the high
7 NOx emissions below the respective emission limit for many solid biofuels investigated.
8

9 **6. Conclusions**

10 The main aspects regarding the NOx emissions from biomass combustion in domestic heat
11 production can be synthesized as:
12

13 - NOx formation in biomass combustion is dominated by the fuel bound nitrogen (fuel-N).
14 mechanism, hence, the main parameter that influences the emissions is the fuel-N content.
15 However, the fuel composition in terms of ash, volatile matter and fixed carbon content will also
16 affect the transformation of the released N-species. The conversion of fuel-N to the nitrogen in
17 NOx emissions is not linear: the conversion rate decreases exponentially with increasing fuel-N.
18

19 - Consistent with the fuel-N mechanism especially non-woody biomass utilization should be
20 accompanied by proper abatement measures given the usually high fuel-N content in these
21 biomasses.
22

23 - The control of NOx emissions from residential biomass combustion however is not
24 straightforward as the available control techniques are not feasible or less efficient when applied
25 to small systems due to technological/operational aspects and excessive costs of the abatement
26 with respect to the heating appliance cost.
27

28 - Air-staging strategy is widely used to control NOx emissions however its application to small
29 appliances should carefully consider the trade-off between NOx and CO emissions since air
30 staging may cause an increase in CO and unburnt hydrocarbons.
31

32 - Operational parameters for NOx emission control are the excess air ratio, and the distribution of
33 primary and secondary air, residence time and temperature. Some authors conclude that the
34 optimum primary air ratio is independent of the fuel used for any given technology whereas the
35 actual primary air ratio minimizing NOx emissions is a characteristic of the technology/boiler
36 design. Residence times required to optimize NOx reduction are hardly achieved in small scale
37 appliances as the combustion chambers are frequently too small (short residence time). The
38 effect of temperature is reported to be limited for temperatures lower than 1000°C.
39

40 - Biomass combustion systems emit relatively high levels of PM and NOx with respect to the
41 combustion systems of light fuel oil or natural gas. Nevertheless, the comparison of
42 environmental performance of the appliances should not be limited to the emission factors but a
43 more complete analysis (cradle to grave) should be performed with the aid of for example life
44 cycle analysis methodology, which may surface aspects not directly related to stack emissions.
45

46 The present review study highlighted the need to conduct further research on NOx abatement
47 technologies in small scale heating appliances. Since the use of alternative solid biofuels with
48 higher fuel bound nitrogen such as residual biomass (e.g., agricultural, industrial residues) for
49 heat production may potentially cover a strategic role in circular economy it is fundamental to
50
51
52
53
54
55
56
57
58
59
60
61

develop after-treatment equipment (i.e., secondary removal measures) also for domestic heat production appliances. Expanding to centralized heating (district heating) where the relatively larger scale of the appliances helps to overcome the techno-economical barrier in the application of both primary and secondary NO_x control, may also be an option to reduce the emissions related to this emission source.

7. References

- [1] Vicente ED, Alves CA. An overview of particulate emissions from residential biomass combustion. *Atmos Res* 2018; 199:159-85.
- [2] Nussbaumer T. Combustion and co-combustion of biomass: fundamentals, technologies, and primary measures for emission reduction. *Energy Fuels* 2003; 17:1510-21.
- [3] EMEP/EEA. Air pollutant emission inventory guidebook 2016 - 1.A.4 Small combustion 2016, <https://www.eea.europa.eu/publications/emep-eea-guidebook-2016/part-b-sectoral-guidance-chapters/1-energy/1-a-combustion/1-a-4-small-combustion-2016/view> [accessed 30 January 2019]
- [4] Phyllis2. Database for biomass and waste. <https://phyllis.nl/ECN.TNO>; [accessed: April 2019]
- [5] Vassilev SV, Baxter D, Andersen LK, Vassileva CG. An Overview of the Chemical Composition of Biomass. *Fuel* 2010; 89:913-33.
- [6] Pettersson E, Boman C, Westerholm R, Boström D, Nordin A. Stove Performance and Emission Characteristics in Residential Wood Log and Pellet Combustion, Part 2: Wood Stove. *Energy Fuels* 2011; 25:315-23.
- [7] Sippula O, Hytonen K, Tissari J, Raunemaa T, Jokiniemi, J. Effect of Wood Fuel on the Emissions from a Top-Feed Pellet Stove, *Energy Fuels* 2007; 21:1151-60.
- [8] Alakangas E. Properties of Wood Fuels Used in Finland, Technical Research Center of Finland, VTT processes, Project Report PRO2/P2030/05 (Project C5SU00800), Jyväskylä 2005.
- [9] Verma VK, Bram S, Gauthier G, De Ruyck J. Evaluation of the Performance of a Multi-Fuel Domestic Boiler With Respect to the Existing European Standard and Quality Labels: Part-1, *Biomass Bioenerg* 2011;35:80-9
- [10] García R, Pizarro C, Lavín AG, Bueno JL. Spanish biofuels heating value estimation. Part I: Ultimate analysis data. *Fuel* 2014;117:1130-8.
- [11] García R, Pizarro C, Lavín AG, Bueno JL. Spanish biofuels heating value estimation. Part II: Proximate analysis data. *Fuel* 2014;117:1139-47.
- [12] van Loo S, Koppejan J. *The Handbook of Biomass Combustion and Co-firing*. Earthscan 2008.
- [13] Glarborg P, Jensen AD, Johnsson JE. Fuel Nitrogen Conversion in Solid Fuel Fired Systems. *Prog Energ Combust* 2003;29:89-113.
- [14] Karlström O, Perander M, DeMartini N, Brink A, Hupa M. Role of ash on the NO formation during char oxidation of biomass. *Fuel* 2017;190: 274-80.
- [15] Ren Q, Zhao C, Evolution of fuel-N in gas phase during biomass pyrolysis, *Renewable and Sustainable*. *Energy Reviews* 2015;50:408-18.
- [16] Giuntoli J, de Jong W, Verkooijen AHM, Piotrowska P, Zevenhoven M, Hupa M. Combustion Characteristics of Biomass Residues and Biowastes: Fate of Fuel Nitrogen, *Energy Fuels* 2010;24:5309-19.
- [17] Darvell LI, Jones JM, Gudka B, Baxter XC, Saddawi A, Williams A, Malmgren A. Combustion Properties of Some Power Station Biomass Fuels. *Fuel* 2010;89:2881-2890.
- [18] Werther J, Saenger M, Hartge EU, Ogada T, Siagi Z. Combustion of Agricultural Residues. *Prog Energ Combust* 2000;26:1-27.

- 1 [19] Williams A, Jones JM, Ma L, Pourkashanian M, Pollutants from the Combustion of Solid
2 Biomass Fuels. *Prog Energy Combust* 2012;38:113-37.
- 3 [20] Speth K, Martin Murer M, Spliethoff H. Experimental Investigation of Nitrogen Species
4 Distribution in Wood Combustion and Their Influence on NO_x Reduction by Combining Air
5 Staging and Ammonia Injection. *Energy Fuels* 2016;30:5816-24.
- 6 [21] Anca-Couce A, Sommersacher P, Evic N, Mehrabian R, Scharler R. Experiments and
7 modelling of NO_x precursors release (NH₃ and HCN) in fixed-bed biomass combustion
8 conditions. *Fuel* 2018;222:529-37.
- 9 [22] Liu X, Luo Z, Yu C. Conversion of Char-N into NO_x and N₂O During Combustion of
10 Biomass Char. *Fuel* 2019;242:389-97.
- 11 [23] Garijo EG, Jensen AD, Glarborg P. Kinetic Study of NO Reduction over Biomass Char
12 under Dynamic Conditions. *Energy Fuels* 2003;17:1429-36.
- 13 [24] Zhou H, Li Y, Li N, Qiu R, Meng S, Cen K. Experimental Study of The NO And N₂O
14 Emissions During Devolatilization and Char Combustion of a Single Biomass Particle in O₂/N₂
15 and O₂/H₂O Under Low Temperature Condition. *Fuel* 2017;206:162-70.
- 16 [25] Zabetta EC, Hupa M, Saviharju K. Reducing NO_x Emissions Using Fuel Staging, Air
17 Staging, and Selective Noncatalytic Reduction in Synergy. *Ind. Eng. Chem. Res* 2005; 44:4552-
18 61.
- 19 [26] Liu H, Chaney J, Li J, Sun C. Control of NO_x Emissions of a Domestic/Small-Scale
20 Biomass Pellet Boiler by Air Staging. *Fuel* 2013;103:792-98.
- 21 [27] Houshfar E, Skreiberg O, Lovas T, Todorovic D, Sorum L. Effect of Excess Air Ratio
22 and Temperature on NO_x Emission from Grate Combustion of Biomass in the Staged Air
23 Combustion Scenario. *Energy Fuels* 2011;25:4643-54.
- 24 [28] Houshfar E, Lovas T, Skreiberg O. Experimental Investigation on NO_x Reduction by
25 Primary Measures in Biomass Combustion: Straw, Peat, Sewage Sludge, Forest Residues and
26 Wood Pellets. *Energies* 2012;5:270-90.
- 27 [29] Carroll J P, Finnan J M, Biedermann F, Brunner T, Obernberger I. Air staging to reduce
28 emissions from energy crop combustion in small scale applications. *Fuel* 2015;155:37-43.
- 29 [30] Nussbaumer T. Primary and secondary measures for the reduction of nitric oxide
30 emissions from biomass combustion. In: *Developments in thermochemical biomass conversion*.
31 Blackie Academic and Professional; 1997.
- 32 [31] Biedermann F, Brunner T, Obernberger I, Sippula O, Boman C, Öhman M, et al.
33 Summary and evaluation of existing strategies on air staging strategies. Report produced as part
34 of the ERANET Futurebiotec project; 2010.
- 35 [32] Bugge M, Skreiberg O, Haugen NEL, Carlsson P, Seljeskog M. *Egy. Pro.*, Predicting
36 NO_x Emissions from Wood Stoves using Detailed Chemistry and Computational Fluid
37 Dynamics 2015;75:1740-45.
- 38 [33] Bugge M, Skreiberg O, Haugen NEL, Carlsson P, Lovas T. Numerical Simulations of
39 Staged Biomass Grate Fired Combustion with an Emphasis on NO_x Emissions. *Egy. Pro.*
40 2015;75:156-61.
- 41 [34] Viren A, Lamberg H, Tissari J, Sippula O, Jokiniemi J, Obernberger I et al. Guidelines
42 for Low Emission Chimney Stove Design. Report produced as part of the ERANET Futurebiotec
43 project; 2012.
- 44 [35] Carvalho L, Wopienka E, Pointner C, Lundgren J, Verma VK, Haslinger W, Schmidl C.
45 Performance of a Pellet Boiler Fired with Agricultural Fuels. *Ap. Energy* 2013;104:286-96.
- 46 [36] Petrocelli D, Lezzi AM. CO and NO Emissions from Pellet Stoves: An Experimental
47 Study. *Phys Conf Ser* 2014;501 012036.
- 48 [37] Roy MM, Dutta A, Corscadden K. An Experimental Study of Combustion and Emissions
49 of Biomass Pellets in a Prototype Pellet Furnace. *Appl Energy* 2013;108:298-307.
- 50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

- [38] Regueiro A, Patino D, Porteiro J, Granada E, Míguez JL. Effect of Air Staging Ratios on the Burning Rate and Emissions in an Underfeed Fixed-Bed Biomass Combustor. *Energies* 2016;9:940.
- [39] Lamberg H, Sippula O, Tissari J, Jokiniemi J. Effects of Air Staging and Load on Fine-Particle and Gaseous Emissions from a Small-Scale Pellet Boiler. *Energy Fuels* 2011;25:4952-60.
- [40] Schmidt G, Trouvé G, Leyssens G, Schönnenbeck C, Genevray P, Cazier F et al. Wood washing: Influence on gaseous and particulate emissions during wood combustion in a domestic pellet stove. *Fuel Process Technol* 2018;174:104-17.
- [41] Zeng T, von Sonntag J, Weller N, Pilz A, Lenz VM. CO, NO_x, PCDD/F, and Total Particulate Matter Emissions from Two Small Scale Combustion Appliances Using Agricultural Biomass Type Test Fuels, *Energy Fuels* 2017;31:7540-51.
- [42] Sommersacher P, Brunner T, Obernberger I. Fuel Indexes: A Novel Method for the Evaluation of Relevant Combustion Properties of New Biomass Fuels. *Energy Fuels* 2012;26:380-90.
- [43] Feldmeier S, Wopienka E, Schwarz M, Schön C, Pfeifer C. Applicability of fuel indexes for small-scale biomass combustion technologies, Part 2: TSP and NO_x emissions. *Energ Fuel* 2019;33:11724-730.
- [44] Rabaçal M, Fernandes U, Costa M, Combustion and Emission Characteristics of a Domestic Boiler Fired with Pellets of Pine, Industrial Wood Wastes and Peach Stones. *Renew Energ* 2013;51:220-26.
- [45] Lamberg H, Tissari J, Jokiniemi J, Sippula O. Fine Particle and Gaseous Emissions from a Small-Scale Boiler Fueled by Pellets of Various Raw Materials. *Energy Fuels* 2013;27:7044-53.
- [46] Roy MM, Corscadden KW. An Experimental Study of Combustion and Emissions of Biomass Briquettes in a Domestic Wood Stove. *Appl Energ* 2012;99:206-12.
- [47] Johansson LS, Leckner B, Gustavsson L, Cooper D, Tullin C, Potter A. Emission characteristics of modern and old-type residential boilers fired with wood logs and wood pellets. *Atmos Environ* 2004;38:4183-95.
- [48] Dzurenda L, Hroncová E, Ladomerský J. Extensive Operating Experiments on the Conversion of Fuel-Bound Nitrogen into Nitrogen Oxides in the Combustion of Wood Fuel. *Forests* 2017;8:1-9.
- [49] Pleckaitine R, Buinevicius K. The Factors which Have Influence on Nitrogen Conversion Formation. *Environmental Engineering The 8th International Conference May 19–20, 2011, Vilnius, Lithuania.*
- [50] Verma VK, Bram S, Gauthier G, De Ruyck J. Performance of a Domestic Pellet Boiler as a Function of Operational Loads: Part-2. *Biomass Bioenerg* 2011;35:272-79.
- [51] Vermeulen I, Block C, Vandecasteele C. Estimation of Fuel-Nitrogen Oxide Emissions from the Element Composition of the Solid or Waste Fuel. *Fuel* 2012;94:75-80.
- [52] Kaivosoja T, Jalava PI, Lamberg H, Virén A, Tapanainen M, Torvela T et al. Comparison of Emissions And Toxicological Properties of Fine Particles From Wood and Oil Boilers in Small (20–25 kW) and Medium (5–10 MW) Scale. *Atmos Environ* 2013;77:193-201.
- [53] Monteleone, B, Chiesa M, Marzuoli R, Verma VK, Schwarz M, Carlon E et al. Life Cycle Analysis of Small Scale Pellet Boilers Characterized by High Efficiency and Low Emissions. *Appl Energ* 2015;155:160-70.
- [54] Ozgen S, Ripamonti G, Cernuschi S, Giugliano M. Ultrafine Particle Emissions for Municipal Waste-To-Energy Plants and Residential Heating Boilers. *Reviews in Environmental Science and Biotechnology* 2012;11:407-15.
- [55] Win KM, Persson T, Bales C. Particles and Gaseous Emissions from Realistic Operation of Residential Wood Pellet Heating Systems. *Atmos Environ* 2012;59:320-7.

- [56] Win KM, Persson T. Emissions from Residential Wood Pellet Boilers and Stove Characterized into Start-up, Steady Operation, and Stop Emissions. *Energy Fuels* 2014;28:2496-2505.
- [57] Czech H, Pieber SM, Tiitta P, Sippula O, Kortelainen M, Lamberg H et al. Time-Resolved Analysis of Primary Volatile Emissions and Secondary Aerosol Formation Potential From a Small-Scale Pellet Boiler. *Atmos Environ* 2017;158:236-45.
- [58] Reda AA, Czech H, Schnelle-Kreis J, Sippula O, Orasche J, Weggler B, et al. Analysis of Gas-Phase Carbonyl Compounds in Emissions from Modern Wood Combustion Appliances: Influence of Wood Type and Combustion Appliance. *Energy Fuels* 2015;29:3897-3907.
- [59] Bhattu D, Zotter P, Zhou J, Stefenelli G, Klein F, Bertrand A et al. Effect of Stove Technology and Combustion Conditions on Gas and Particulate Emissions from Residential Biomass Combustion. *Environ Sci Technol* 2019;53:2209-19.
- [60] Ozgen S, Caserini S, Galante S, Giugliano M, Angelino E, Marongiu A et al. Emission factors from small scale appliances burning wood and pellets. *Atmos Environ* 2014;94:144-53.
- [61] Kistler M, Schmidl C, Padouvas E, Giebl H, Lohninger J, Ellinger R et al. Odor, gaseous and PM10 emissions from small scale combustion of wood types indigenous to Central Europe, *Atmospheric Environment*, Vol. 51, pp 86-93, 2012.
- [62] Schmidl, C., Luisser, M., Padouvas, E., Lasselsberger, L., Rzaca, M., Ramirez-Santa Cruz, C., Handler, M., Peng, G., Bauer, H., Puxbaum, H., Particulate and Gaseous Emissions from Manually and Automatically Fired Small Scale Combustion Systems. *Atmos Environ* 2011;45:7443-54.
- [63] Boman C, Pettersson E, Westerholm R, Bostrom D, Nordin A. Stove Performance and Emission Characteristics in Residential Wood Log and Pellet Combustion, Part 1: Pellet Stoves. *Energy Fuels* 2011;25:307-14.
- [64] Tissari J, Lyyränen J, Hytönen K, Sippula O, Tapper U, Frey A et al. Fine Particle and Gaseous Emissions from Normal and Smouldering Wood Combustion in a Conventional Masonry Heater. *Atmos Environ* 2008;42:7862-73.
- [65] Czech H, Miersch T, Orasche J, Abbaszade G, Sippula O, Tissari J et al. Chemical Composition and Speciation of Particulate Organic Matter from Modern Residential Small-Scale Wood Combustion Appliances. *Sci Tot Environ* 2018:636-48.
- [66] Fachinger F, Drewnick F, Gieré R, Borrmann S. How the User Can Influence Particulate Emissions from Residential Wood and Pellet Stoves: Emission Factors for Different Fuels and Burning Conditions. *Atmos Environm* 2017;158:216-26.
- [67] Mitchell EJS, Lea-Langton AR, Jones JM, Williams A, Layden P, Johnson R. The Impact of Fuel Properties on the Emissions from the Combustion of Biomass and other Solid Fuels in a Fixed Bed Domestic Stove, *Fuel Processing Technology* 2016;142:115-23.
- [68] Price-Allison A, Lea-Langton AR, Mitchell EJS, Gudka B, Jones JM, Mason E, Williams A. Emissions Performance of High Moisture Wood Fuels Burned in a Residential Stove. *Fuel* 2019;239:1038-45.
- [69] Fellin. M, Negri M, Antolini D, Baggio P, Pieratti E. Biomass Use Best Practices: Monitoring Biomass and Process Emissions for Sustainable Use: A Case Study. *Contemporary Engineering Sciences* 2016;9:1535-46.
- [70] Bignal KL, Langridge S, Zhou JL. Release of polycyclic aromatic hydrocarbons, carbon monoxide and particulate matter from biomass combustion in a wood-fired boiler under varying boiler conditions. *Atmos Env* 2008;42:8863-71.
- [71] Ozgen S, Becagli S, Bernardoni V, Caserini S, Caruso D, Corbella L et al. Analysis of the chemical composition of ultrafine particles from two domestic solid biomass fired room heaters under simulated real-world use. *Atmos Environ* 2017;150:87-97.
- [72] Ozgen S, Cernuschi S, Giugliano M. Experimental evaluation of particle number emissions from wood combustion in a closed fireplace. *Biomass Bioenerg* 2013;50:65-74.

- 1 [73] Tissari J, Hytönen K, Lyyräinen J, Jokiniemi J. A novel field measurement method for
2 determining fine particle and gas emissions from residential wood combustion. *Atmos Environ*
3 2007;41:8330-44.
- 4 [74] Vicente E, Duarte M, Nunes T, Tarelho L, Alves C. Particulate and gaseous emissions
5 from residential pellet combustion, SPEIC14 – Towards Sustainable Combustion November 19-
6 21, 2014, Lisboa, Portugal.
- 7 [75] Hrdlicka J, Skopec P, Dlouhy T, Hrdlicka F. Emission factors of gaseous pollutants from
8 small scale combustion of biofuels. *Fuel* 2016;165:68-74.
- 9 [76] Seljeskog M, Goile F, Skreiberg O. Recommended Revisions of Norwegian Emission
10 Factors for Wood Stoves. *Energy Proced* 2017;105:1022-8.
- 11 [77] Cereceda-Balic F, Toledo M, Vidal V, Guerrero F, Diaz-Robles LA, Petit-Breuilh X,
12 Lapuerta M. Emission factors for PM_{2.5}, CO, CO₂, NO_x, SO₂ and particle size distributions
13 from the combustion of wood species using a new controlled combustion chamber 3CE. *Sci*
14 *Total Environ* 2017;584-585:901-10.
- 15 [78] Klauser F, Carlon E, Kistler M, Schmidl C, Schwabl M, Sturmlechner R et al. Emission
16 Characterization of Modern Wood Stoves Under Real-Life Oriented Operating Condition.
17 *Atmos Environ* 2018;192:257-66.
- 18 [79] Kortelainen M, Jokiniemi J, Tiitta P, Tissari J, Lamberg H, Leskinen J et al. Time-
19 resolved Chemical Composition of Small-Scale Batch Combustion Emissions from Various
20 Wood Species. *Fuel* 2018;233:224-36.
- 21 [80] Venturini E, Vassura I, Agostini F, Pizzi A, Toscano G, Passarini F. Effect of Fuel
22 Quality Classes on The Emissions of a Residential Wood Pellet Stove. *Fuel* 2018;211:269-77.
- 23 [81] Lamberg H, Nuutinen K, Tissari J, Ruusunen J, Yli-Pirila Y, Sippula O et al.
24 Physicochemical Characterization of Fine Particles from Small-Scale Wood Combustion. *Atmos*
25 *Environ* 2011;45:7635-43.
- 26 [82] Pettersson E, Lindmark F, Öhman M, Nordin A, Westerholm R, Christoffer Boman C.
27 Design Changes in a Fixed-Bed Pellet Combustion Device: Effects of Temperature and
28 Residence Time on Emission Performance. *Energy Fuels* 2010;24:1333-40.
- 29 [83] Dasch JM. Particulate and gaseous emissions from wood-burning fireplaces. *Environ.*
30 *Sci. Technol.* 1982;16:639-45.
- 31 [84] Boman C, Nordin A, Westerholm R, Pettersson E. Evaluation of a Constant Volume
32 Sampling Setup for Residential Biomass Fired Appliances-Influence of Dilution Conditions on
33 Particulate and PAH Emissions. *Biomass Bioenerg* 2005;29:258-68.
- 34 [85] Koyuncu T, Pinar Y. The Emissions from a Space-Heating Biomass Stove. *Biomass*
35 *Bioenerg* 2007;31:73-9.
- 36 [86] Arranz JI, Miranda MT, Montero I, Sepúlveda FJ, Rojas CV. Characterization and
37 combustion behavior of commercial and experimental wood pellets in South West Europe. *Fuel*
38 2015;142:199-207.
- 39 [87] Guidelines for assessment of appropriate performance conditions of small domestic
40 heating appliances with relevant Mediterranean solid biofuels. 2018.
41 <http://biomasudplus.eu/wp-content/uploads/2018/12/D5.5.-Guidelines-in-ENGLISH.pdf>; 2018.
42 [accessed 18 december 2019]
- 43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

Figure1
[Click here to download high resolution image](#)

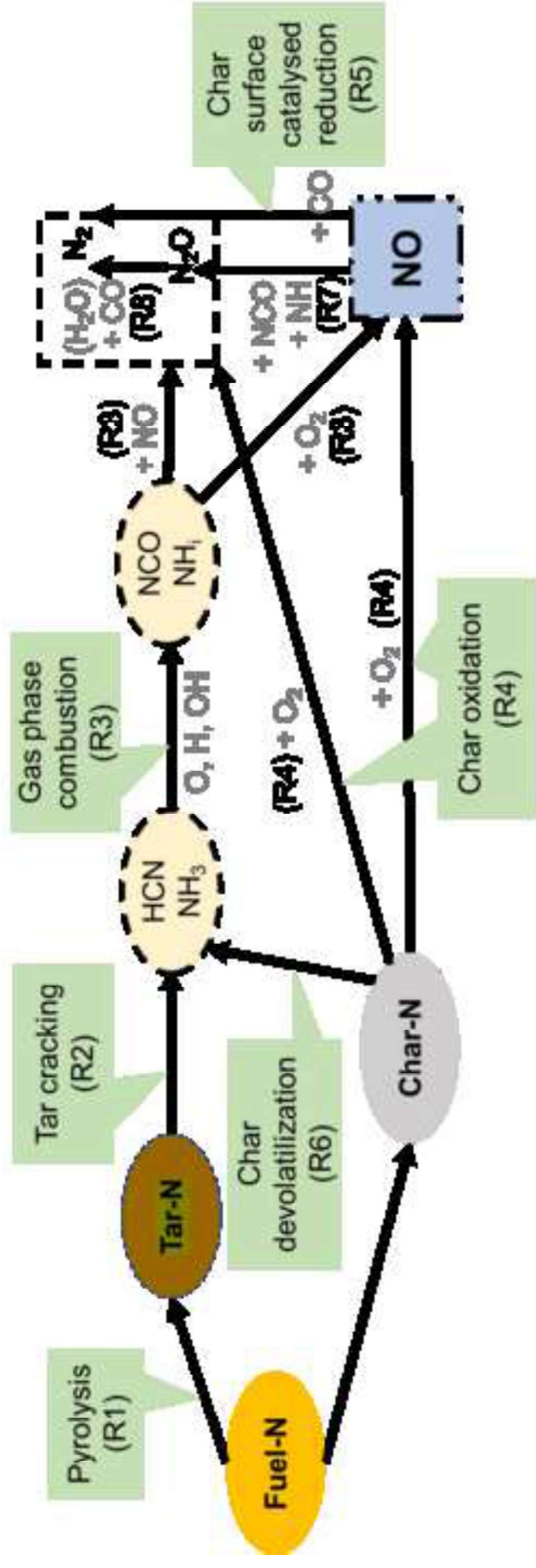


Figure 2
[Click here to download high resolution image](#)

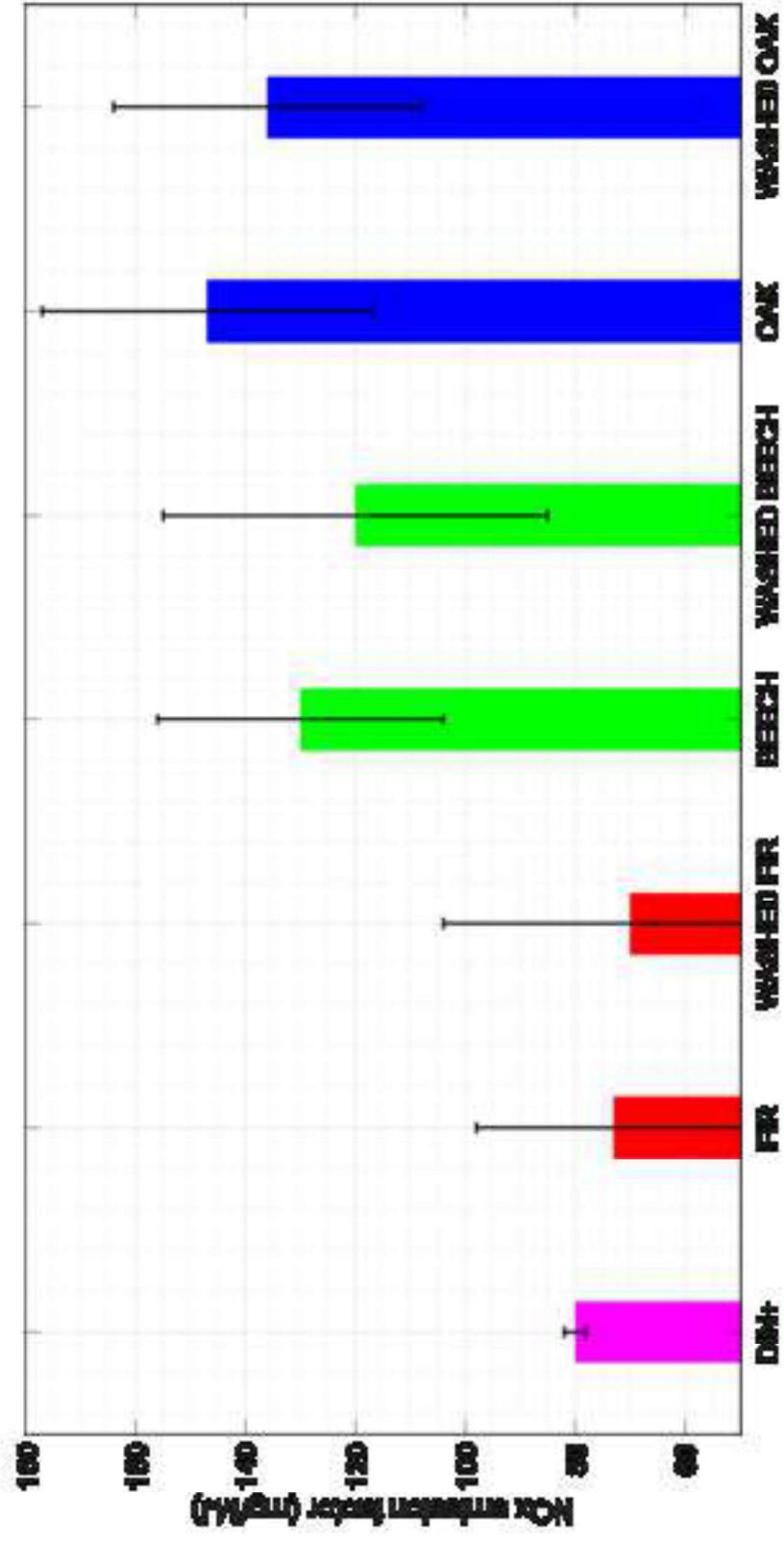


Figure 3
[Click here to download high resolution image](#)

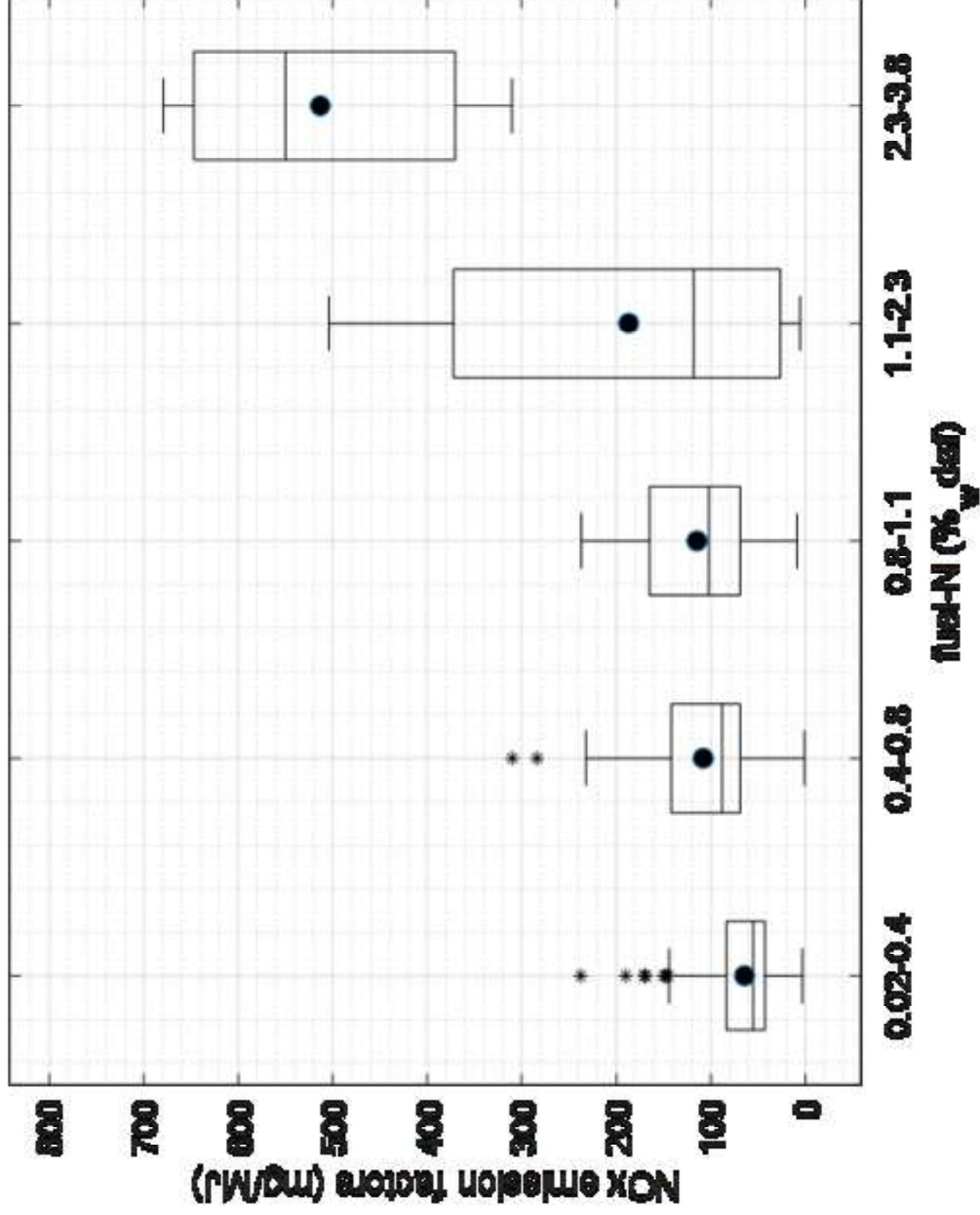


Figure 4

[Click here to download high resolution image](#)

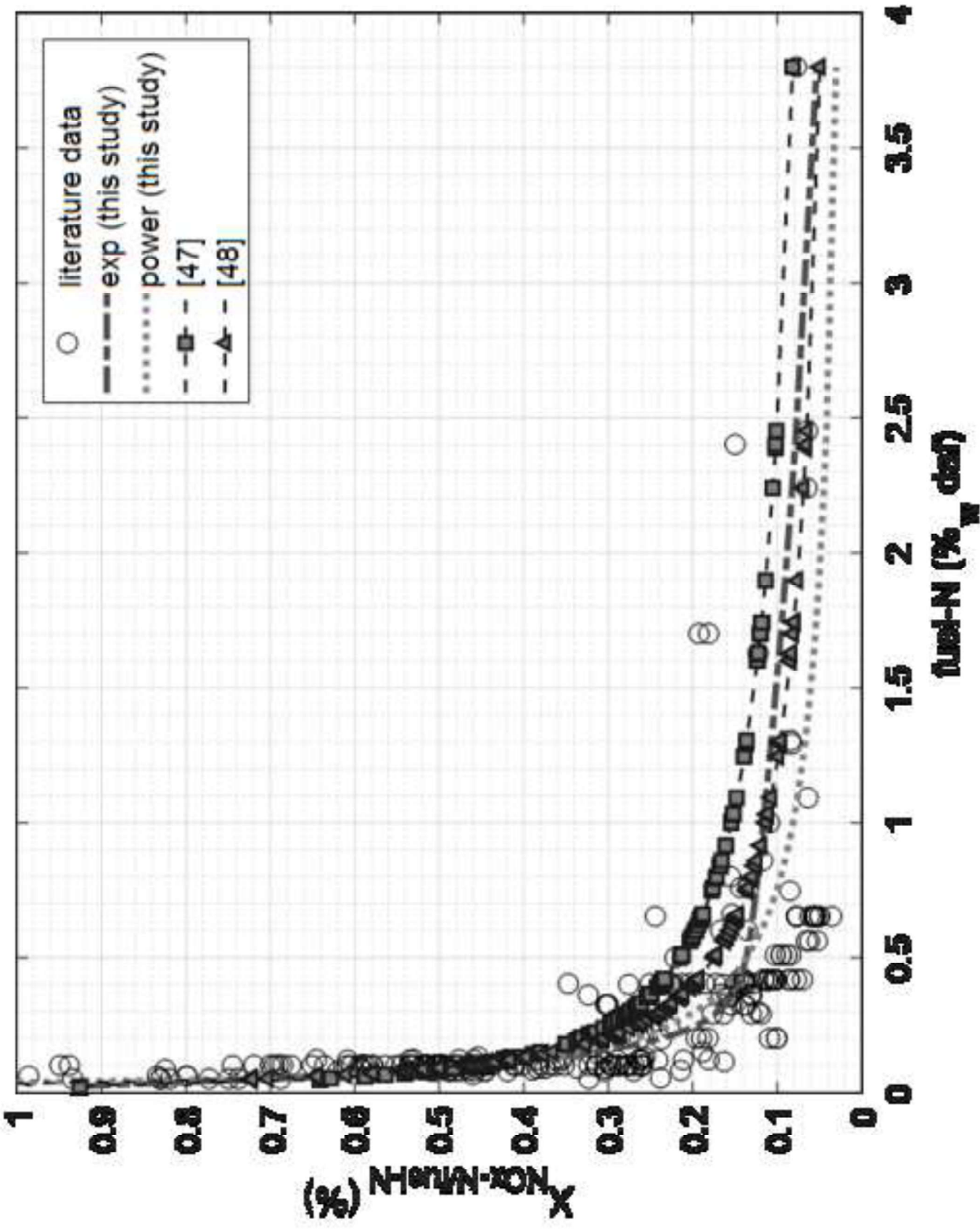


Figure 5
Click here to download high resolution image

