Evaluation of the quality of TORWASH® pellets as a bioenergy carrier

paper sludge, olive pomace and orange peels

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Executive Summary

The Heat Systems (HS) indirect fired pilot kiln was used for pilot trials on the combustion of pellets made from F-CUBED's three different feedstocks, namely paper sludge, olive pomace and orange peels. These feedstocks were previously TORWASHed at pilot scale in WP2, WP3 and WP4, dewatered to produce solid cakes, and the cakes were dried and pelletized. Therefore the feedstocks were provided in pellet form to HS. Pellets were converted to char/ash (solids) and syngas.

Solid (char/ash) samples were collected, labelled and stored. Syngas samples were tested on-line (live readings) and subsequently incinerated in an afterburner, with further 'flue gas' testing (live readings) downstream the afterburner.

Feed samples were weighed pre- and post-processing, and residual char/ash weights (i.e., post processing samples) were compared to proximate analyses for the feed-types to determine the extent of pyrolysis achieved versus what was theoretically possible.

In all three cases, excellent overlap with theoretical conversion calculations was achieved.

At scale, if the commercial intent is syngas production, olive pomace feedstock appears to be the best fit (maximum syngas output). If on the other hand the primary goal is char production, paper bio-sludge and orange peels are better options. However all feed-types are suitable for both syngas as well as char generation.

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1 Introduction

1.1. Description of the document

This document evaluates the quality of TORWASH® pellets as a bioenergy carrier. Specifically:

- The produced pellets are characterized with standard fuel analysis and ash analysis methods. Standard fuel analysis includes proximate, ultimate, higher heating value, organic (convertible) matrix and ash-forming elemental analyses.

- Combustion and gasification testing of the pellets is performed by HS. Parameters to be tested include NOx, SOx and particulate formation as well as fouling and agglomeration.

The results from the pilot kiln tests can be used as a basis for design for an indirect-fired kiln pyrolyser at full-scale.

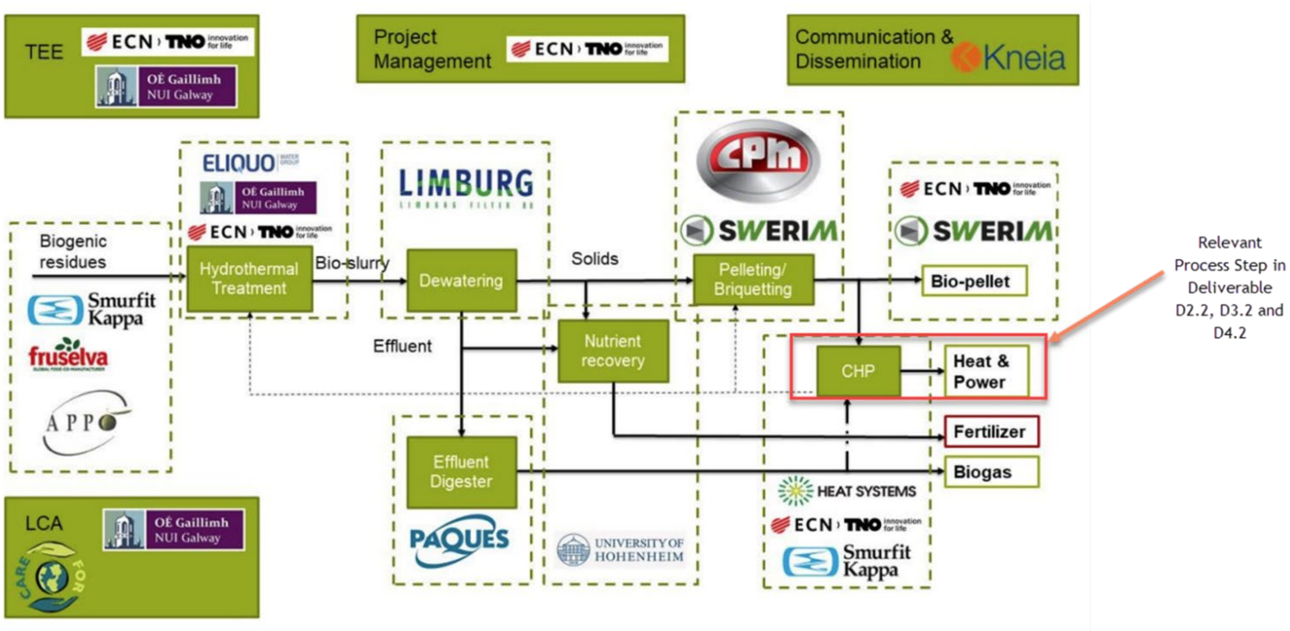
1.2. WPs and Tasks related with the deliverable

Related work packages and deliverables are:

WP2	Task 2.4	Production of Paper Sludge Pellets (CPM/TNO)
	Task 2.6	Characterisation of Paper Sludge Feedstock (TNO). Advanced thermal processing of pellets by HS. Further testing by TNO.
	D2.2	Technical data on Evaluation of the quality of TORWASH® pellets as bioenergy carrier produced from paper sludge (HS)
WP3	Task 3.4	Production of Olive Pomace Pellets (CPM/TNO)
	Task 3.6	Characterisation of Olive Pomace Feedstock (TNO). Advanced thermal processing of pellets by HS. Further testing by TNO.
	D3.2	Technical data on Evaluation of the quality of TORWASH® pellets as bioenergy carrier produced from Olive Pomace (HS)
WP4	Task 4.4	Production of Fruit and Vegetable waste (Orange) Pellets (CPM)
	Task 4.6	Characterisation of Fruit and Vegetable waste (Orange) Feedstock (TNO). Advanced thermal processing of pellets by HS. Further testing by TNO.
	D4.2 (this document)	Technical data on Evaluation of the quality of TORWASH® pellets as bioenergy carrier produced from paper sludge, waste olive pomace and fruit & vegetable waste (HS)
WP5	Task 5.3	Value Chain Techno-Economic Evaluation - D4.2 is used as an input for tasks in WP5

1.3. Relevant Process Steps

The relevant process steps for this deliverable (D4.2) in the overall project architecture can be seen in the schematic below:



1.4. General outline of the test infrastructure and plan

1.4.1. Pilot test material flow

The flow of material from the feed side to the discharge side of the pilot kiln can be seen in Figure 1.

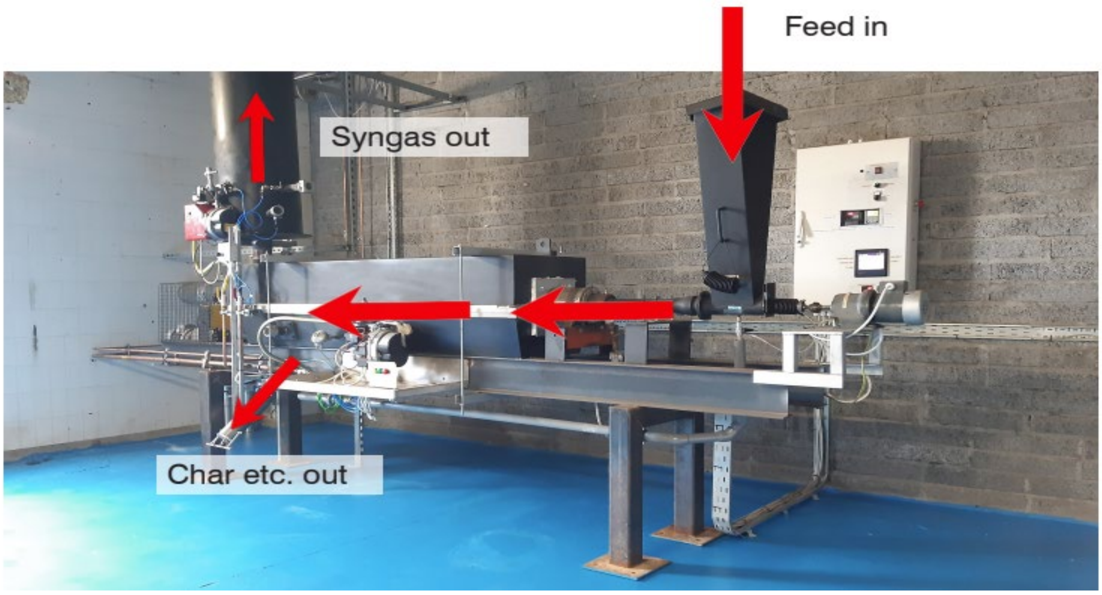


Figure 1 : Pilot Kiln used for Bio-energy carrier testing.

Figure 2 illustrates the location of gas sampling point 1 (pre-combustion, upstream the afterburner). Figure 3 illustrates the location of gas sampling point 2, prior to insulation addition (post-combustion, downstream the afterburner). Figure 4, Figure 5 and Figure 6 illustrate the location of temperature probes.

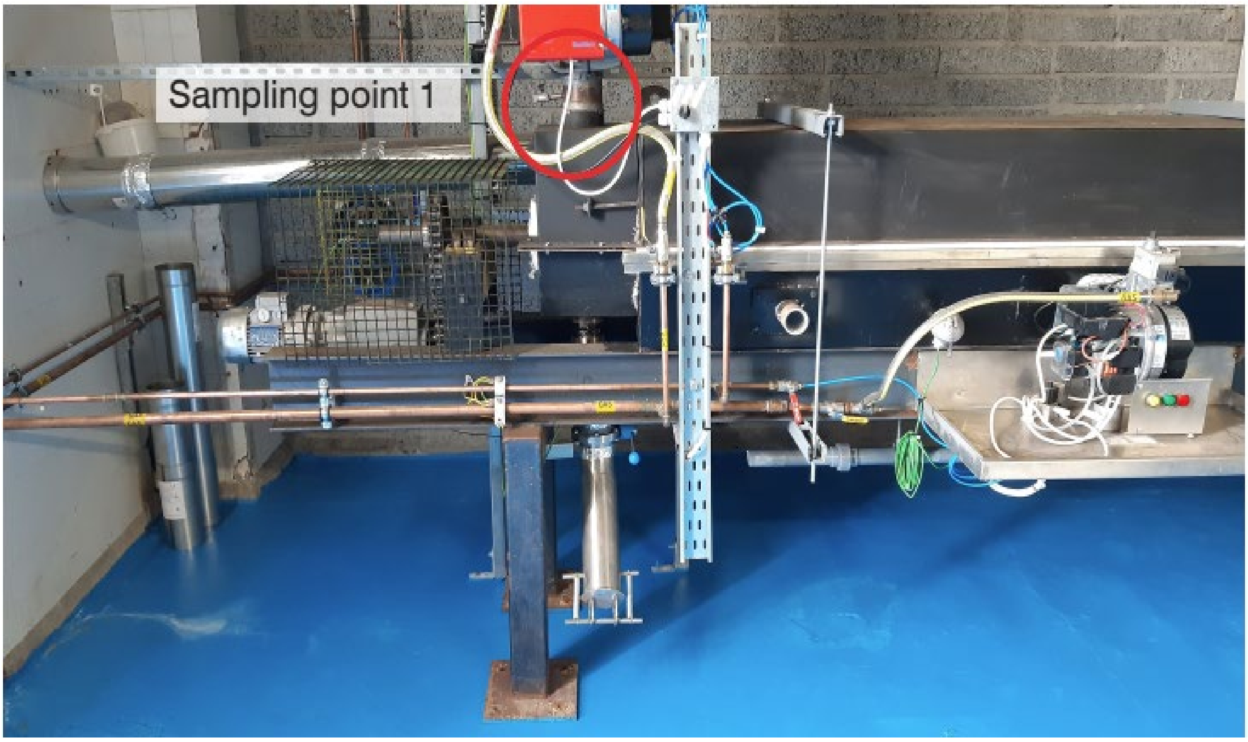


Figure 2: Sampling Point 1.

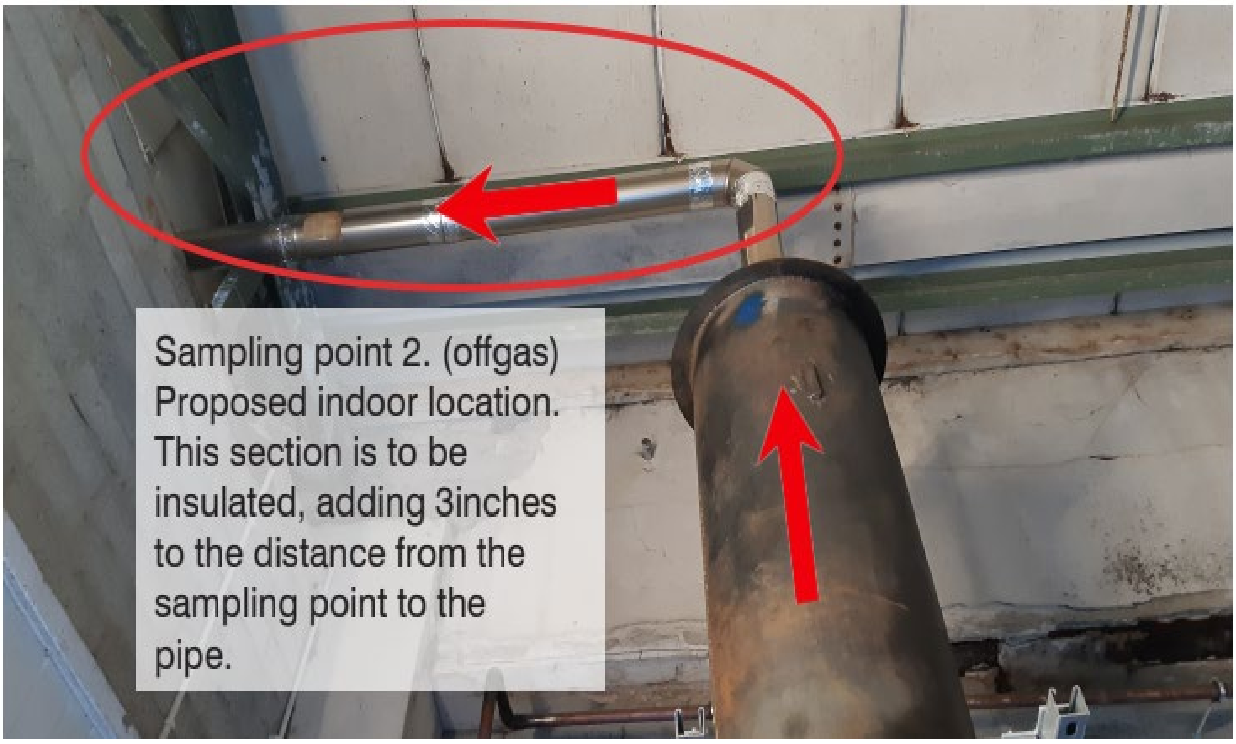


Figure 3: Sampling Point 2.

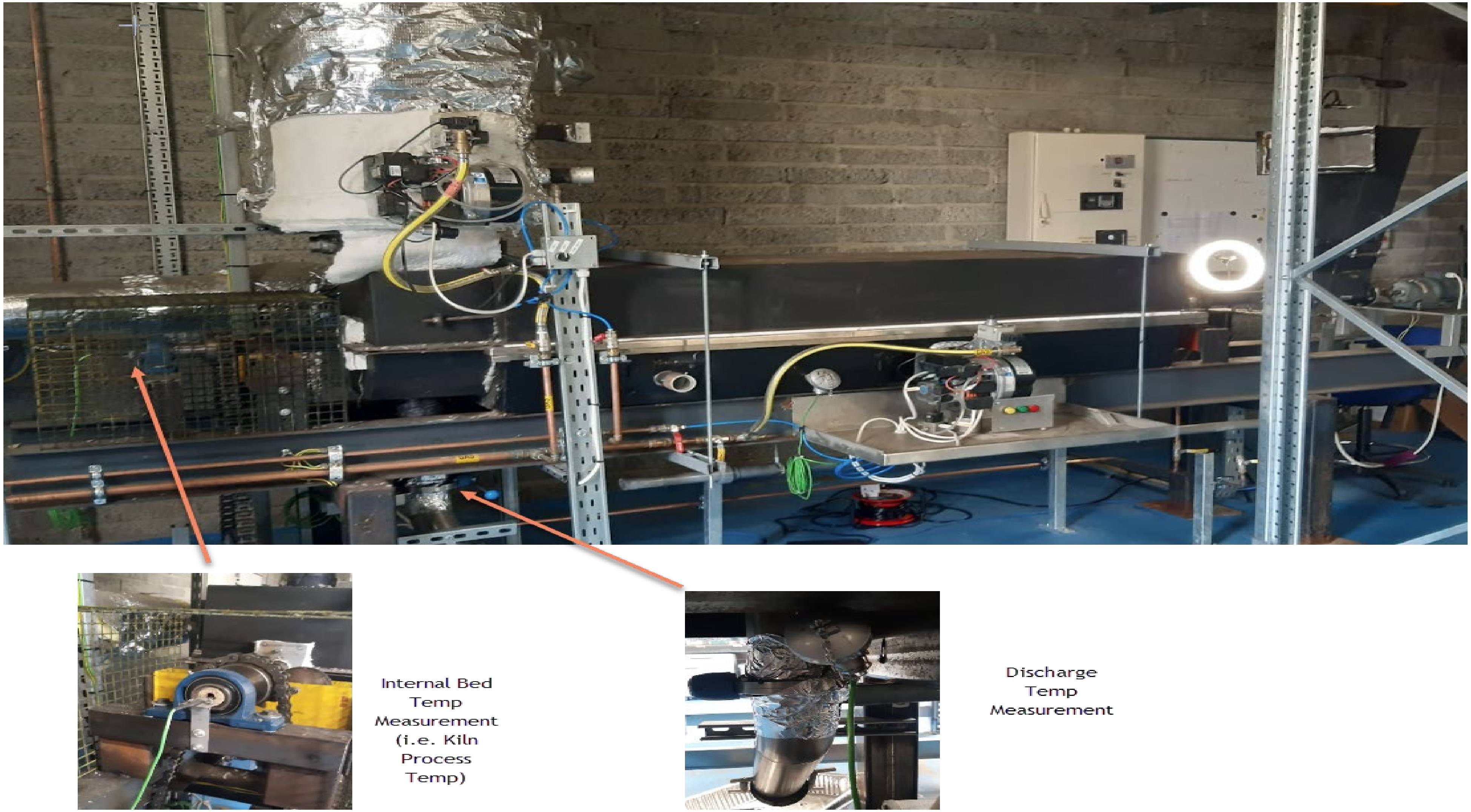


Figure 4: Temperature Probe Locations

Figure 5: Temperature Probe Locations - continued

Figure 6: Temperature Probe Locations

2 Test Results

2.1 Feedstock Samples Characterisation

Table 1 summarises the composition of the TORWASH pellet samples from different feedstock materials, used in this study. A full evaluation of the conversion steps and material qualities from the previous steps of the processing can be found in Deliverable 1.1 of the F-Cubed project.

Table 1: Summary of the compositions of the feedstock materials used in this study

component/element	unit	Orange peel TW pellets	Olive pomace TW pellets	Paper sludge TW pellets
Br	mg/kg	<10	< 10	30
Cl	mg/kg	1700	180	120
F	mg/kg	<10	< 10	64
Ash contents (550°C)	% db	3,2	1,7	24,9
Ash contents (815°C)	% db	2,2	1,3	23,4
Volatile matter	% db	74,7	83,6	59,9
Moisture contents	% ar	4,9	<10	<10
C	% db	56,3	63,8	46
N	% db	2	1,5	4,2
H	% db	6,3	8,3	5,8
O	% db	32,1	24,3	22,2
Al	mg/kg d.b.	130	130	18000
As		<0.1	< 1	< 4
B		19	20	9,8
Ba		3,5	1,4	820
Ca		11000	5100	21000
Cd		<0.02	< 0.1	12
Co		18	< 0.3	1,7
Cr		3,2	0,99	40
Cu		21	40	69
Fe		560	210	6300
K		1000	1700	1300
Li		<0.4	< 0.3	3,1
Mg		150	80	3200
Mn		3,5	1,5	12000
Mo		<0.8	< 0.8	7,9
Na		58	63	1400
Ni		3,2	1,2	18
P		180	250	22000

Pb		1,3	<0.6	43
S		1300	1200	9300
Sb		<0.08	< 3	< 10
Se		<0.2	< 1	< 4
Si		310	230	35000
Sn		<0.9	< 0.9	< 3
Sr		23	4,9	110
Ti		6	6,1	860
V		0,22	0,47	29
W		33	< 1	< 4
Zn		23	25	1200

As can be seen Table 1, the compositions of the feedstock materials vary quite widely in terms of both convertible matrix as well as the ash levels and composition. It is clear that the materials from the agricultural/food origin are relatively leaner in ash while the convertible matrix/volatile matter levels are significantly higher in the case of the paper residue pellets – this is the main aspect influencing the pyrolytic+oxidative conversion presented in this report.

2.2 Pelletization Test Results

Table 2 summarises the pelletization parameters required for the generation of **Orange peels derived** Pellets.

Table 2: Pelletization parameters for the generation of Orange pellets (data received from CPM).

Pellet Mill Results

Test Run	1
Moisture Content [%]	±4,9
Bulk Density [kg/m^3]	-
Sample Size [kg]	108
Particle Size [micron]	-
Die Speed [rpm]	150
Die Type	6xET60
Average Power [kW]	~60
Capacity [kg/hr]	~1000[1]
Specific Energy [kWh/t]	~60
Pellet Durability Index (PDI)	95,3
Additions	-
Roll Left	Corrugated 4”
Roll Right	Corrugated 4”
Remarks	Good pellets

I. Tests are performed using a CPM 2016 Pellet mill.

A robust pellet was produced from TORWASHed Orange peel residue (Figure 7). The resultant char after combustion (Figure 8) was also mechanically very stable.

Figure 7: Orange Pellets – mechanically strong and easy to handle

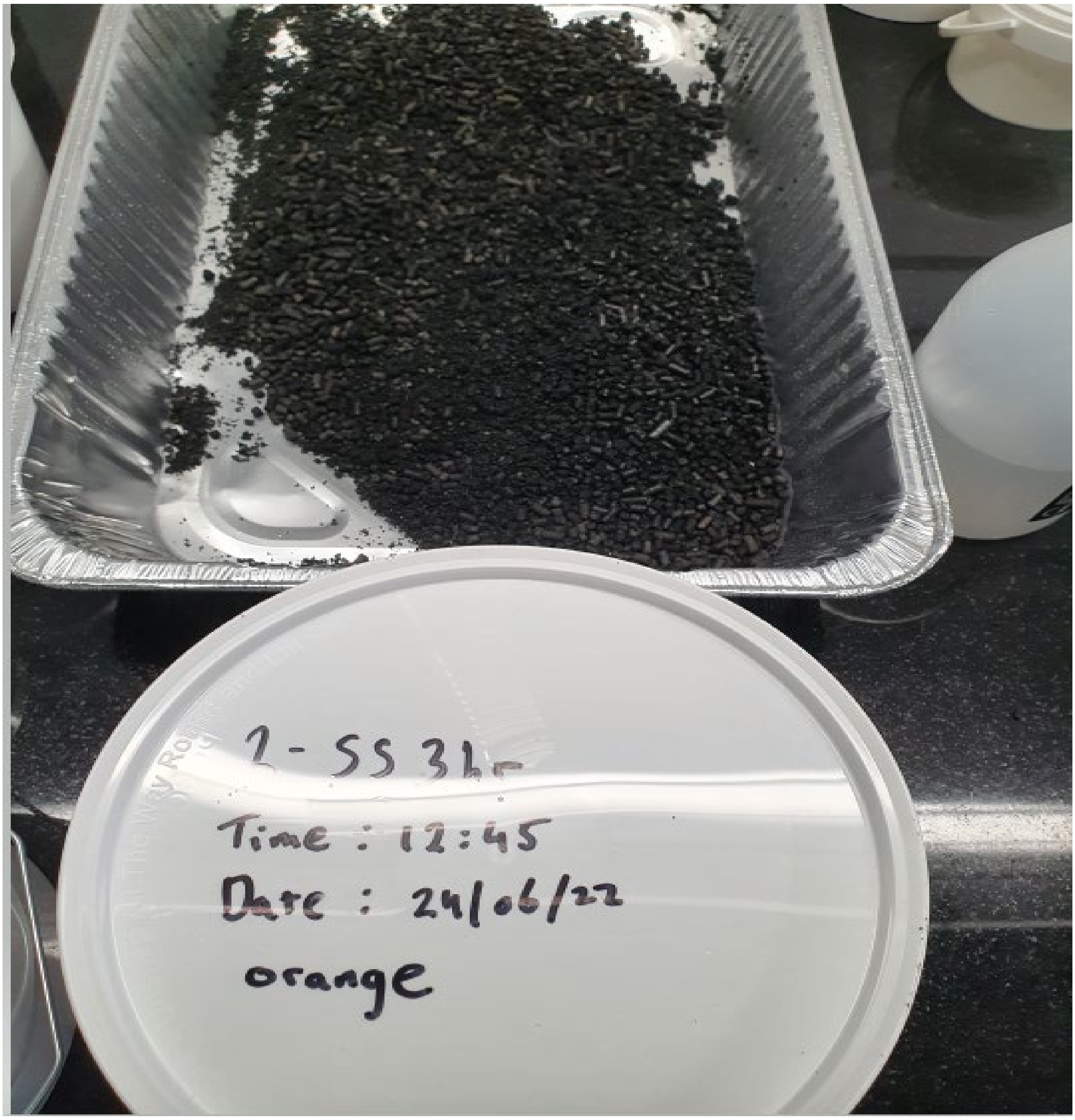


Figure 8: Orange Pellets – easily converted to char and retaining shape/mechanical strength

Table 3 summarises the pelletization parameters required for the generation of **Olive** derived Pellets.

Table 3: Pelletization parameters for the generation of Olive pellets (data received from CPM).

Pellet Mill Results

Test Run	1	2	3	4	5	6
Moisture Content [%]	±7	-	-	-	-	-
Bulk Density [kg/m^3]	-					
Sample Size [kg]	61					
Particle Size [micron]						
Die Speed [rpm]	150					
Die Type	6xET32	6xET45	6xET60	6xET85	6xET110	6xET85
Average Power [kW]	-	-	-	-	-	-
Capacity [kg/hr]	-	-	-	-	-	-
Specific Energy [kWh/t]	-	-	-	-	-	-
Pellet Durability Index (PDI)	-	-	-	-	-	10,8
Additions	-	-	-	-	-	2% starch
Roll Left	Corrugated 2"		Corrugated 4"			
Roll Right	Corrugated 2"		Corrugated 4"			
Remarks	Soft pellets				No pellets, too much press length	Soft pellets even after triple pelleting

I. Tests are performed using a CPM 2016 Pellet mill.

It was clear that the Olive Pellets were most resistant to forming a robust pellet, with much more 'powder' present when compared to the other pellets (Figure 9). These pellets were re-pelletised at TNO using a top-feed, flat-die pelletiser (not a ring die as used by CPM). This resulted in a more durable pellet, however it is postulated that the high oil content in the olive residue (up to 18%) is responsible for the difficulties in achieving a robust pellet. One possible recommendation is to perform the F-CUBED process on exhausted (twice extracted) olive pomace to reduce this oil content (resulting in a more durable pellet with acceptable loss of calorific value).

Figure 9: Olive Pellets – soft and powdery

Note: Pelletization of Paper Sludge was carried out at TNO (not CPM) and on account of the smaller volume of material available no report was generated. A robust pellet was formed from Paper Sludge waste. The resultant char was also retained favourable mechanical properties and shape (Figure 10).

Figure 10: Conversion of robust Paper Pellets to consistent char

2.3 Thermal Processing Trials

An indirectly-fired rotary kiln and producer gas (syngas) afterburner were used to test the bio-energy carriers' performance (Figure 11). As well as producing energetic syngas which was further combusted, the system also produced a char from each of the feedstocks.

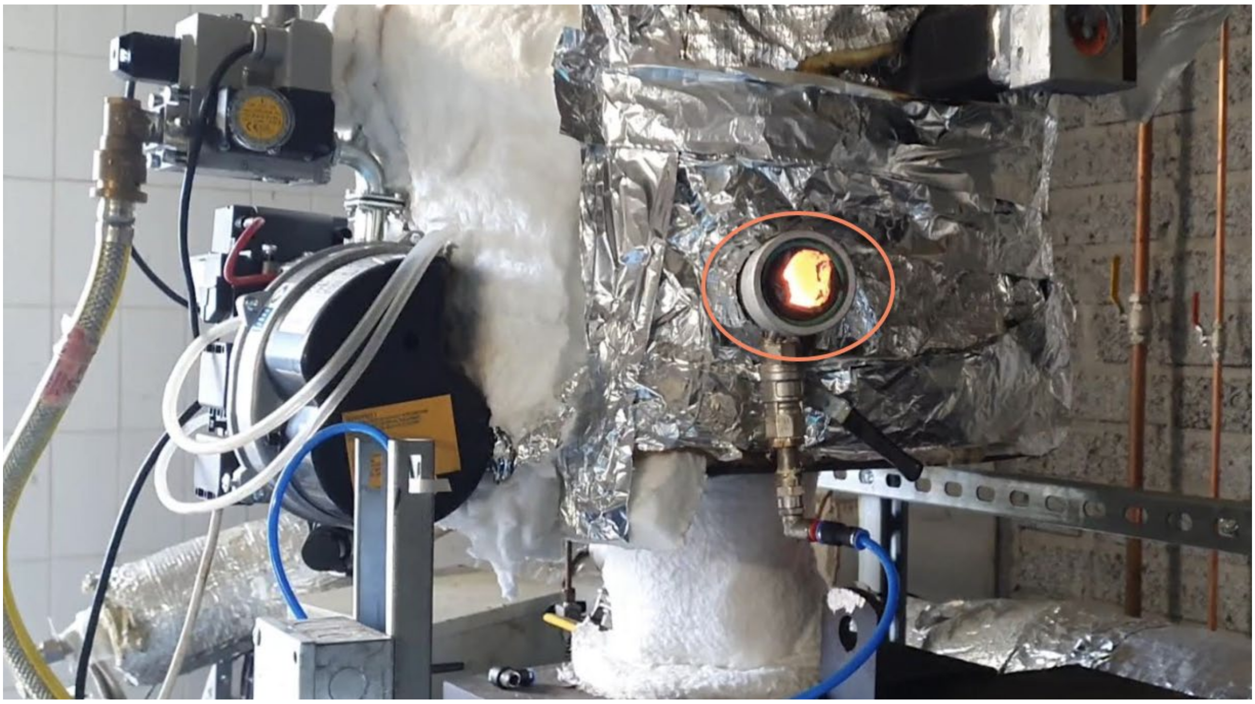


Figure 11: Combustion of Syngas

In the next sections, the observations regarding the thermal behaviour of different feedstocks are described. The composition of the resulting product and flue gasses, alongside the resulting char compositions, are reported on the subsequent sections per group of products, for the ease of comparison.

2.3.1 Paper Sludge Processing

The following observations were noted during paper sludge pellet thermal conversion.

- Performance was steady, with stable temperatures and good material flow.
- Cleaning of the gas sample probes was required to remove some char build-up.
- Based on the proximate analysis the max theoretical mass char yield achievable was 39% (i.e. 39% of the feed mass exits as char and ash). This would be the case when the conversion conditions would be similar to

the analytical devolatilization conditions (temperature, residence time, bed depth, etc.). The calculated output was 46% of the input feed, which is logically higher than the theoretical yield, mainly due to the lower conversion temperature. Still it is representing a very good pellet conversion to char, closely approximating the theoretical value, thereby validating the calculated settings (i.e. temperature: 700°C, Retention Time: 45mins, Regime: Rolling, Bed Depth: 13%). These parameters can be applied to equipment design and OPEX calculations at large scale.

- Charred pellet colour, shape and flowability all appeared satisfactory. The processed material still retained mostly the pellet form and was hence easy to handle, although some (fine) dust was also formed.

The following Mass Balance was observed (Table 4):

Table 4: Basic mass balance – Paper Sludge

Volatiles	*59.9%*		
Ash	*24.9%*		
Moisture	*1.6%*		
Total In	*9.00*	*kg*	
Total Out	*4.11*	*kg*	
Theoretical Best Conversion Out	*3.47*	*kg*	*(i.e. only Ash and Fixed Carbon remaining)*
Total Out	*46%*		
Theoretical Best Conversion Out	*39%*		

2.3.2 Olive Pomace Processing

The following observations were noted during olive pomace pellet thermal conversion.

- Performance was steady, with stable temperatures and reasonable material flow after some olive powder compaction issues were overcome in the feed-screw. The material was not pellet-like, and more closely resembled lumps and dust. It may benefit from blending with paper sludge, orange or similar to form a more robust pellet.
- A significant quantity of syngas was generated, possibly overloading the afterburner. This material is well suited to syngas generation, having the

benefit of a very high volatile fraction. Gas handling equipment will present the bottleneck for scale-up sizing (likely requiring de-rating of kiln throughput to accommodate).

- Based on the proximate analysis the max theoretical conversion achievable was 15% (i.e. 15% of the feed mass exits as char and ash). This would be the case with optimum operating conditions. The calculated output was 18% of the input feed, representing excellent feed conversion to char, closely approximating the theoretical value, thereby validating the calculated settings (i.e. temperature: 700°C, RT: 30mins, Regime: Rolling, Bed Depth: 13%). These parameters can be applied to equipment design and OPEX calculations at large scale.
- Charred product colour, shape and flowability all appeared as expected. The processed material appeared easy to handle.

The following Mass Balance was observed (Table 5):

Table 5: Basic mass balance – Olive Residue

Volatiles	*83.6%*		
Ash	*1.7%*		
Moisture	*1.1%*		
Total In	*16.00*	*kg*	
Total Out	*2.90*	*kg*	
Theoretical Best Conversion Out	*2.45*	*kg*	*(i.e. only Ash and FC remaining)*
Total Out	*18%*		
Theoretical Best Conversion Out	*15%*		

2.3.3 Orange Peels Processing

The following observations were noted during orange peels pellet thermal conversion.

- Performance was steady, with stable temperatures and good material flow.

- Based on the proximate analysis the max theoretical conversion achievable was 29% (i.e. 29% of the feed mass exits as char and ash). This would be the case with optimum operating conditions (temperature, residence time, bed depth etc). The calculated output was 28% of the input feed (accounting for minor losses, scales calibration error etc) representing a very satisfactory pellet conversion to char, thereby validating the calculated settings (i.e. temperature: 700°C, RT: 45mins, Regime: Rolling, Bed Depth: 13%). These parameters can be applied to equipment design and CAPEX / OPEX calculations at large scale.
- Charred pellet colour, shape and flowability all appeared as expected. The processed material appeared easy to handle.

The following Mass Balance was observed (Table 6):

Table 6: Basic mass balance – Orange Peels

Volatiles	*69.5%*		
Ash	*2.0%*		
Moisture	*1.5%*		
Total In	*9.00*	*kg*	
Total Out	*2.53*	*kg*	
Theoretical Best Conversion Out	*2.61*	*kg*	*(i.e. only Ash and FC remaining)*
Total Out	*28%*		
Theoretical Best Conversion Out	*29%*		*((i.e. ~100% conversion accounting for dust losses, scales calibration, natural variation in composition etc)*

2.4 Process stability and products quality evaluation

In general it should be observed that the pyrolysis/combustion tests reported on in this section are of highly explorative character. The newly-built system has not been previously applied with the specific fuels and the time available for testing and sampling was also limited within this project. Hence the results of the tests, as far as the quality of the products – and in particular that of the producer and flue gas quality – are still subject to further optimisation.

2.4.1 Primary process control and test course

In Figures 12-17 presented next, the details of the primary process settings (fuel/carrier gas/air flows) and the resulting output parameters (mainly temperatures) are presented. Also in these Figures, the main observations from the experimental log are correlated with the observed course of the recorded parameters.

As can be seen in these graphs, the variability and the experimental range of the conditions was varied actively throughout the tests. This was in order to accommodate the changing fuel qualities (between the different runs) as well as the dynamic variations of the changing producer gas and incinerator operating characteristics.

As will be shown in the section with the gaseous products analyses, this resulted in producer- and flue-gas quality changes – often beyond the ranges optimal for typical "syngas" applications or compliance with theoretical, full-scale emission limits. Nevertheless it can be concluded that the main goal of the test runs, namely a stable char output, producer gas production and its on-site incineration have been achieved for all three, widely varying feedstocks. This is signified by the excellent stability of the kiln temperatures, as in all three feedstock cases the envisaged conversion temperature of 700°C has been achieved.

Also, as discussed in the previous sections, the yield of the chars was also well in line with the theoretically expected yield, based on the compositions of the feedstocks. In Figures 18-20, the compositions of the chars are summarised and compared as well.

In all the cases, the (relatively) stable running conditions were achieved for at least in a part of the running time, enabling also quantification of the resulting producer and - upon incineration – the corresponding flue gas quality. These are all summarised in Figures 21-22 and discussed in detail in this report. Also, where possible a brief evaluation of the end-use options is provided alongside the directions for further optimisation and scale-up of the technology, particularly from the point of view of the emissions.

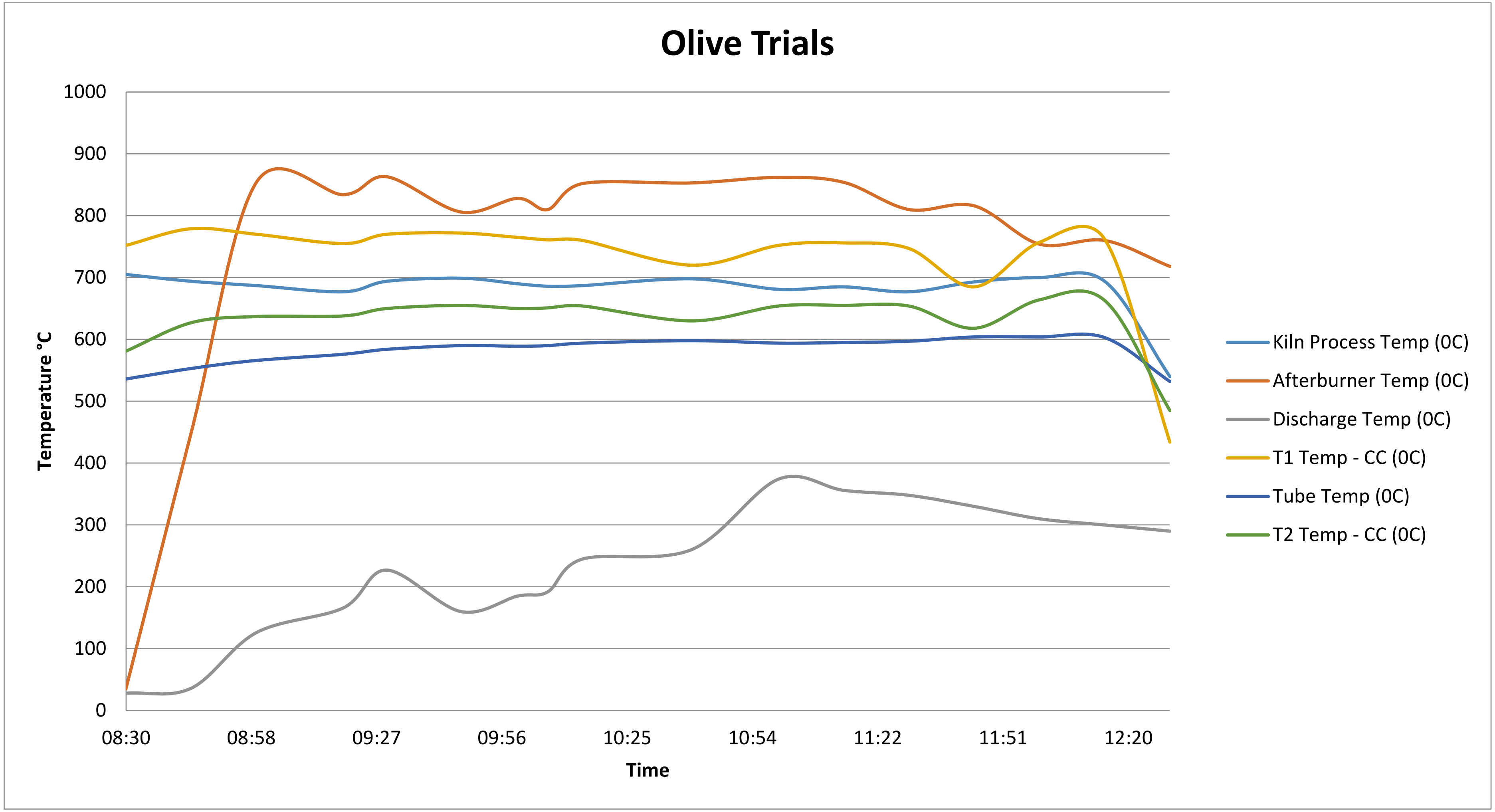


Figure 12: Temperature profiles – olive pomace trials

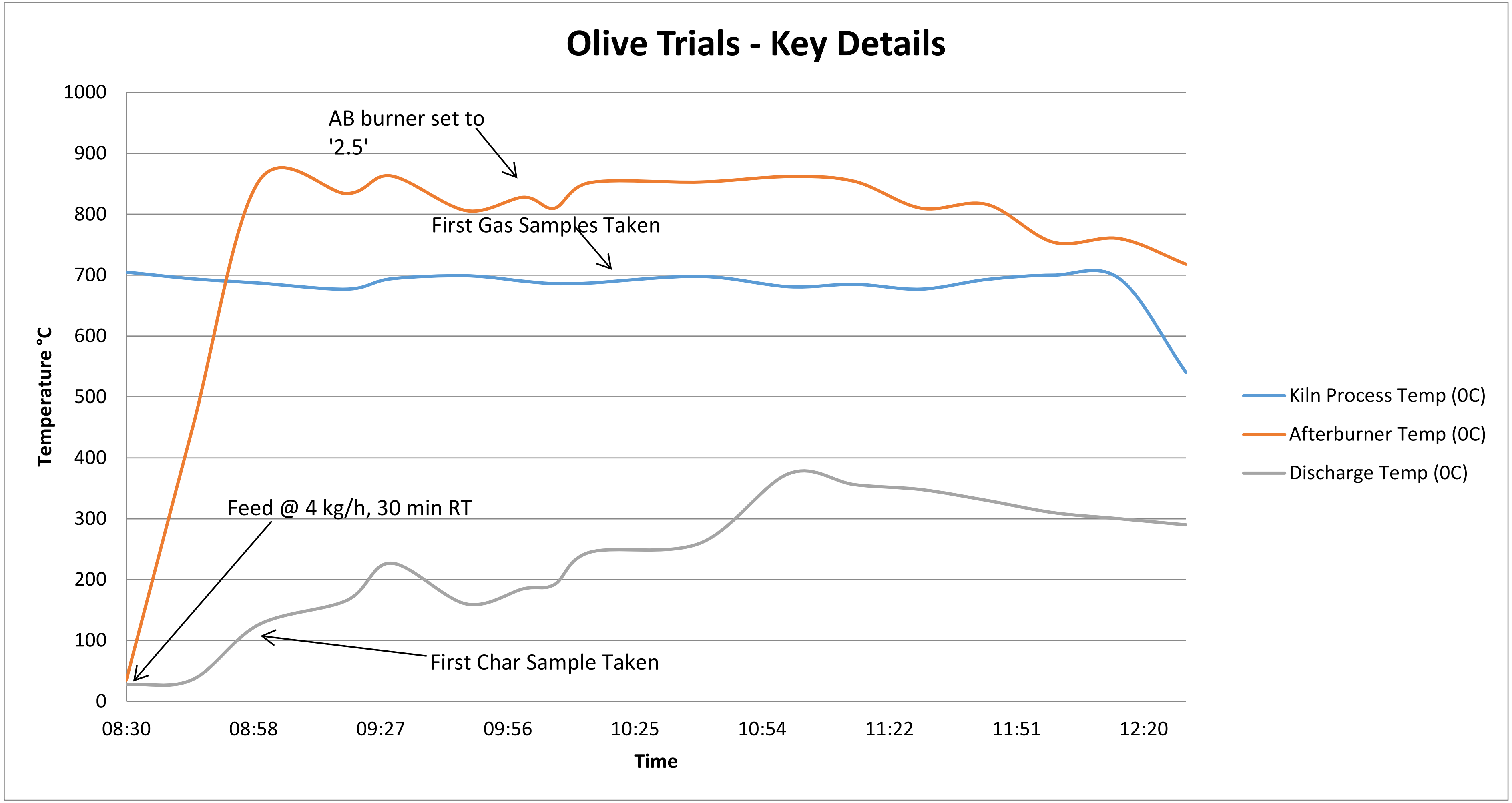


Figure 13: Temperature profiles – olive pomace trials, details of the settings and sampling times

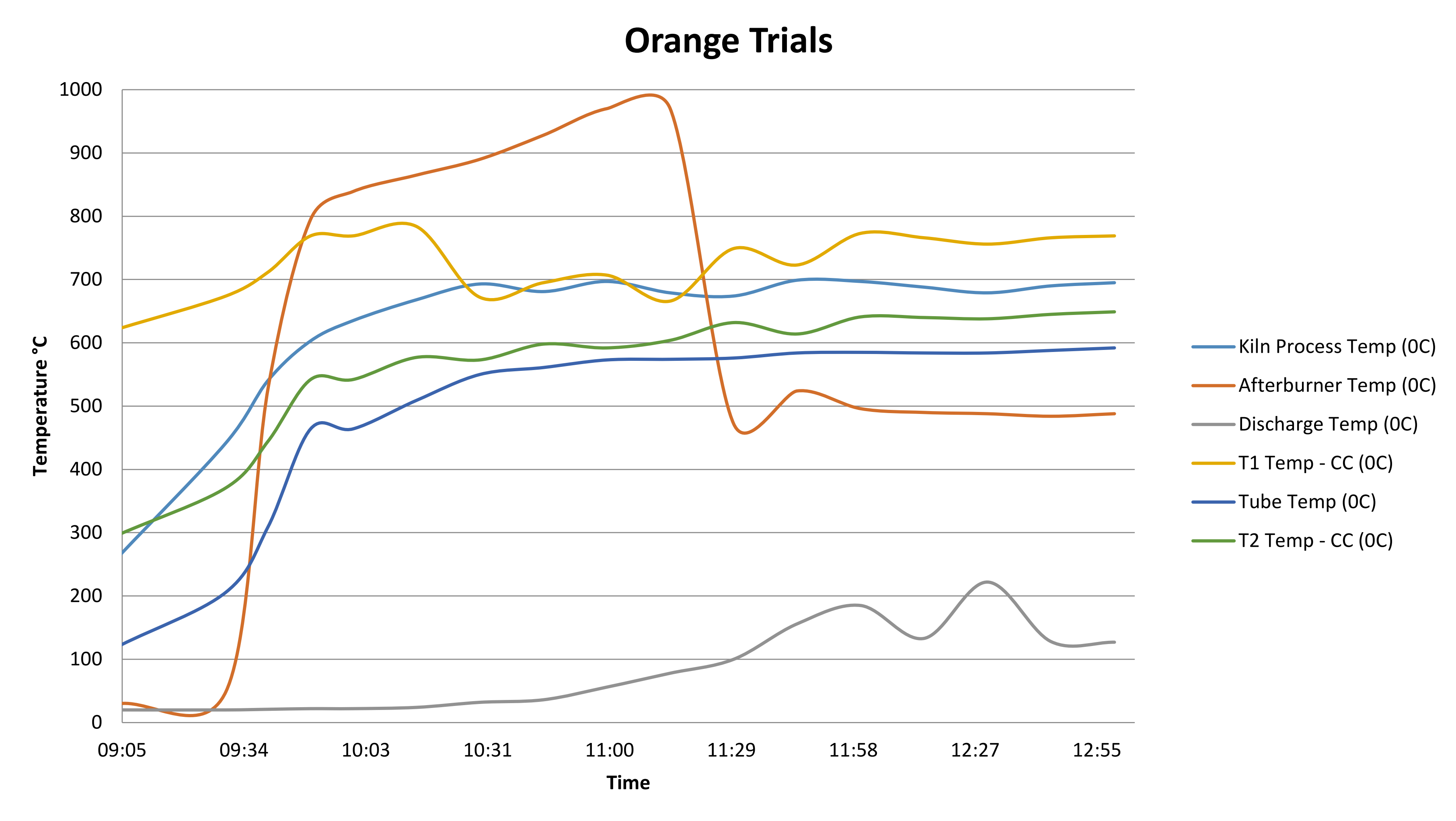


Figure 14: Temperature profiles – orange peels trials

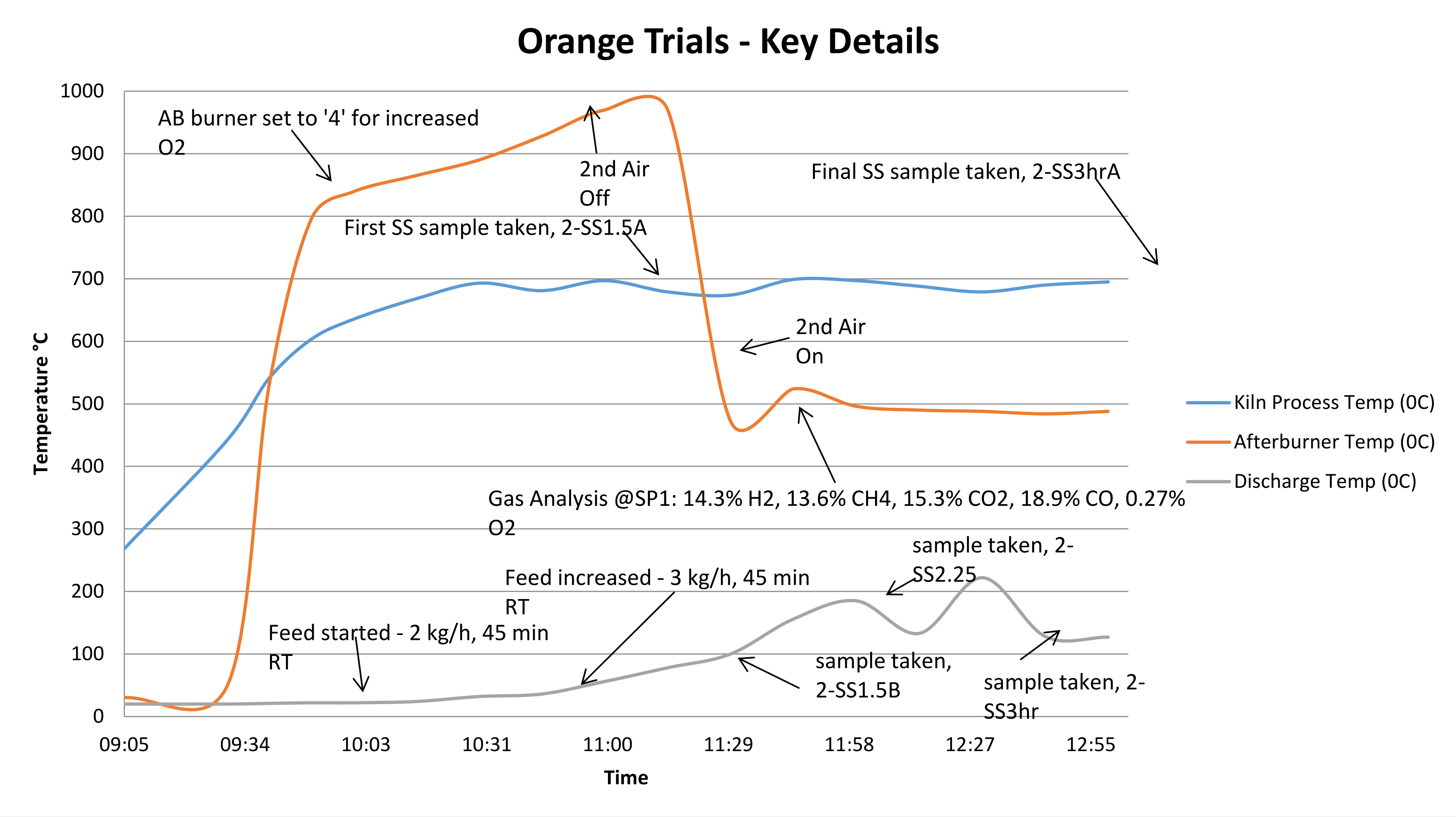


Figure 15: Temperature profiles – orange peels trials, details of the settings and sampling times

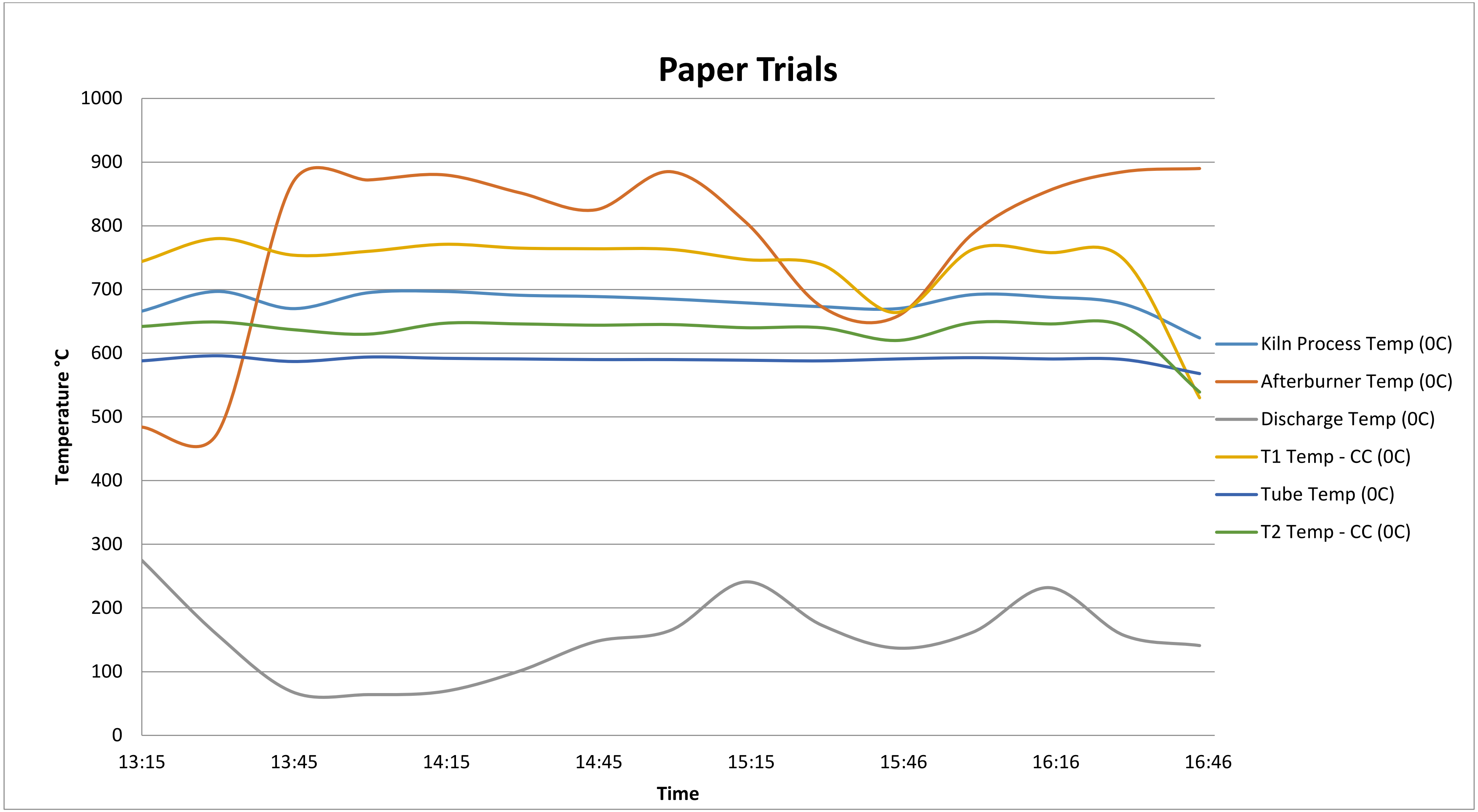


Figure 16: Temperature profiles – paper residue trials

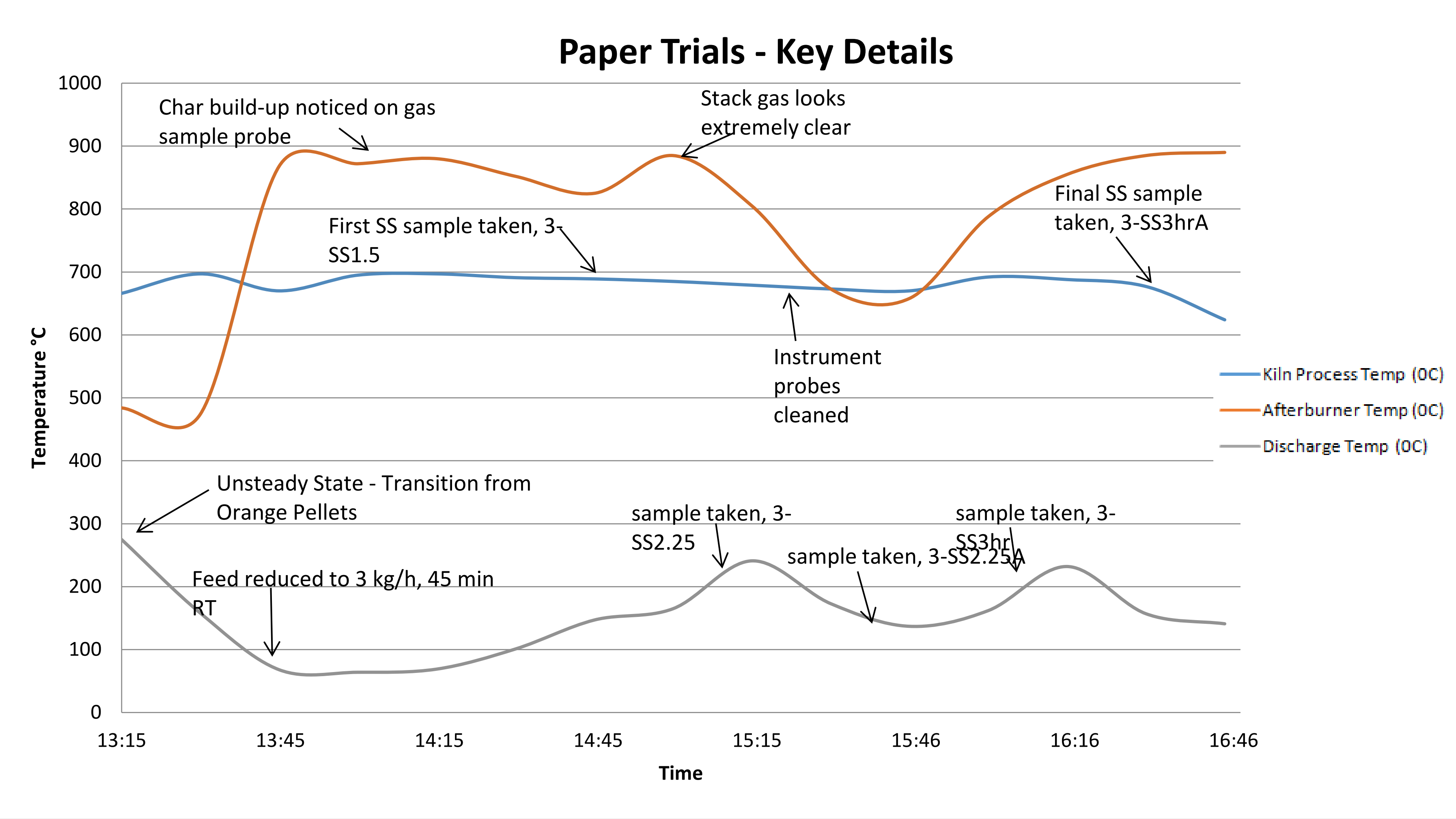


Figure 17: Temperature profiles – paper residue trials, details of the settings and sampling times

2.4.2 Solid products quality

In Table 7 compositions of chars resulting from the tests is shown.

Table 7: Compositions of the chars resulting from the pyrolysis experiments of different feedstocks; TWP = TORWASH pellet

Component/element	Units	Orange peel TWP char	Olive pomace TWP char	Paper sludge TWP char
Br	mg/kg	<10	85	50
Cl	mg/kg	111	438	244
F	mg/kg	10	32	175
Ash contents (550°C)	% db	9,3	9,3	54,1
Ash contents (815°C)	% db	6,0	7,1	51,6
Volatile matter	% db	bdl	bdl	bdl
Moisture contents	% ar	28,5	3,1	4,0
C	% db	82	84	43
N	% db	2,8	2,2	2,7
H	% db	1,9	1,6	0,7
O	% db	7,1	2,7	8,5
Al	mg/kg d.b.	344	4013	42208
As		0,26	0,30	5,99
B		65	98	26
Ba		14	29	1845
Ca		32861	24624	48780
Cd		< 0.04	< 0.04	12,6
Co		0,33	0,54	4,17
Cr		13,4	17,6	89,5
Cu		69,9	314	155
Fe		1721	2470	14949
K		3965	7294	3218
Li		0,48	0,44	7,34
Mg		345	490	7440
Mn		17	125	27327
Mo		1,0	3,0	20
Na		942	537	3722
Ni		10	20	35
P		535	1578	51057
Pb		5,1	2,1	103
S		942	1304	6342
Sb		0,3	7,0	2,1
Se		< 0.2	< 0.2	0,4
Si		852	1809	67219
Sn		2,6	22	8,1
Sr		79	25	230
Ti		12	32	2033
V		0,8	2,8	67
W		0,8	0,7	8,1
Zn		40	129	2592

The above compositions are further graphically summarised and compared with the parent TORWASH Pellet (TWP) compositions in Figure 18 through Figure 20.

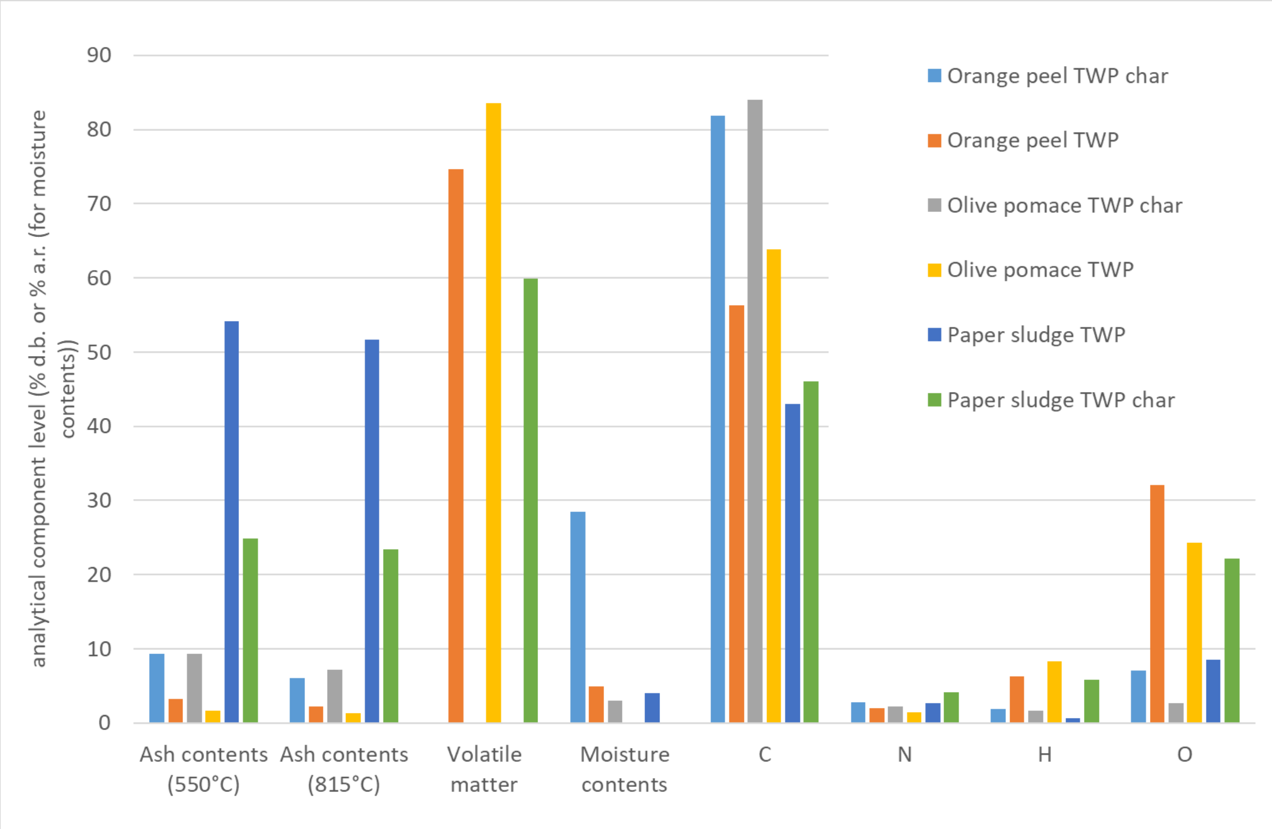


Figure 18 Proximate/ultimate analyses of the produced chars compared with the feedstocks

As can be seen in Figure 18, the pyrolysis process gives in all cases a clear and deep devolatilization of the feedstock materials. This is well in-line with the observed and theoretical mass yields of the char, as was explained in the previous section. Another important observation is that in all three cases, the remaining char is deeply deoxygenated, compared with the feedstock. This is also expected, as C-O and C-H bonds are substantially weaker than C-C bonds and therefore preferentially (or disproportionately) break up during this pyrolysis project, hence leaving a carbon-enriched matrix behind. As the result of the above partitioning processes, the levels of the non-convertible mineral matrix (ash) is increased, in line with the mass loss. Also, as clearly signified, the resulting ash levels are stable regarding different ashing temperatures. This is also an expected result, since the mobile part of the inorganics is partly volatilised alongside the organic matrix.

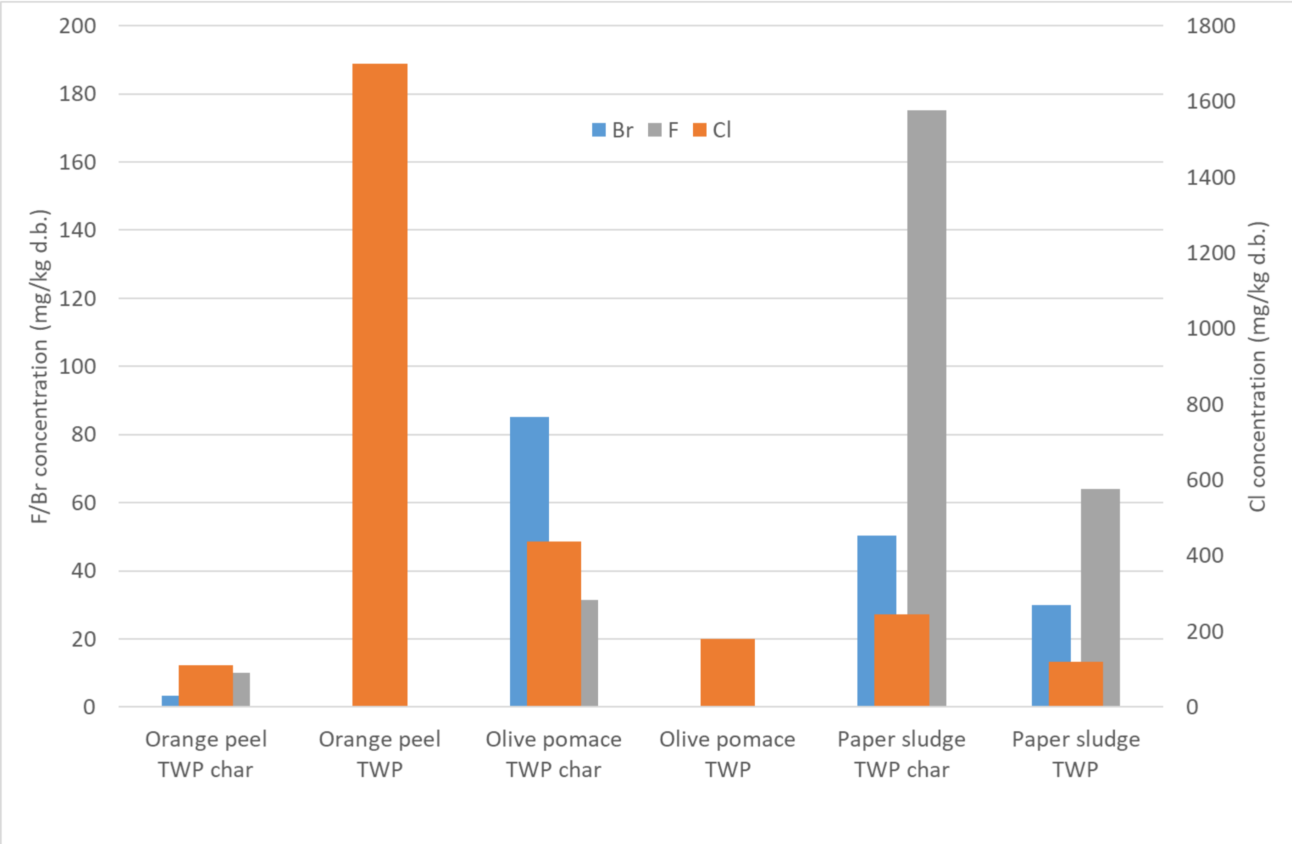


Figure 19 Halogens contents analyses of the produced chars compared with the feedstocks

Keeping in mind the mass loss as discussed earlier, it can be concluded that the pyrolysis process leads to a significantly depletion in chlorine and bromine elements of the original matrix. This has to do with the highly mobile character of these elements, both in the inorganic as well as organic speciation. Under complex conditions in thermochemical systems (combustion and pyrolysis) the typical alkali and, for a part, the earth chloride/bromide volatilisation temperature is <700°C; these elements do volatilise. Also under reducing conditions in the presence of other mineral oxides, much of these salts may decompose, yielding hydrochloric acid, hydrogen fluoride and bromides as the products, whereby the alkaline metals are incorporated into complex (alumino)silicates, etc. However, at higher levels of the earth alkali metals and lacking the appropriate reactive inorganics, part of the halogens can be retained. This is certainly the case for fluoride, which is detected in all chars, while it was under the detection limit in the fresh feedstocks. It should be stressed nonetheless that this is merely the result of the conservative (i.e. non-volatile/convertible) matrix enrichment, due to the convertible mass loss. With this "concentration", the relative share of the alkali and earth metals increases, hence enhancing the retainment of the halogens. This mineral matrix enrichment is discussed in the next paragraph. For now it can nonetheless be proposed that a non-negligible part of the bromine, chlorine and fluorine are volatilised in the pyrolysis process and need to be dealt with in the producer- and flue-gasses resulting from the downstream processing.

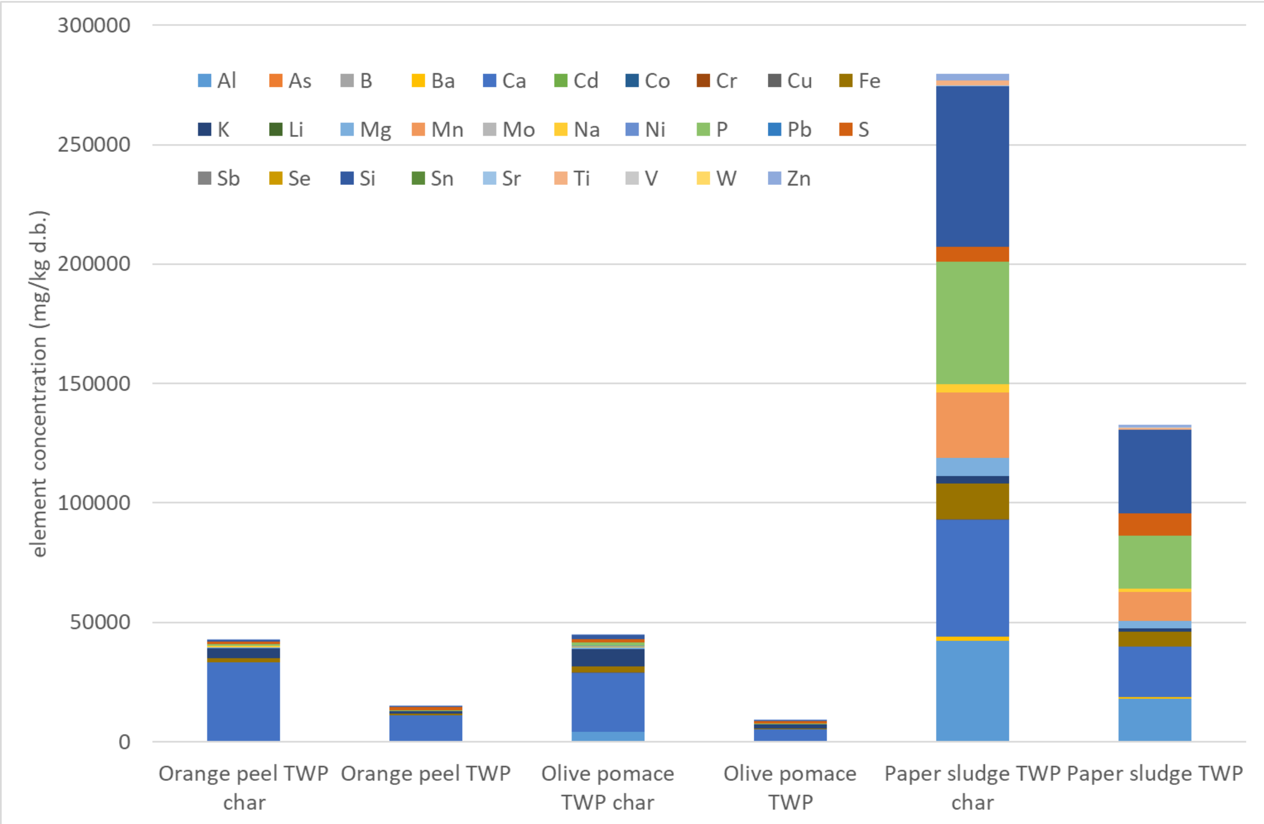


Figure 20 Inorganic matter analyses of the produced chars compared with the feedstocks

As can be seen in Figure 20, and from the proximate/ultimate analyses, the levels of the inorganic matrix are significantly higher than in the feedstock TORWASH pellets. For all the materials, this enrichment factor is roughly linear with the observed mass loss. Hence it can be proposed that the majority of the minerals are retained in the char matrix. Also the fractions of the specific elements do not seem to be significantly affected. This has primarily to do with the relatively mild conversion conditions, with the peak temperature of only around 700°C and relatively low mechanical stress experienced by the pellets (since most material is still recovered as large particles). Also, as the draft in the kiln is also quite low (being the devolatilised pyrolysis gas with ca. 50% dilution of the carrier gas), the potential to carry out fine particles of char and alongside with those also the inorganics into the incinerator, is low. Hence it can be proposed that no significant devolatilization nor mechanical carry-over of inorganics takes place in the current design of the kiln.

2.4.3 General evaluation of char usage potential

The behaviour of the different feedstocks was roughly comparable, the quality of the resulting char mostly relates to the quality of the feedstock itself. Hence it can be seen that the very ash-rich and transition metals-laden (Zn, Mn) matrix of the paper sludge, is different from the other two feedstocks which are significantly lower in both ash as toxic components. In view of these large differences it can be proposed that Orange Peels TWP and Olive Pomace TWP-derived materials are potentially suitable as reducing agents for metallurgy, as well as that they might be potentially used for soil improvement, as they also contain valuable nutrients (K) and soil-balancing (Ca) elements – although at moderate levels. Their halogens levels are moderate (Orange Peels TWP char<Olive pomace TWP char), hence these pellets may potentially also be used as solid fuel replacing non-volatile coal use. The Paper sludge TWP char is a different story. Given the low levels of convertible, carbonaceous matrix, any thermal or thermochemical use is highly unfavourable. Nonetheless this char represents a highly concentrated mineral matrix, containing a whole variety of recoverable elements (Ca, P, Mn, Zn) and therefore may rather be seen as a highly enriched mineral ore.

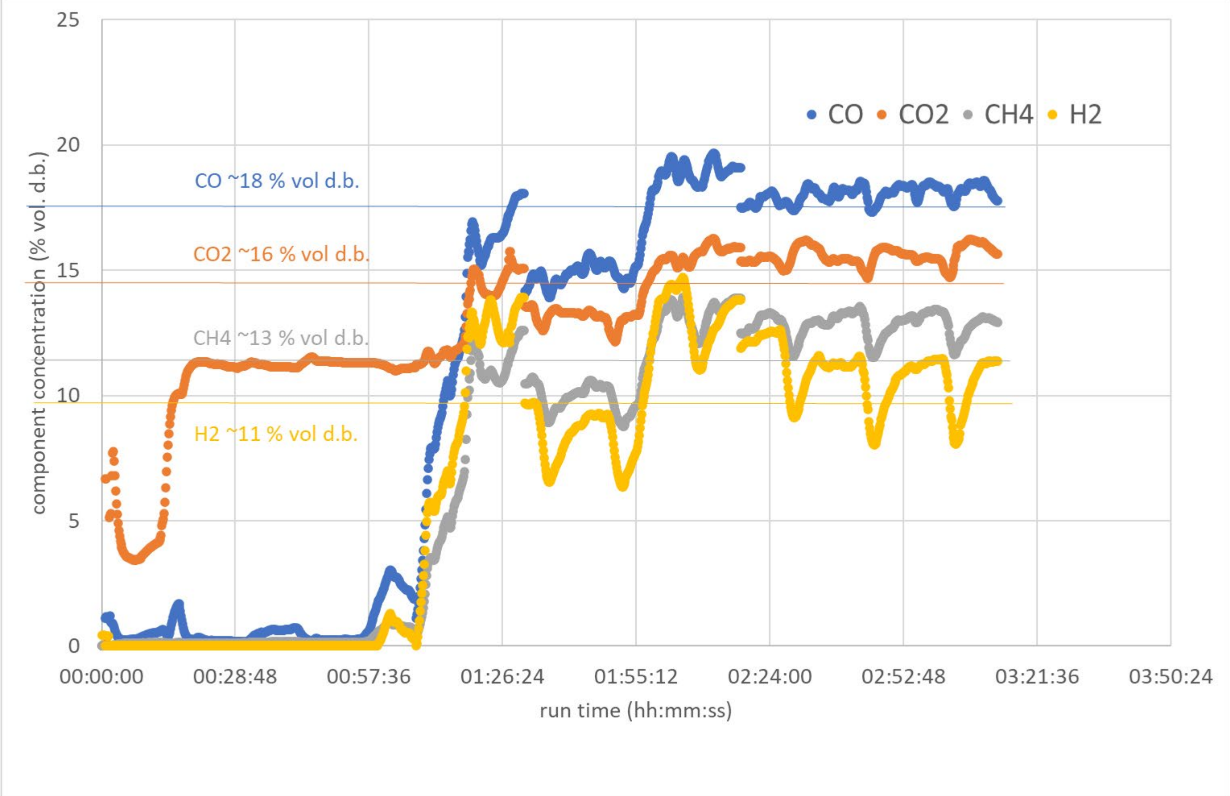
2.4.4 Pyrolysis/producer gas quality and use options

In Figure 21 a)-c) the quality of the producer/syngas resulting from the pyrolysis tests from different feedstocks is shown. As mentioned earlier, since these tests are of a highly explorative nature, the variability of the compositions during the test runtime is considerable, however average compositions gives some clues as to the nature and usability of these gasses. Also, the kiln and the sampling conditions were not optimised, which might have also adversely affected the gas quality (yet had less impact on the char quality). The overall, approximated compositions of the gas are summarised in Table 8.

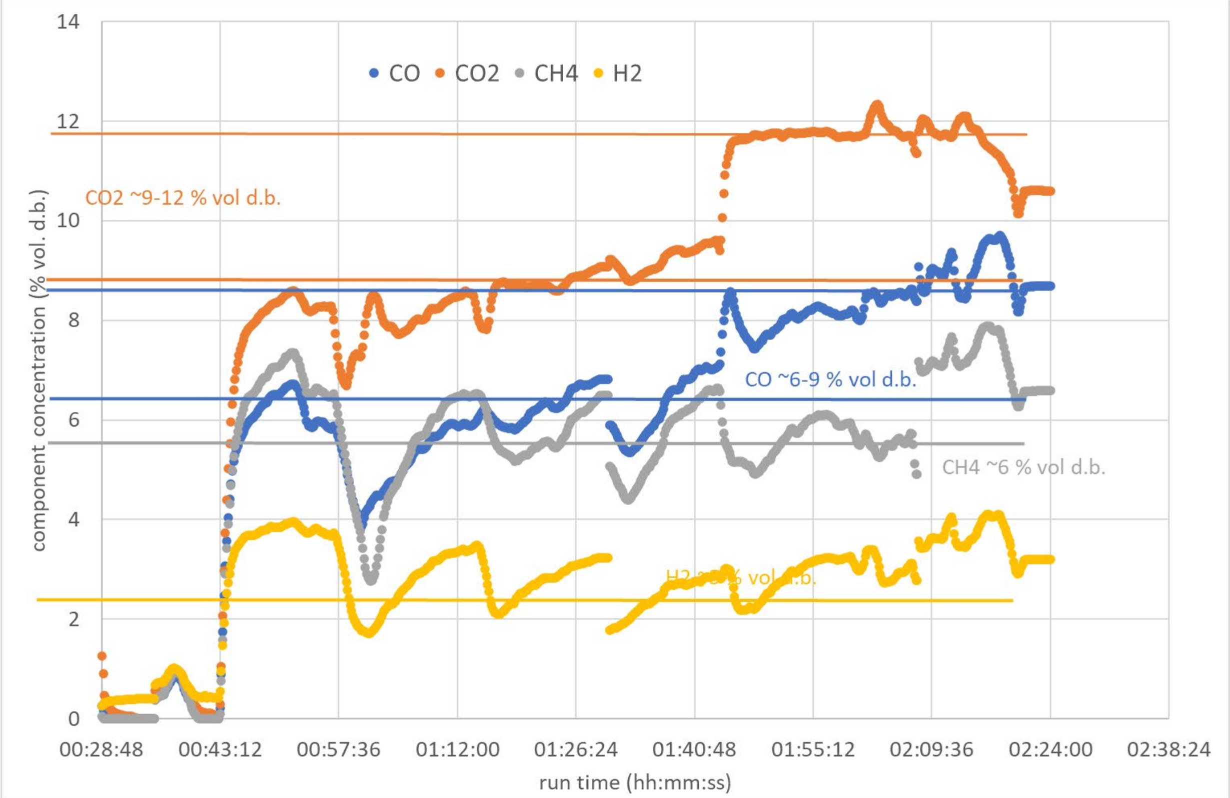
Table 8: Summary of approximate syngas compositions from different feedstocks

	H_2	CO	CO_2	CH_4	Sum combustible components
	(vol % d.b.)				
Orange peels TWP syngas	11	18	16	13	42
Olive pomace TWP syngas	3	6-9	9-12	6	18
Paper sludge TWP syngas	6	7	10	7	20

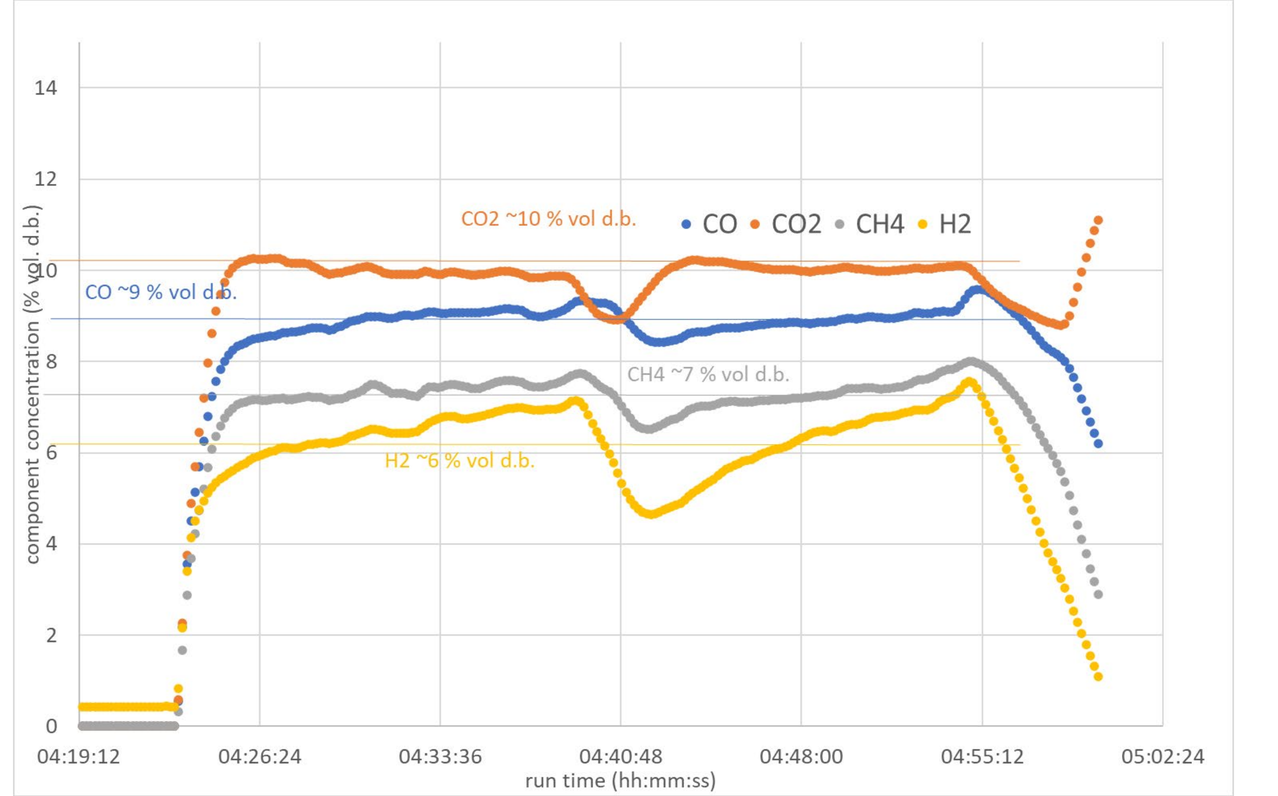
As can be seen in Table 8, the produced gasses are quite diluted, with the share of the combustible components only accounting for 18-42 % vol. of the gas. Overall, the concentrations and speciation of the combustible components are typical for slow pyrolysis, with relatively lesser levels of hydrogen and CH_4 compared with CO/CO_2. This is also associated with the relatively high levels of oxygen in the starting matrix and low conversion temperature, whereby CO_2 is not capable of functioning as a gasification medium. Nonetheless all three gasses are well-combustible without a support fuel, which will be shown in the next section. Naturally, in-line with the largely varying mass loss and the resulting gas volume from different feedstocks, the volume of the produced gas also varies. This means that the current system throughput is limited by the incineration capacity and needs further optimisation and appropriate scaling. In any case, all three resulting gasses are judged as well suited for a local, combined char and heat generation, though char-CHP options might be less feasible at least at the lower-end of the envisaged full-size plant scale.



a) Orange peels TWP pyrolysis



b) Olive pomace TWP pyrolysis

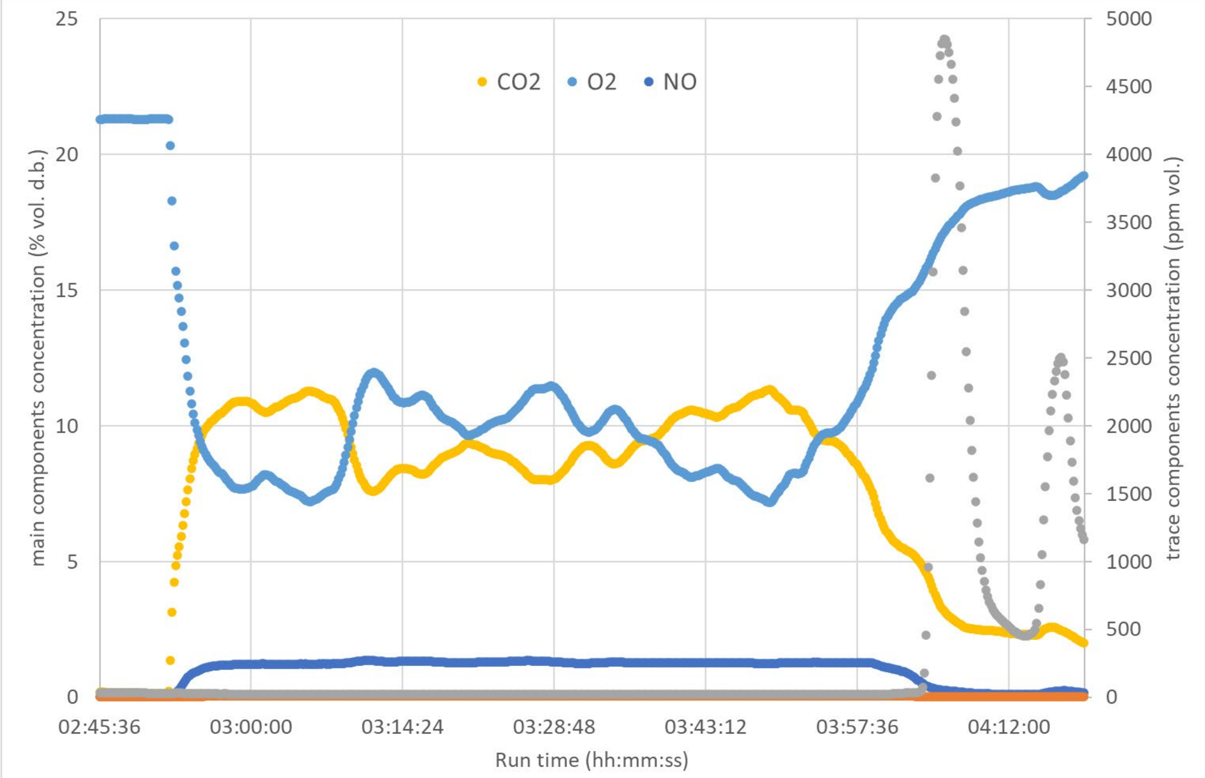


c) Paper sludge TWP pyrolysis

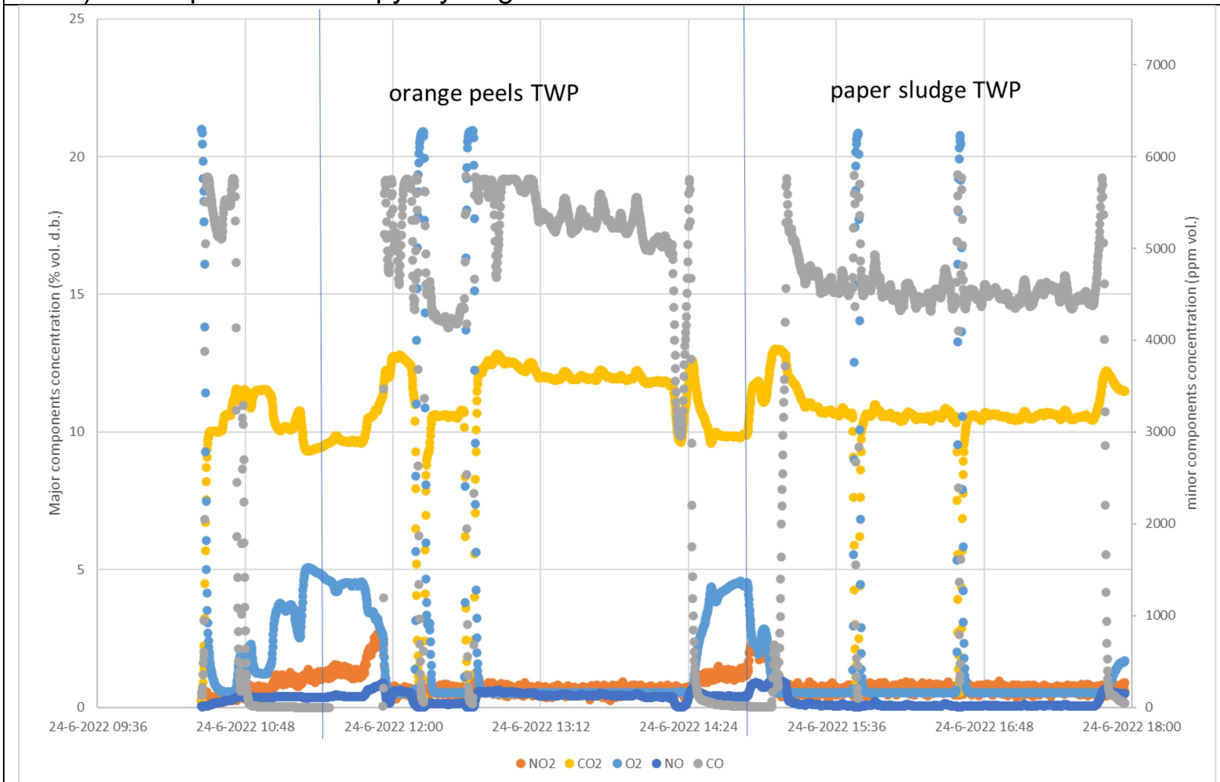
Figure 21: Summary of the pyrolysis gas compositions obtained during pyrolysis experiments with different feedstocks

2.4.5 Flue gas quality

In Figure 22 a)-b) the flue gas quality resulting from the combustion of the producer gas from the kiln in the on-site incinerator is shown. Also here it should be stressed that the current tests were carried out in an explorative way, in fact also constituting the hot commissioning of the installation. Hence in particular on the first day of the trials (with Orange peels TWP and Paper sludge TWP), the combustion was somewhat unstable as the incinerator air supply turned out to be insufficient for the realised throughputs. This manifested itself by (too) low excess oxygen levels after combustion. This was accompanied by relatively high levels of unconverted CO (up to ca. 0.5 % vol., see Figure 22 b) and also soot formation. The latter made it ultimately impossible to properly judge the particulate matter emissions. Nonetheless, on the second test day, using olive pomace, good combustion performance was achieved. This shown in Figure 22 a), where low levels of CO are observed, with appropriate levels of oxygen (and in fact even too high for optimal combustion). Under these (still non-optimised) conditions, NO levels are sizeable (ca. 300-400 mg NO @ 6% O_2), though quite typical for small-scale installations without any additional deNOx provisions. This is likely due to sizeable levels of hydrogen in the gas, which without a properly air-staged combustion results in high (local) flame temperatures and hence NOx formation. In all it can be concluded that the gas combustion is certainly possible and well controllable with typical, standard combustion technology means. Nonetheless during the scale up, appropriate attention must be paid to designing the combustion chamber adequately for specific envisaged throughputs and gas quality, including adequate de-NOx (preferentially SCR) and PM emissions (preferably a suitable fine-woven fabric filter) provisions.



a) Olive pomace TWP pyrolysis gas incineration



b) Orange peel and paper sludge TWP pyrolysis gas incineration

Figure 22: Summary of the flue gas compositions from the incineration of the producer gas obtained during pyrolysis experiments with different feedstocks

4. Commercial Gasifier Sizing

2.5 Olive Pomace – Scale Up Analysis

Based on trial settings, equivalent conditions can be achieved @ 750 kg/h throughput in an indirect fired rotary kiln with a heat tube sized at 1.2 x 7m (DxL). Similarly, 2,720 kg/h can be achieved in a unit with a heat tube sized at 2.1 x 12m (DxL). HS refers to these model sizes as TR1200 and TR2100 respectively, which typically meet most commercial requirements. However the afterburner and downstream syngas handling equipment would need to be sized for a substantial syngas load on account of the volatile nature of this feed (i.e. ~628 kg/h and ~ 2,278 kg/h for a TR1200 and TR2100 respectively). Excess Air requirements for syngas combustion will add significantly to the load, increasing downstream piping and equipment sizing. As discussed previously, utilising olive pomace with added front end extraction would not only limit oil content (for a more robust pellet and handling), but would also reduce the volatile load on the gas handling system. Alternatively the system could be de-rated to run at throughputs more consistent with what is being recommended for scale-up of paper and orange in the following sections.

Kiln Sizing - TNO - Olive				
Kiln Model		**Trial Kiln**	**TR1200**	**TR2100**
Process Info				
Throughput (wet in)	kg/h	4	750	2720
Throughput (Dry & DeVol Out)	kg/h	0.65	122	442
Bulk Density	kg/m^3	610	610	610
Moisture in	%	1%	1%	1%
Moisture out	%	0%	0%	0%
Target Temperature	degC	700	700	700
Volatiles in dry Feed	%	83.6%	83.6%	83.6%
Residence Time	Min	30	30	30
Rotation Speed	rpm	5.5	2	1.5
Physical Dimensions / Fill:				
Diameter	M	0.1651	1.2	2.1
Length	M	2	7	12
Bed Depth In	%	13%	13%	10%
Bed Depth Out	%	6%	6%	5%
Solids Motion				
Froude Number		0.00279	0.00268	0.00264
Motion Form		Rolling	Rolling	Rolling

3.1. Paper Sludge – Scale Up Analysis

Based on trial settings, equivalent conditions can be achieved @ 550 kg/h throughput in an indirect fired rotary kiln with a heat tube sized at 1.2 x 7m (DxL). Similarly, 2,000 kg/h can be achieved in a unit with a heat tube sized at 2.1 x 12m (DxL). The afterburner and downstream syngas handling equipment can be sized for a very manageable syngas load at commercial scale (i.e. ~333 kg/h and ~ 1,210 kg/h for a TR1200 and TR2100 respectively). There is less syngas generated with a paper sludge feed when compared to olive, partially because olive required less residence time for full volatilisation on account of its smaller particle size (lots of powder) and lower density, but also because it had an inherently higher volatile fraction.

Kiln Sizing - TNO - Paper				
Kiln Model		**Trial Kiln**	**TR1200**	**TR2100**
Process Info				
Throughput (wet in)	kg/h	3	550	2000
Throughput (Dry & DeVol Out)	kg/h	1.18	217	790
Bulk Density In	kg/m^3	690	690	690
Moisture in	%	2%	2%	2%
Moisture out	%	0%	0%	0%
Target Temperature	degC	700	700	700
Volatiles in dry Feed	%	59.9%	59.9%	59.9%
Residence Time	minutes	45	45	45
Rotation Speed	rpm	3.7	1.4	1.05
Physical Dimensions / Fill:				
Diameter	m	0.1651	1.2	2.1
Length	m	2	7	12
Bed Depth In	%	13%	13%	10%
Bed Depth Out	%	6%	6%	5%
Solids Motion				
Froude Number		0.00126	0.00131	0.00129
Motion Form		Rolling	Rolling	Rolling

3.2. Orange Peels – Scale Up Analysis

Based on trial settings, equivalent conditions can be achieved @ 550 kg/h throughput in an indirect fired rotary kiln with a heat tube sized at 1.2 x 7m (DxL). Similarly, 2,000 kg/h can be achieved in a unit with a heat tube sized at 2.1 x 12m (DxL). Interestingly, this is identical to scaled up conditions for paper, and given that both orange and paper formed robust and very similar sized pellets (similar density etc) it is not surprising that similar outcomes can be predicted at scale. The afterburner and downstream syngas handling equipment can be sized for a very manageable syngas load at commercial scale (i.e. ~385 kg/h and ~ 1,399 kg/h for a TR1200 and TR2100 respectively).

Kiln Sizing - TNO - Orange				
Kiln Model		**Trial Kiln**	**TR1200**	**TR2100**
Process Info				
Throughput (wet in)	kg/h	3	550	2000
Throughput (Dry & DeVol Out)	kg/h	0.90	165	601
Bulk Density	kg/m^3	682	682	682
Moisture in	%	2%	2%	2%
Moisture out	%	0%	0%	0%
Target Temperature	degC	700	700	700
Volatiles in dry Feed	%	69.5%	69.5%	69.5%
Residence Time	Min	45	45	45
Rotation Speed	rpm	3.7	1.4	1.05
Physical Dimensions / Fill:				
Diameter	M	0.1651	1.2	2.1
Length	M	2	7	12
Bed Depth In	%	13%	13%	10%
Bed Depth Out	%	6%	6%	5%
Solids Motion				
Froude Number		0.00126	0.00131	0.00129
Motion Form		Rolling	Rolling	Rolling

3.3. Synergy Potential

The schematic below shows the potential synergy and integration between F-Cubed processes, Anaerobic Digestion and Pyrolysis. Combining all systems amplifies benefits in terms of value-added outputs.