

# D3.1 Feedstock characteristics and behaviour in dry gasification





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## 1. Introduction

Fuels-C will develop an integrated platform of innovative energy-efficient conversion technologies validated at TRL5 including first gasification and anaerobic digestion, followed by bioelectrochemically assisted CH<sub>4</sub> production, bioelectrochemical NH<sub>3</sub> production, microbial electrosynthesis, and electroreduction. Various biogenic residues (biodegradable and non-biodegradable) will be converted under mild conditions into CH<sub>4</sub>, NH<sub>3</sub>, formic acid and ethanol, by two main production routes, using renewable energy, thereby enabling efficient energy surplus storage as chemicals. The 4 biofuels can be used as drop-in, but Fuels-C will also test them in FCs for electricity production: gaseous NH<sub>3</sub> and CH<sub>4</sub> in SOFCs, liquid ethanol and formic acid in DLFCs.

The first steps of this integrated platform is either anaerobic digestion or gasification of biowastes. This report presents a literature review on selected wastes and on their behavior in a fluidized bed gasification process.

In order to select three feedstocks, they were classified in different categories (urban, forestry, agriculture, and industrial and FACSA did a qualitative analysis of each one taking account different aspects:

- The European areas where these feedstocks are mainly generated
- The approximate production of each one at EU level
- The production seasonality (during all year or in a specific period in the year). This is important to take into account possible pretreatment and storage of these feedstocks.
- The qualitative composition (lignocellulosic, biological, plastics, etc.)
- The humidity range
- The possible pretreatment to be applied before gasification
- The possibility for FACSA to supply them to CEA.

Taking into account different criteria, three feedstocks are selected for this study:

1. Anaerobic digestate from sewage sludge, which is a typical waste that is produced across EU. This kind of waste has no alternative use (agriculture use but the norms become more and more restrictive with time).
2. Woody tree pruning waste is produced in large quantities around EU. It is the second main coproduct in agriculture sector.
3. Plastic fraction from the mechanical separation of solid waste after crushing in small pieces. It is an interesting waste produced around EU.

General physico-chemical properties of each feedstock are presented in this report, as well as their behavior in fluidized bed gasifiers. For anaerobic digestate from sewage sludge, and for the plastic fraction, the study more largely considers sewage sludge and solid recovered fuel (SRF) respectively, because of similarities in the composition.

## 2. Overview on fluidized bed gasification

### 2.1 Description of gasification reactions

Gasification is a thermochemical conversion which can be described as a succession of different steps depicted in Figure 1.

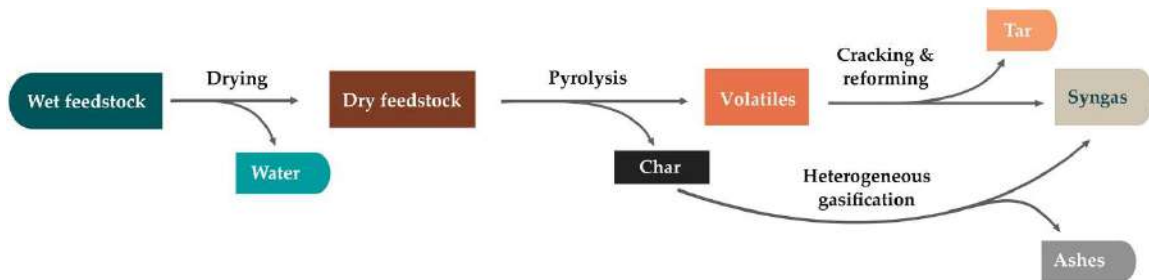


Figure 1: Gasification reactions steps, from feedstock to syngas

TABLE 5.2 Typical Gasification Reactions at 25 °C

Reaction Type	Reaction
<b>Carbon Reactions</b>	
R1 (Boudouard)	$C + CO_2 \leftrightarrow 2CO + 172 \text{ kJ/mol}^1$
R2 (water-gas or steam)	$C + H_2O \leftrightarrow CO + H_2 + 131 \text{ kJ/mol}^2$
R3 (hydrogasification)	$C + 2H_2 \leftrightarrow CH_4 - 74.8 \text{ kJ/mol}^2$
R4	$C + 0.5 O_2 \rightarrow CO - 111 \text{ kJ/mol}^1$
<b>Oxidation Reactions</b>	
R5	$C + O_2 \rightarrow CO_2 - 394 \text{ kJ/mol}^2$
R6	$CO + 0.5O_2 \rightarrow CO_2 - 284 \text{ kJ/mol}^4$
R7	$CH_4 + 2O_2 \leftrightarrow CO_2 + 2H_2O - 803 \text{ kJ/mol}^3$
R8	$H_2 + 0.5 O_2 \rightarrow H_2O - 242 \text{ kJ/mol}^4$
<b>Shift Reaction</b>	
R9	$CO + H_2O \leftrightarrow CO_2 + H_2 - 41.2 \text{ kJ/mol}^4$
<b>Methanation Reactions</b>	
R10	$2CO + 2H_2 \rightarrow CH_4 + CO_2 - 247 \text{ kJ/mol}^4$
R11	$CO + 3H_2 \leftrightarrow CH_4 + H_2O - 206 \text{ kJ/mol}^4$
R14	$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O - 165 \text{ kJ/mol}^2$
<b>Steam-Reforming Reactions</b>	
R12	$CH_4 + H_2O \leftrightarrow CO + 3H_2 + 206 \text{ kJ/mol}^3$
R13	$CH_4 + 0.5 O_2 \rightarrow CO + 2H_2 - 36 \text{ kJ/mol}^3$

<sup>1</sup>Source: Higman and van der Burgt, 2008, p. 12.

<sup>2</sup>Source: Klass, 1998, p. 276.

<sup>3</sup>Source: Higman and van der Burgt, 2008, p. 3.

<sup>4</sup>Source: Knoef, 2005, p. 15.

Figure 2: Typical gasification reactions

The solid particles, when they are placed in conditions of gasification (temperature around 800°C for fluidized bed gasification, in presence of O<sub>2</sub>, air, steam and/or CO<sub>2</sub>), undergo a series of different transformation:

- Drying,
- Pyrolysis: thermal decomposition, which takes place without any reaction with the gas environment, and which leads to the formation of volatiles and char (solid residue)
- Gas phase reactions: involving the volatiles, and the gas environment
- Gasification of char: reaction with O<sub>2</sub>, H<sub>2</sub>O, CO<sub>2</sub>.

As shown Figure 1 carbon contained in feedstock is either oxidized or reduced, thanks to both endothermic and exothermic reactions with fluidizing agents used such as O<sub>2</sub>, H<sub>2</sub>, H<sub>2</sub>O, CO<sub>2</sub>, air.

The composition of the syngas coming out of the reactor depends on the reactor technology, on the composition of the atmosphere, on the feedstock nature and composition, on pressure and temperature.

## 2.2 Fluidized bed gasification

### Overview on fluidization and types of reactors

“Winkler’s process operated in a fluidization regime, where a clear distinction exists between the dense phase or bed and the freeboard where the solid particles disengage from the gas. This regime is the classic or stationary fluid bed. With increasing gas velocity, a point is reached where all the solid particles are carried with the gas and full pneumatic transport is achieved. At intermediate gas velocities, the differential velocity between gas and solids reaches a maximum, and this regime of high, so-called “slip velocity” is known as the circulating fluid bed. Over the years gasification processes have been developed using all three regimes, each process exploiting the particular characteristics of a regime to the application targeted by the process development. These differences are portrayed in Figure 3 and Figure 4. In fluid-bed gasification processes the blast has two functions: that of a reactant and that of the fluidizing medium for the bed. Such solutions, where one variable has to accomplish more than one function, will tend to complicate or place limitations on the operation of the gasifier, as in for example, turndown ratio. These problems are especially severe during start-up and shutdown. In most modern gasification processes oxygen/steam mixtures are used as blast. However, when the gas is to be used for power generation, gasification with air may be applied—and in the case of biomass gasification, it often is. Some simplified reactor sketches for bubbling fluid beds (BFB), circulating fluid beds (CFB), and transport reactors are given in Figure 3 and Figure 4 extracted from one of the most significant book reference on gasification process description: Chris Higman and Maarten van der Burgt, 2003.

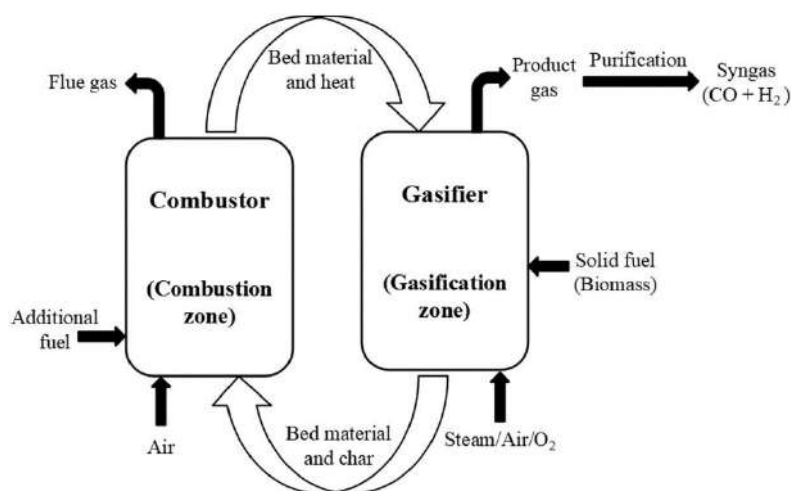


Figure 3: Scheme of a dual fluidized bed allothermal reactor ((Hanchate et al. 2021)

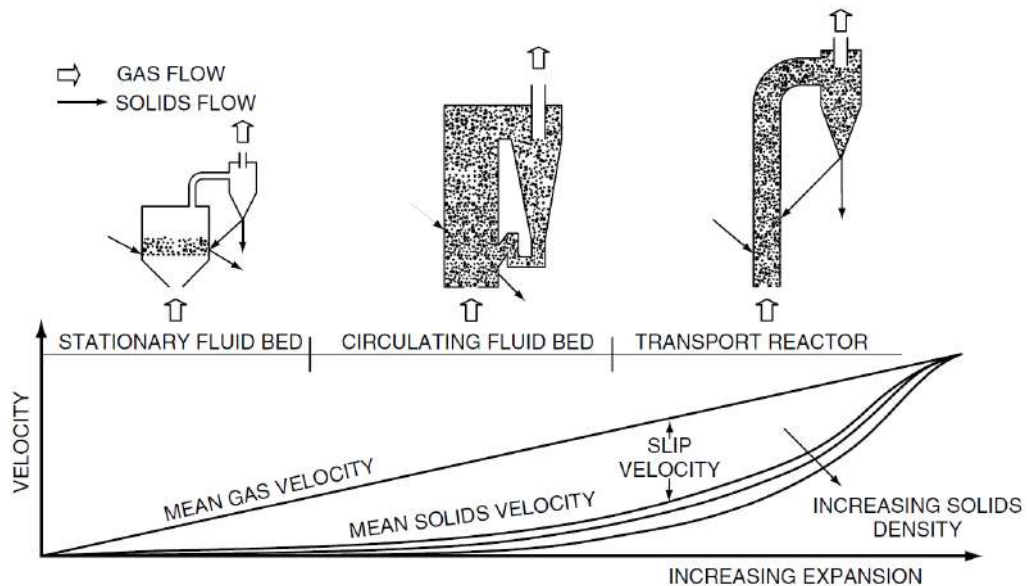


Figure 4: Fluidized bed regimes (Source: Greil and Hirschfelder, 1998)

More recently (1950), dual fluidized bed gasifiers were developed to produce a N<sub>2</sub> free syngas without the need to use pur oxygen as gasification, which is a very interesting technology for biofuels applications. As shown Figure 3, dual fluidized bed consists of two interconnected vessels: a BFB for biomass conversion to syngas and a CFB combustor which role is to oxidize residual char and provide heat to endothermic gasification reactions.

Bed particles are generally sand or some inert solid phase, catalysts can also be added. Fluidized beds have wide range of applications: heat, electricity, methanation, biofuels, it is interesting for intermediate unit (1 MW-100MW), very large extrapolation is difficult (< 30 MW). One major drawback about this reactor technology is high risk of ash agglomeration (melting) and difficult operation under pressure.

### Operating parameters

The biomass is generally introduced with a screw at a flow rate between 1 to 50-100 kg/h for pilot scale. The reactor built in special steel is heated until 1000°C, but generally gasification takes place at maximum 950°C, thanks to the injection of steam water / oxygen / air / N<sub>2</sub> / CO<sub>2</sub> as gasification agent and electrical heating (allothermal at pilot or lab scale).

Oxygen or air (providing heat and allowing for biomass particles and bed fluidization) flowrates are calculated depending on the Equivalence Ratio (ER), the minimal fluidization speed and the reactor geometry. The ER is defined in the equation below, as the ratio of the actual oxygen supply (oxygen in the gasification agent and in the biomass) to the stoichiometric oxygen required for complete combustion. It must be significantly below 1.0 to ensure a condition far from a complete combustion.

$$ER = \text{Actual O}_2 \text{ supply} / \text{Stoichiometric O}_2 \text{ requirement}$$

At industrial scale, biomass feeding rate is around 20 T/h (maximum size for fluidized bed reactor corresponding to 100 MWth for a 17 MJ/kg LHV biomass). Depending on the gasification agent strategy, either the air/oxygen or the steam flowrate is used for the fluidization, and a part of biomass is used for internal combustion (bringing heat needed for the gasification, this is called autothermal), to maintain the ER around 0.3, biomass feeding rate is adjusted.

Gases produced during the gasification of the biomass are generally measured by a gas chromatograph whereas tars are collected into cold traps or cracked. Syngas produced is cooled down by droplet catchers connected to chillers or burnt.

Effects of some operating parameters on the gasification reactions and gas yields are crucial and have been largely studied:

- Temperature between 750 and 950°C (average study around 850°C)
- Steam, air, oxygen or other gasification agent flow rates such as N<sub>2</sub> and/or CO<sub>2</sub> have been studied, varying their flow rates and velocities
- Pressure
- ER , H<sub>2</sub>O/Biomass ratio
- Type of biomass : Wood chips, forestry residues, wood pellets, bark, straw, polyethylene beads, SRF pellets, tires powder, plastic waste, SRF, municipal waste...

## 2.3 Biomass pretreatment for fluidized bed gasifiers

When it comes to fluidized bed gasification, biomass pre-treatment consists of drying (20% moisture content maximum) and pelletization mainly: first grinding in small size and then forming pellets of a few mm with starch as a binding agent. Size of pellets usually does not exceed a centimeter, depending on the conveying screw of chosen gasifier. Nature and quantity of bio resources can induce significant pelletization costs, it has to be considered in terms of cost and energy demand.

Pelletization energy demand : An average 1% of LHV of biomass

Typical electrical consumption for:

Primary grinding (cm) 70 kJ/kg of raw biomass

Secondary grinding (cm) 360 - 720 kJ/kg of biomass (100 – 200 Wh/kg)

Generally, between 150 and 200% of latent heat of dried water is necessary for the biomass drying.

## 2.4 Process performance and syngas composition

### Mass and Energy balance, yield/ efficiency and conversion rates

For a pilot scale reactor, about the global energy balance is not a completely relevant parameter, because a part of the heat is brought by electrical power (allothermal as described earlier in the document) and part from exothermic reactions with O<sub>2</sub> and air which is not used at industrial scale (autothermal). Generally, to estimate an “energy balance”, the Cold Gas Efficiency (CGE) is calculated as the ratio between the Lower heating Values (LHV) of product gas and LHV of fuel feedstock fed in the system. Usually, in typical fluidized bed gasification conditions, the CGE is at best 70%.

Carbon Conversion Rate or Efficiency (CCR or CCE) is usually around 90% only calculated on carbon going in the gas phase (10% going into tars and char, on a dry weight basis) for “clean” biomass (wood), not waste like bioresources

Examples of gas yields and conversion rates depending on key process parameters and type of reactors are presented below :

- **Oxygen steam gasification in a bubbling (stationary) fluidized bed:** Considering a gasifying temperature of 800°C (preheated oxy steam mixture at 300°C), biomass at 15% relative humidity and containing 10% of ashes (on a dry basis), with a pure oxygen flowrate of 0.1 kg/kg and 0.275 Nm<sup>3</sup>/kg of ash free dried biomass, corresponding to an ER of 0.29, simulations give a carbon conversion rate of 90% (10% going into tars, residues, char, on a dry weight basis). Syngas produced is composed of (Nm<sup>3</sup>/kg of dried biomass) : 0.327 of CO, 0.381 of CO<sub>2</sub>, 0.498 of H<sub>2</sub>, 0.284 of H<sub>2</sub>O, 0.0855 of C<sub>2</sub>H<sub>4</sub>. Air gasification is often used with wood chips as a reference, and give a syngas rich in N<sub>2</sub>.

- **Steam gasification in a circulating / dual fluidized bed:** Same conditions but with a bed temperature of 850°C and air flow in the dual bed instead of oxygen (not necessary in this configuration as explained earlier), approximately 1.04 Nm<sup>3</sup> of syngas/kg of biomass is produced, with 42% H<sub>2</sub>, 23% CO<sub>2</sub>, 20% CO, 9 %CH<sub>4</sub>, 3% C<sub>2</sub>H<sub>4</sub>.

## 3. Sewage Sludge

Anaerobic digestate production is 19 MT annually from every European areas, its seasonality is a real advantage since it is available daily (storage 20 to 30 days), for these reasons Fuels-C project is studying this waste as a biomass resource for gasification.

However, the bibliographic review is widened to sewage sludge feedstock as a whole (both raw and after digestion) for a more global picture.

### 3.1 Physico-chemical characterization

A recent review gives a great overview of sewage sludges ultimate and proximate analyses presented in Figure 5 (Gao et al. 2020). Sewage sludge generally presents high ash, moisture, and volatile matter contents. Due to the high volatile matter content, it is expected to observe relatively low solid char yield and high gas production, but also unstable operating conditions and process difficulties (Nunes, De Oliveira Matias, et Da Silva Catalão 2018).

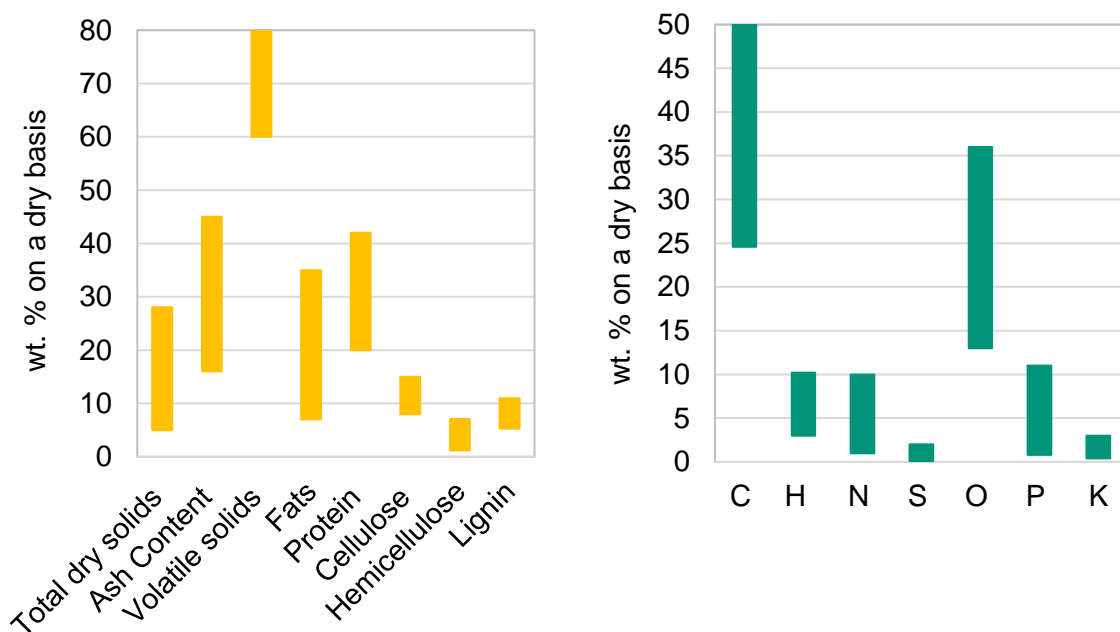


Figure 5: Ultimate and proximate analysis on the left, elemental analysis on the right of sewage sludge in different regions (Gao et al. 2020)

Usually Lower Heating Value (LHV) of sludges is comprised between 11 to 29 MJ/kg on dry basis, about 15 MJ/kg on an average, which is sufficient for gasification. Their high alkalinity and organic acids content can also vary significantly : from 500 - 1900 (mg/l CaCO<sub>3</sub>) and 200 – 2000 (mg/l acetate) respectively (Gao et al. 2020). As shown FX, fibers and polysaccharides are not predominant (Liu et Smith 2022) but lipids and proteins (bacteria) represent the major part of organic matter, which are often identified as model compounds for kinetics study.

Inorganic compounds are mainly constituted of metals and micronutrients (phosphorus, potassium, nitrogen and sulphur). Heavy metals account for up to 20% of sewage sludge dry matter, see Figure 6, this is a major concern about process equipment lifetime and ashes production. Silicon, calcium, aluminium, iron, magnesium and copper are the main elements found in sludge metals. Heavy metals and other metals tend to accumulate and cause reactors clogging.

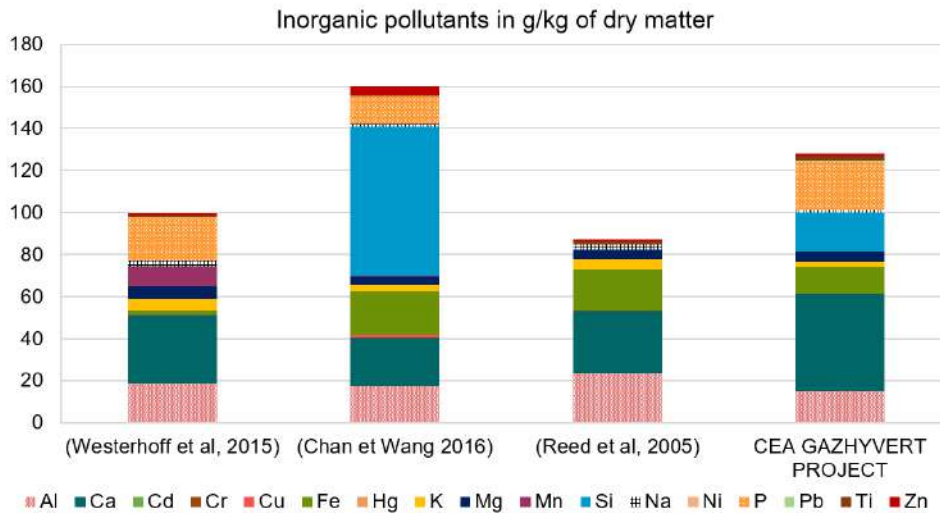


Figure 6: Inorganic pollutants in g/kg of dry matter of different municipal sewage sludges

Organic contaminants, micropollutants (microplastics) and inorganic matter (heavy metals) can have harmful effect on the environment if dispersed in soil and water and are more and more regulated by EU, making sewage sludge less suitable for land spreading or composting (Mailler et al., 2017; Jardé, 2005; Clarke et Smith, 2011; Blanchard et al., 2004). In this way, this is an interesting biogenic waste for gasification.

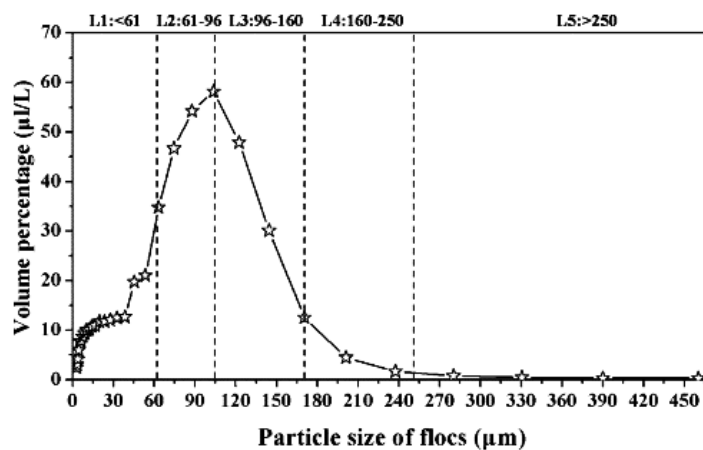


Figure 7: Particle Size Distribution of sewage sludge (Han et al. 2012)

Activated, digested and raw sludge are dominated by particles of size 10 – 200 µm (Wu et al. 2009), (Han et al. 2012), see Figure 7. This is too low for fluidized bed gasification and it must be pelletized. Bacteria cells are mostly in 1-10µm size range (Ekama et al. 1997).

The characteristics of anaerobic digestate from urban sewage sludge (cosubstrates), provided by FACSA are presented in Table 1. These wastes come from the wastewater treatment plant of Castelló, Spain.

*Table 1: FACSA sewage sludge anaerobic digestate characteristics*

Current fate	Feedstock production (t/y)	Water content (mass content on raw basis)	Feedstock production (tDM/y)	Ash content (mass content on dry basis)	Elemental composition (mass content on dry basis)	Inorganics (mass content on dry basis)
Land spreading	9700	75,00%	2425	34,80%	36,19% C ; 5,26% N	57 g P <sub>2</sub> O <sub>5</sub> /kg

Anaerobic digestate supplied by FACSA presents a low carbon content, and a very high water content, respectively below and above median value of the literature. These characteristics are unfavorable for gasification. However, the water content can be reduced with drying. The lower carbon content than in raw sewage sludge can be ascribed to digestion which transforms a part of the organic matter into biogas, as already foreseen in Fuels-C.

## 3.2 Pretreatment

The total dry solid content of primary and secondary sludges (included digested sludges after concentration by sedimentation or centrifugation but not dried) does not exceed 30 wt% on a dry basis, meaning that a drying step must be added prior to gasification.

Free conditioning dewatering, bio drying, thermal drying and pressurized electro osmotic dewatering with bio drying were assessed in terms of water removal efficiency and energy consumption (Gao et al. 2020). Sizing and pelletization are also necessary due to their low particle size distribution.

## 3.3 Gasification behavior

Air / steam fluidized bed gasification of dried sewage sludge anaerobic digestate was performed in different conditions to investigate the influence of ER and temperature especially on gas yields, LHV, CGE et CCR (Gil-Lalaguna et al. 2014). As usual, temperature influences positively CGE, and the best performances were obtained between 770 and 850°C (ER 0.23 and 0.32). Overall CGE values reached in this study vary from 39 to 66%, CCR from 78 to 92%, syngas yields from 0.9 to 1.3 Nm<sup>3</sup> dry and N<sub>2</sub> free basis/ kg dry ash free feedstock, with a LHV between 4 to 6 MJ/Nm<sup>3</sup>.

Continuous steam gasification of aerobic digestate pellets was studied in a pilot scale fluidized bed , with a feeding rate between 0.5 and 4 kg/h, a bed temperature of 800 – 900°C and olivine as bed material (Sid Ahmed Kessas, 2019). CCR up to 0.75 allows for the production of a H<sub>2</sub>/CO rich syngas, yield from 0.6 to 1.8 Nm<sup>3</sup>/kg daf, LHV comprised between 11 to 17 kJ/ Nm<sup>3</sup>. Influence of temperature and H<sub>2</sub>O/Biomass ratio, were studied, on X<sub>cg</sub> (carbon conversion rate), PG (syngas yield), and H<sub>2</sub>/CO ratio. In Figure 8, the influence of temperature is represented for a H<sub>2</sub>O/Biomass ratio of 0.8 kg/kg. It must be mentioned that carbon conversion rates within the set-up of experiments that have been done in this study are low compared to other studies.

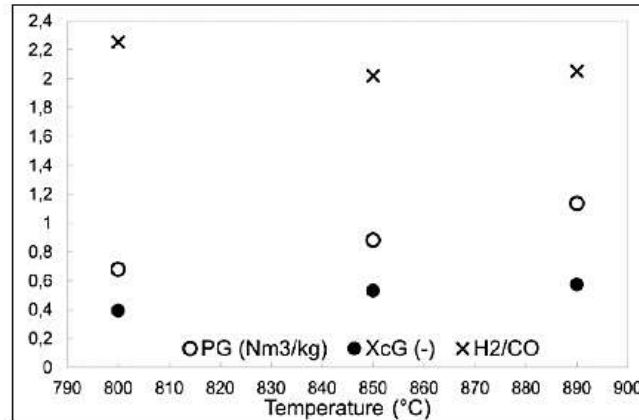


Figure 8: Influence of steam gasification temperature on Xcg (carbon conversion rate), PG (syngas yield), and H<sub>2</sub>/CO ratio of aerobic sewage sludge pellets steam gasification at fluidized bed pilot scale (Sid Ahmed Kessas, 2019)

Another study was performed at pilot scale on sewage sludges, municipal waste, wood waste, olive oil waste and meat and bone waste in a fluidized bed gasifier fed with air (Campoy et al. 2014). Syngas yield produced from dried sewage sludge with feeding rate from 9 to 16 kg/h (ER 0.3 – 0.35) can go from 1 to 1.4 Nm<sup>3</sup> dry and N<sub>2</sub> free basis/ kg dry ash free feedstock. LHV of produced gas does not exceed 4.5 MJ/ Nm<sup>3</sup>. Results are very similar to the ones obtained at lab scale, with high H<sub>2</sub>, CO<sub>2</sub>, CO contents. However, difficulties were reported in this study such as ash sintering and agglomeration, which made it impossible to maintain stable operation during gasification after a few hours. In addition, low process efficiency (CGE, CCR) can raise a question of reliability and make sewage sludge gasification contestable.

Indeed, the sewage sludge high ash content (39 – 44% on an average), makes its gasification very challenging compared to other resources. Their high ash content as detailed in 0 triggers ash accumulation, possible agglomeration which can lead to bed defluidization and reactor clogging. This is a major issue (Gao et al. 2020).

NH<sub>3</sub>, H<sub>2</sub>S, HCl commonly end up in the gas phase and should be removed with adequate syngas cleaning, according to the specifications of the upstream process bricks. Their concentrations directly depend on the N, S and Cl contents in the feedstock respectively. Several problems have been reported such as tar formation and inorganics corrosion or high quantities. Tar removal should be considered and can be overcome with in situ tars cracking elimination with catalysts, or process optimization. Catalytic reforming during gasification for inorganics and tar removal efficiency with different additives have been widely studied for sewage sludge (Mun et al., 2013; Mun et al., 2014; (Hu Mian et al., 2016; Roche et al., 2014). Syngas depollution and inorganics pollutants reduction has shown interesting results with Fe or Ni impregnated activated charcoal (Minh Quan et al. 2022).

Co-gasification of sludges has been widely studied and allows for the reduction of NH<sub>3</sub> and H<sub>2</sub>S, tars, and heavy metals pollutants. Results from different experimental papers on co-gasification are presented in Table 2, cold gas efficiency (CGE) does not exceed 60% and carbon conversion efficiency or rate (CCE) 67% (Gil-Lalaguna et al. 2014), (Chiang Kung-Yuh et al. 2016), (Peng Lixin et al. 2012).

*Table 2: Gas yield and composition, LHV, CGE and CCE of different experimental studies of co-gasification sewage sludge (Gil-Lalaguna et al. 2014), (Chiang Kung-Yuh et al. 2016), (Peng Lixin et al. 2012)*

Product yields of co-gasification of sewage sludge.

	SS/WP [211]	SS/PS [220]	SS/WP [221]	SS/FW [222]
Gas yield (Nm <sup>3</sup> /kg) <sup>a</sup>	1.32	n. r	1.72	0.62
Tar (wt.%)	n. r	n. r	n. r	16.1
<b>Gas composition (vol.%)<sup>a</sup></b>				
H <sub>2</sub>	4.5	4.13	4.61	35.1
CO	18.5	4.70	17.10	29.3
CO <sub>2</sub>	14.9	22.37	14.3	21.4
CH <sub>4</sub>	1.93	3.65	2.45	7.3
C <sub>n</sub> H <sub>m</sub>	4.42	1.24	4.8	6.9
LHV (MJ/Nm <sup>3</sup> )	5.38	2.42	5.41	12.17
CGE (%)	59.3	61.6	52.3	n. r
CCE(%)	n. r	n. r	n. r	68.55

a= dry ash free base, n. r= not reported, WP=wood pellets, PS= paper sludge, FW= forestry waste, C=coal.

Pilot scale, commercial and demonstration reactors already exists for the gasification of sewage sludge for biofuels production (Gao et al. 2020), they are listed in the Table 3.

*Table 3: Pilot, commercial and demonstration reactors for the gasification of sewage sludge*

Reactor	Location and Type	Details	Reference
Circulating fluidized bed reactor	Denmark Pilot scale	Capacity: 100kWth Co-Co-gasification of SS	(Thomsen et al. 2017)
Fluidized bed reactor	Seville, Spain Pilot scale	Capacity: 100kWth Gasification of SS	(Campoy et al. 2014)
Bubbling fluidized bed reactor	Germany Demonstration Unit	Capacity: 2.2MWth, CGE:70% Gasification of SS	(Judex et al. 2012)
Fixed bed reactor	Pisa Italy Pilot scale	Co-gasification of SS and WP LHV 5.79 MJ/Nm <sup>3</sup> dry	(Seggiani et al. 2012)
Bubbling fluidized bed reactor	Germany Pilot scale	Capacity:20 kW Co-gasification of SS with WP, CaO an additive	(Schweitzer et al. 2018), (Schmid et al. 2018)

It must be considered that even if it is a novel and low TRL process, most studies carried out about sewage sludges valorization are focusing on hydrothermal treatment such as supercritical water gasification, hydrothermal

carbonization or liquefaction. Fluidized bed gasification is not the preferred process technology for liquid resources, or high water content resources: as mentioned in section 1.2.

Char kinetics are generally a limiting factor of the conversion rate in gasification process. A particular and positive aspect on sludges' ashes is that their biochar has a greater specific surface and its conversion is enhanced by its natural metals containing with catalyst effect, as shown in Figure 9 (Nowicki et al. 2015), (Nilsson et al. 2012).

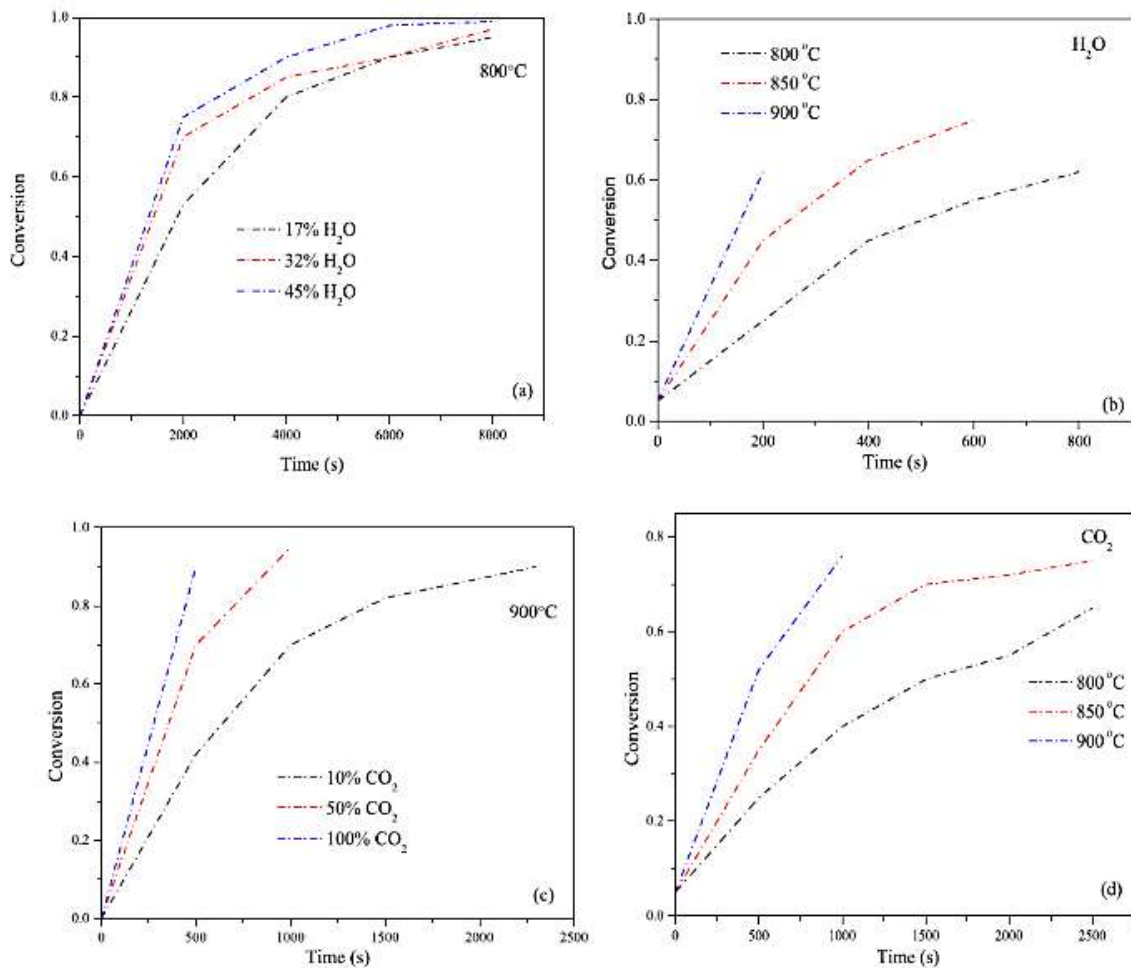


Figure 9: Sewage sludges char kinetics prior to gasification, positive effect of inorganics (Nowicki et al. 2015), (Nilsson et al. 2012)

## 4. Fruit tree pruning

Within agricultural residues from crop fields produced in the European area, woody trees pruning waste is a biomass resource, which is considered in this study. It is available during harvest time and quantities vary depending on their location, for example:

- 25 MT of fruit trees pruning mainly come from Spain (33%), Italy (22%) and Poland (13%)

- 9.6 MT of grapevine (shoot-sarmiento) are produced mainly in Italy (75%), France and Spain
- 12 MT of olive trees pruning are mainly produced in Italy and Spain

## 4.1 Physico-chemical characterization

Olive tree pruning is largely studied for fluidized bed gasification as its higher heating value (19 MJ/kg on a dry basis) its chemical composition (47% carbon content) and proximate analysis (80% volatiles) make it suitable fuel for gasification (Nilsson et al. 2014). As well as pear, apple, hazelnut, vine, which elemental composition are presented in Figure 10, the elemental composition of fruit tree pruning is really close to that of wood.

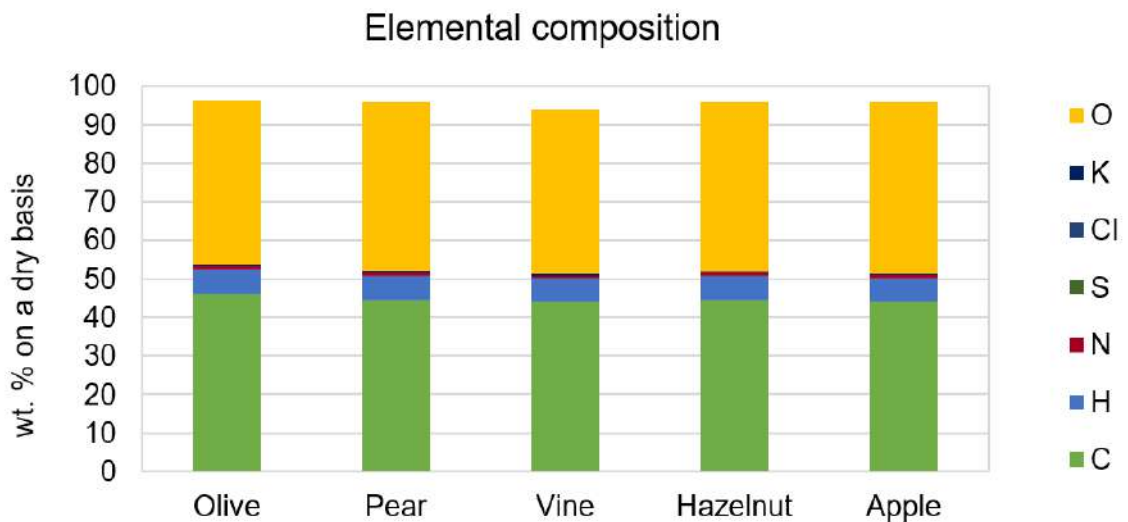


Figure 10: Elemental composition of main fruit tree pruning used for gasification in the literature (Picchi et al. 2018)

Physico-chemical properties of orchard tree pruning are similar to those of forest residues (Picchi et al. 2018). Their ash content varies from 3.7 to 6.1 % on dry weight. This paper focused on orchard crops pruning in different areas of Italy, and documented type of treatment declared by farmers, this is presented in Figure 10.

Table 4: Pruning frequency, and chemical treatment on fruit tree crops in Italy (Picchi et al. 2018)

	Olive	Pear	Vine	Hazelnut	Apple
<b>Variety</b>	Coratina	William	Cabernet	Tonda Gentile	Golden Delicious
<b>Pruning frequency (years)</b>	2	1	1	1	1
<b>Fertilization intensity (N-P-K units ha<sup>-1</sup> year<sup>-1</sup>)</b>	70/50/60	80/40/90	100/40/110	70/30/80	80/40/90
<b>Insecticide treatments (n year<sup>-1</sup>)</b>	6	11	1	0	11
<b>Fungicide treatments<sup>a</sup> (n year<sup>-1</sup>)</b>	5	24	23	1	26

This study emphasizes the impact of fertilization, pesticides and fungicides treatments on the bounding of inorganic compounds (especially Cu) with hazardous chemicals released as pollutants in the flue gas or ash. (Stals et al., 2010) confirmed this negative impact, which is a particular characteristic for tree pruning biomass.

From an energetic point of view, higher heating values of fruit tree pruning wastes make them interesting, and comparable to woody biomass usually valorized with gasification process, see Table 5 (Soria-González et al. 2022).

To conclude this part, a review published in 2021 revealed the composition of pruning residues of fruit trees in an exhaustive approach (Sezgin Koray GÜLSOY 2021) and conclude that their physico-chemical characteristics are comparable to that of hardwood, and could be identified as a classic woody lignocellulosic material.

Table 5: Higher heating values of fruit tree pruning residues measured in the literature (Soria-González et al. 2022)

Biomass	Specification	HHV (MJ/kg)
Avocado	Class B	19.6
	Branches	19.2–19.7
	Branches with leaves	19.7
	Leaves	20.1
olive, almond, cherry, kiwi, lemon, loquat, orange, apple, pear, hazel, guava, chicozapote and mango	Branches	16.30–20.27
<i>Pinus</i> spp.	Sawdust	19.69–19.85
Vid	Branches	18.95

## 4.2 Pretreatment

Fruit tree pruning has high water content, generally higher than 80 % (humidity in weight) according to FACSA data base, thus this kind of resources must be dried before gasification to reach a maximum humidity of 20%. Most studies reviewed in this report show moisture below 10% thanks to air drying (low cost and low energy consumption). Another important pretreatment step is the biomass grinding which is also energy consuming. Many studies have shown that grinding and/or pelletization is a mandatory step for this kind of resources in fluidized bed gasifiers. For example, olive tree pruning were grinded in order to obtain particle size of 1–2.8 mm (average 1.9 mm) and 2.8–4 mm (average 3.4 mm) and then pelletized, in this study, both branches and leaves were used as feedstocks (Picchi et al. 2018). Another strategy is to keep a particle size distribution by grinding between 0.5 and

4mm, which is suitable for FBG, in order to lower energy consumption and avoid pelletization (Nilsson et al. 2016). Best performance was obtained with 2.5 to 4 mm particle size.

### 4.3 Gasification behaviour

Main fruit tree pruning residues used for gasification in the literature are listed below:

- Olive tree
- Apple and pear tree (branches and/or leaves)
- Vineyard pruning (grapevine, fruit, branches, marc of grape)
- Peach tree
- Hazelnut, walnut, almond tree mostly shells and hulls (McCaffrey et al. 2019)
- Palm tree
- Plum tree (branches and/or leaves)
- Avocado, lemon, orange, mango tree for potential application to gasification (Soria-González et al. 2022)
- Cherry tree (branches and/or leaves)

Olive tree pruning gasification gives satisfying results such as high gas yield and composition similar to results obtained with wood chips and high carbon conversion rates (Narvaez et al. 1996). As expected, preferred Equivalence Ratio is comparable to the one for woody residues: between 0.25 and 0.35, and give a CO, H<sub>2</sub>, CO<sub>2</sub> rich syngas. LHV of syngas obtained is higher with enriched air (9.3 MJ/Nm<sup>3</sup>) compared to the one produced with air comprised between 4.5 and 7.8 MJ/Nm<sup>3</sup> (Nilsson et al. 2017). Best compromise between cold gas efficiency, LHV and conversion rates were obtained with low ER (around 0.25) and high temperature (around 900°C), as presented Figure 11 and Figure 12. These experimental data were used for gasification industrial scale-up modelling and give similar and reliable results at industrial scale. They also show same trends as woody biomass, high CCR and CGE, low tars content.

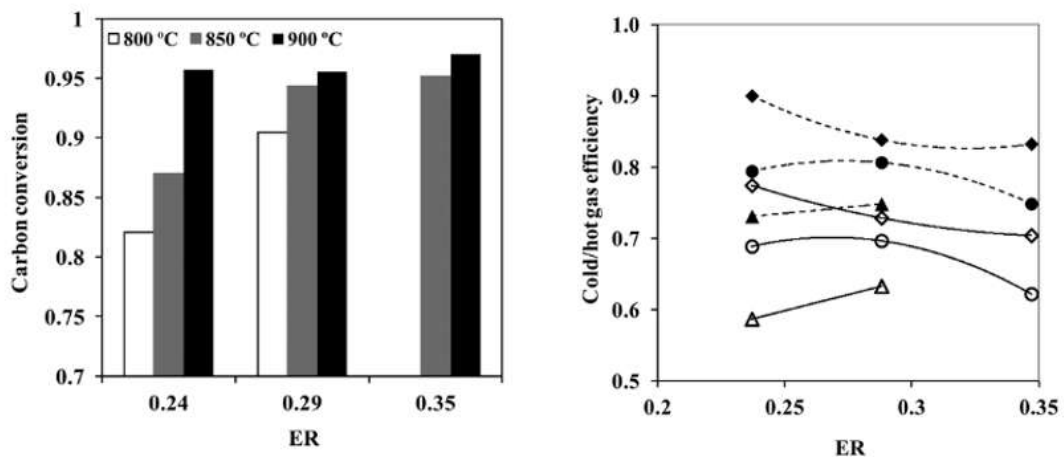


Figure 11: The CGE is represented by open symbols: 800 (Δ), 850 (○), and 900 °C (◇) and solid lines. HGE is represented by solid symbols: 800 (▲), 850 (●), 900 °C (◆)

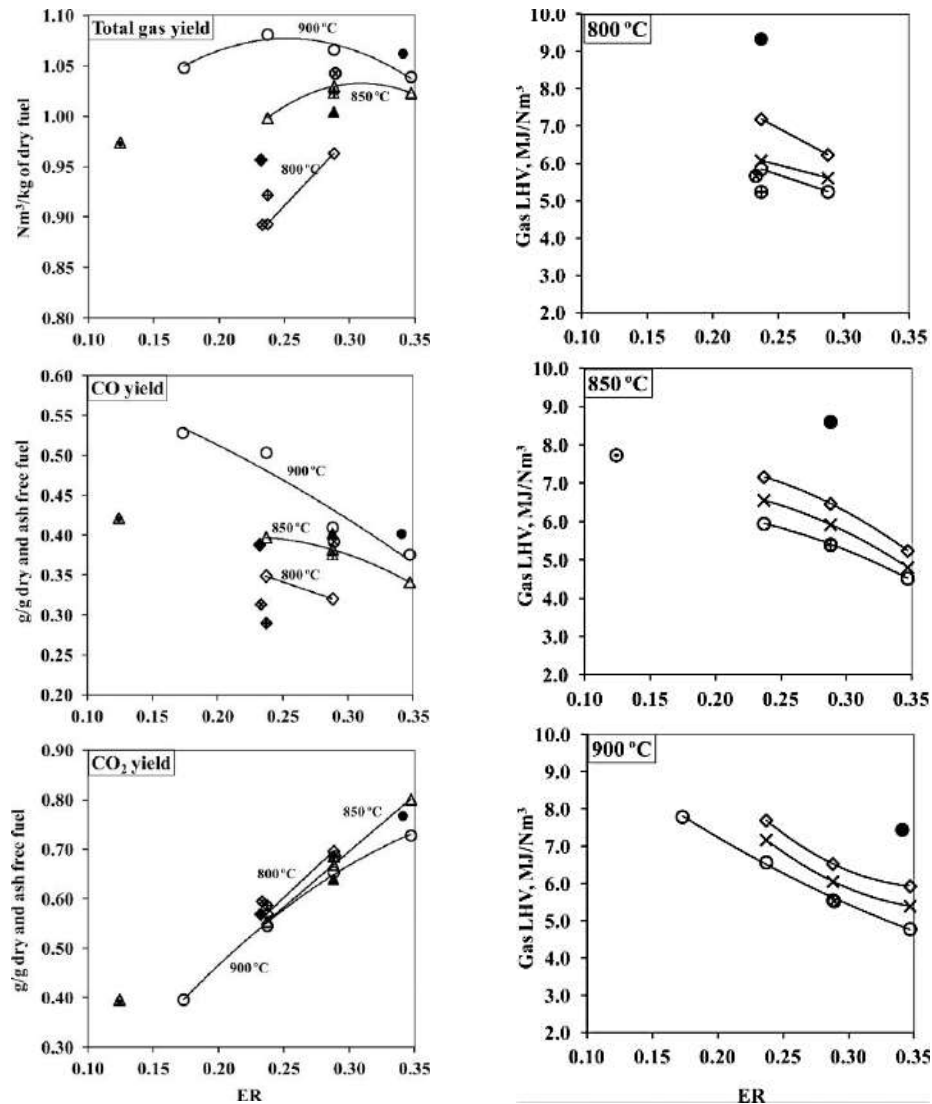


Figure 12: Total gas yield (Nm<sup>3</sup> dry and N<sub>2</sub> free gas) and yields of CO and CO<sub>2</sub> (g/g of dry and ash free fuel) for different temperatures on the left, LHV on the right: (○) only the light gas; (×) light gas and benzene; (◇) light gas, benzene, and tar. Represented as a function of ER. For gas yields, open symbols : air as fluidization agent, fuel particle size of 0.5-4 mm, and fuel feed rate of 1 kg/h, while filled symbols : O<sub>2</sub>-enriched air with 40% O<sub>2</sub>, fuel particle size of 2.5-4 mm (symbols marked with +), fuel feed rate of 1.5 kg/h (symbols marked with ×), and with N<sub>2</sub>-diluted air with 13% O<sub>2</sub> (symbols marked with ●)

What is more, olive tree pruning residues can present similar or better gasification efficiency and syngas yields than forestry and agro-industrial wastes (sawdust, marc of grape, pinus pruning) and stable performance with different feedstock (olive tree pruning, grapevine). This is an interesting aspect concerning process flexibility in terms of feedstock (Lapuerta et al 2008).

Almond shells, peels and pruning residues have been compared and tested in a fixed bed reactor, satisfying gasification results were also obtained at 800°C for pruning residues with a carbon conversion rate off 78%. “The gas yields obtained were 1.66, 1.85 and 1.71 N m<sup>3</sup>/kg of residue and the gas HHV were 5.8, 6.5 and 6.4 MJ N m<sup>-3</sup> for almond shell peel, almond shell and almond tree pruning, respectively” (Gonzales et al. 2006). Nevertheless, almond shells seem to give more interesting results than almond tree pruning.

However, apple tree pruning were gasified with air as fluidizing agent at pilot scale (atmospheric pressure, reactor volume 47l), with two different experimental conditions, resumed in Table 6 (Marchelli et al. 2019). Kinetic modelling was the main aim off this study, showing representative results for industrial scale up of apple tree pruning fluidized bed gasification, see Figure 13. Surprisingly, poor CGE were obtained at ER = 0.42, as well as poor LHV. It can be assumed that lower ER would have given better results.

*Table 6: Air gasification of apple tree pruning operating parameters at pilot scale*

Parameter	ER = 0.42	ER = 0.65
Air inlet flowrate	17 Nm <sup>3</sup> /h	17 Nm <sup>3</sup> /h
Biomass inlet flowrate	9 kg/h	6 kg/h
Bed temperature	880°C	911°C

More recent studies document the kinetics and reactivity of peach tree pruning branches in a CO<sub>2</sub>/O<sub>2</sub> atmosphere in the presence or absence of steam to look at the influence of the media and compare it to waste wood. It was shown that H<sub>2</sub> yield and carbon conversion rate decrease with CO<sub>2</sub> and increase with O<sub>2</sub> flowrate (Koido et al. 2024).

Overall studies show low tars and gas pollutants, gasification behavior similar to woody biomass, with high gas yields and cold gas efficiency. On the other hand, it must be mentioned that many studies have shown that tree pruning is used as a high potential resource for torrefaction, pyrolysis, or hydrothermal carbonization more than for direct gasification due to its high water content (Gonzales-Arias et al. 2022). The results of a feasibility study on biochar production by pyrolysis of residues from orchard tree pruning (apple, pear, and plum) show it is a convenient alternative approach to converting biowaste into a high-quality solid fuel with high HHV and high carbon content (Carrozo et al. 2024).

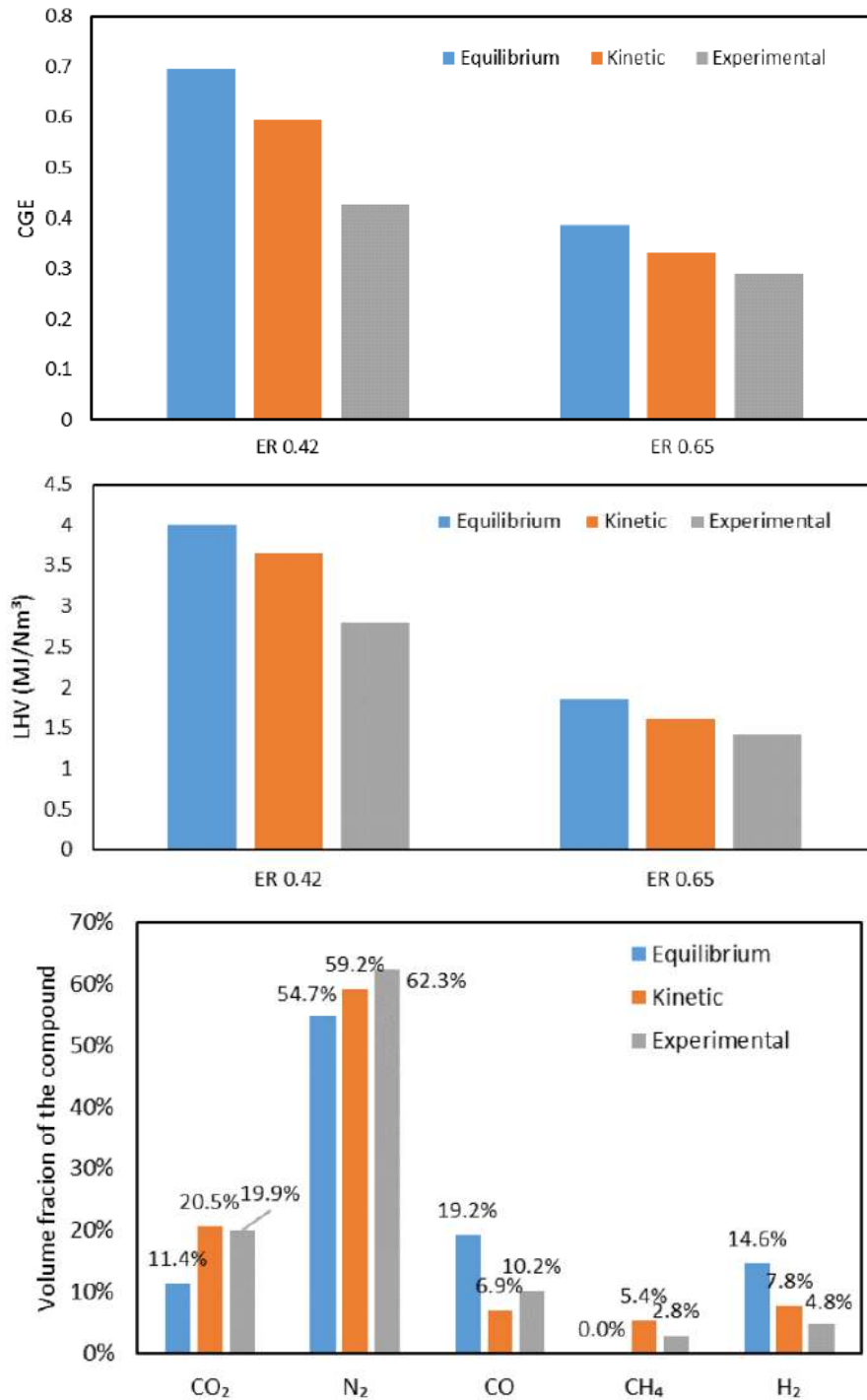


Figure 13: LHV, CGE and syngas composition obtained from apple tree pruning air gasification at pilot scale fluidized bed gasifier (Marchelli et al. 2019)

## 5. Solid recovered fuel

Solid Recovered Fuels (SRF) are produced annually over the EU by 249 MT, of which 48% are recycled. Rejected fraction isolated with mechanical separation represents 50 MT of waste each year, it is available daily and cannot be stored more than 10 days. In the other hand, plastic fraction is produced annually by 25 MT and also available daily in urban treatment plants and household refuse incineration plants. Plastic fraction which is not recycled and rejected fraction are considered as an interesting resource studied in this project.

The third feedstock identified in the Fuels-C project is a plastic fraction coming from solid waste. However, the composition provided by FACSA concerning this plastic fraction also shows a high content of non identified materials, as it will be shown in next section. These materials can come from different source of wastes (textiles, foams, paper and cardboard, etc.) like in solid recovered fuel. That is why this literature review considers solid wastes as a whole, and more specifically SRF.

### 5.1 Physico-chemical characterization

SRF mainly come from industrial (construction and demolition), urban (municipal solid waste) and furniture wastes. They are produced by mechanical and/or biological treatments of solid waste. They are generally composed of paper and wood (between 30 and 60 wt.%), plastics (20-30%wt), textiles (10-15% wt) and inert fraction in a lesser extent. Each component is highly different in terms of physico-chemical characteristics and its proportion variable over time, as shown in Figure 14, which represents SRF particular heterogeneity and composition variability during the year (Porshnov, 2022). Some commercial SRF produced from municipal waste can present higher contents of plastics, up to 54 % (Skodras et al. 2009).

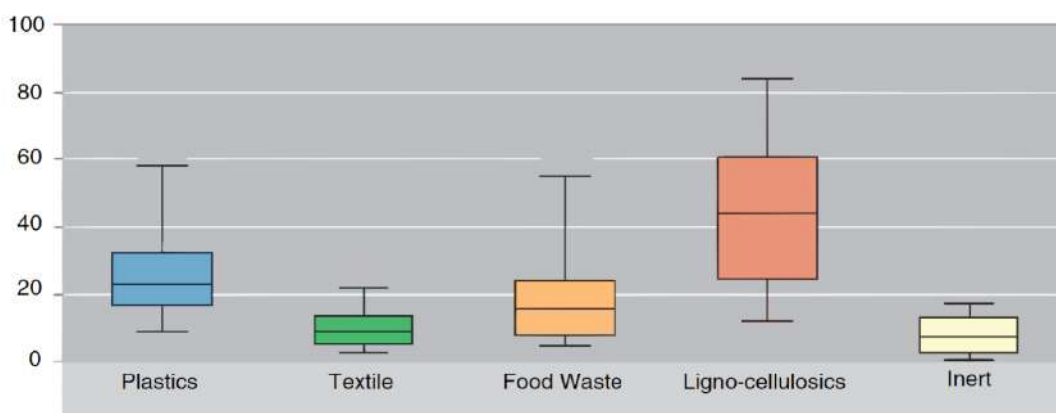


Figure 14: Solid Recovered Fuels major constituents (Porshnov, 2022)

#### Biogenic fraction

The most important part of SRF comes from lignocellulosic, paper and cardboard, textile materials (Oscar Sosa Sabogal, 2022) which mostly account for the biogenic and renewable carbon part of SRF, even if textile can be of biogenic or fossil origins. However, this part varies a lot depending of SRF origin and treatment. Within this biogenic part, ultimate and proximate analyses vary a lot, see Table 7 (Iacovidou et al., 2018; Demirbas, 2004; Kim et al., 2014; Moreno & Font, 2015; Zhou, Long, et al., 2015; Sørnum et al. 2001; Wei et al. 2019).

Table 7: Ultimate, proximate and elemental analysis of the biogenic part of SRF expressed as % on dry basis. V : volatile matter, FC : fixed carbon. (Iacovidou et al., 2018; Demirbas, 2004; Kim et al., 2014; Moreno & Font, 2015; Zhou, Long, et al., 2015; Sørnum et al. 2001; Wei et al. 2019).

Type	LHV MJ/kg	Ash	V	FC	C	H	O	N	S	Cl
Construction wood	16	14.0	72.2	11.0	37.9	4.4	55.6	1.5	0.6	-
Furniture wood	15.8	1.8	77.3	20.9	47.9	6	41.4	2.9	0.1	0.1
Newspaper	15.7	5.4	82.4	12.2	46.7	6.3	46.4	0.2	0.2	0.2
Glossy	10.4	28.0	67.3	4.7	45.6	4.8	49.4	0.1	0.1	-
Cardboard	16.9	8.4	84.7	6.9	48.6	6.2	45.0	0.1	0.0	0.2
Cotton	17.1	1.1	88.0	11.0	47.5	6.3	45.1	0.8	0.1	0.7
Wool	22.8	1.2	85.0	14.0	59.3	5.36	24.8	8.9	1.6	-
Natural rubber	42.0	0.1	98.2	0.5	87.9	10.8	0.4	0.8	0.0	-

### Inorganics

Ash content in SRF can vary from 8% to 30%, most of the time it is comprised between 14 and 20 %. The ash contains inorganic elements, some of them being problematic as they can lead to ash melting or reactor corrosion. The major inorganic elements are the following: Ti, Ca, Mg, Na, K, P, S, Cl, Si, Cu, Zn, Al, Fe (Nasrullah et al. 2015). These inorganics come from various industries, as it was detailed in a recent doctoral thesis (Sandra Antonia Viczek, 2021). Their proportions differ depending on waste streams.

### Plastic fraction

Composition of plastics within the refused plastic fraction depends on selective waste sorting required locally. Most of the time, prevalent plastics in SRF are polyolefins, PET and PVC, as shown Figure 15 (Gerassimidou et al. 2020). Ultimate and proximate analysis of these plastics are presented in Table 8 (Götze et al., 2016; Zhou et al., 2014).

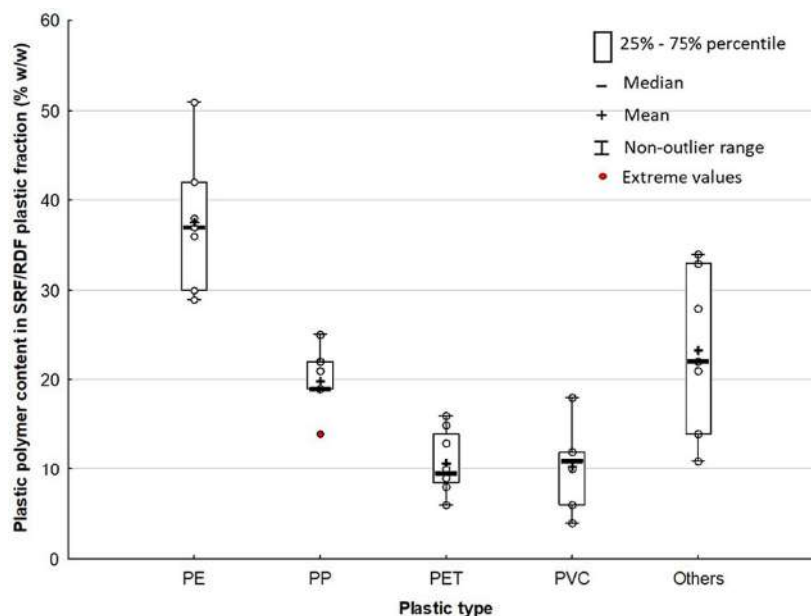


Figure 15: Plastic families within refused plastic fraction of SRF (Gerassimidou et al. 2020)

Table 8: Ultimate, proximate and elemental analysis of plastic families in SRF expressed as % on dry basis. V : volatile matter, FC : fixed carbon. (Götze et al. 2016), (Zhou et al. 2014).

Type	LHV MJ/kg	Ash	V	FC	C	H	O	N	S	Cl
HDPE	41.24	0.60	99.40	0.00	85.50	14.20	0.00	0.00	0.30	0.00
LDPE	41.81	0.30	99.70	0.00	85.50	14.30	0.00	0.00	0.20	0.00
PP	42.42	0.44	99.54	0.03	85.02	13.93	0.96	0.08	0.01	0.00
PET	21.28	0.20	92.27	7.53	62.30	4.43	33.13	0.09	0.05	0.26
PVC	20.85	5.86	83.47	10.67	39.56	4.85	0.02	0.11	0.28	55.2
PS	39.52	0.19	99.48	0.33	90.37	8.64	0.90	0.00	0.09	0.00

In the Fuels-C project, plastics from urban waste are provided by FACSA in Spain. Waste plastics are deposited by citizens in the “yellow container”, this fraction is separated in a “light packaging plant”. In this installation, five different plastics fractions are obtained:

- Bricks
- Polyethylene terephthalate fraction (PET water bottles)
- High density polyethylene (HDPE) (detergent, gel bottles, etc.)
- Low density polyethylene (LDPE) (bags, fil, etc.)
- Plastic mix

In these plants, the different fractions are compacted but not crushed in small pieces. The fractions (PET, HDPE, LDPE...) are recycled to obtain plastics packaging again. The composition of refused plastics provided by FACSA in this project, which are not recycled (see the photo below), is presented Figure 16.

Matter	Percentage (% db)
PET	10.13
PEAD	1.66
PVC	0.42
Film	12.83
Rest of plastics	3.86
Steel	1.17
Aluminium	0.54
Brick	0.47
Wood	0.56
Non identified	68.35



Figure 16: Composition of plastics refused that will be provided by FACSA for Fuels-C project, on the right a photo of the sample

## 5.2 Pretreatment

Rejected fraction and plastics fractions must be dried, sorted with size or mass separation to remove glass and metal, depending on non-identified fraction. As shown by S.A. Viczek et al., particle size is dependent from material origin within shredded and mixed solid waste.

It is also helpful to grind and pelletize to homogenize this resource and reach a minimal particle density, in order to avoid its early dispatching and make it more suitable for bed fluidization.

## 5.3 Gasification behavior

### Solid Recovered Fuel

SRF constituents properties influence on gasification behavior gasification have been summarized in a recent PhD thesis, as shown Table 9 directly extracted from (Oscar Sosa Sabogal 2022).

SRF gasification has been largely studied at lab scale and pilot scale in the literature along the last decades. Gasification at pilot scale has been studied with SRF flowrates from 40 to 60 kg/h in a 6 meter-high-fluidized bed gasifier and olivine bed material (Arena et al. 2014). Usual bed temperature and ER were chosen (850 – 900°C, ER 0.25 – 0.35) for 6 different operating conditions, best performances were obtained with air as fluidizing agent at ER = 0.3, giving a 7 MJ/Nm<sup>3</sup> syngas LHV at a yield off 1 – 2 Nm<sup>3</sup>/kg of SRF, CGE of 60% and CCR of 0.8 – 0.9 (Arena et al. 2014). SRF considered in this experimental study have very low Cl, N and S contents compared to the average, which leads to low inorganics pollutant concentration in the syngas. These results are representative of what could be obtained with industrial scale fluidized bed gasification reactor.

Syngas composition produced from SRF vary a lot depending on the feedstock composition, temperature and fluidizing agent. Papers and plastics content in raw feedstock show a significant influence on syngas composition (Hwang et al. 2014), (Pinto et al. 2014). Characterization of products obtained from steam gasification of wood, Refused Derived Fuel (RDF) with 50% papers and 9% plastics, and Refused Paper and Plastics Fuel (RPF) with 70% papers and 30% plastics are presented in Table 9 (Hwang et al. 2014).

Syngas produced from SRF is more likely to present higher concentrations of inorganic pollutants than woody biomass (tree pruning). This is due to initial high content of N, S, Cl, see Figure 18. Lab scale fluidized bed reactor was used to determine the influence of process parameters on performance and HCl, H<sub>2</sub>S, HCN and NH<sub>3</sub> release in syngas (Recari et al. 2016). Results show that SRF composition itself is the major factor affecting pollutants concentration in the syngas produced, followed by bed material type and temperature. This study focused on low Cl, N and S content SRF and on the influence of the fluidizing agent, comparing O<sub>2</sub>/steam with air gasification. It seems that steam could favor the formation of H<sub>2</sub>S, HCN and HCl compared to air in gasification (Recari et al. 2016).

*Table 9: Impact of materials properties on gasification behavior (Oscar Sosa Sabogal 2022)*

Properties	Materials in waste	Impact on thermochemical conversion
Heating value	Favored by the presence of plastic films, packaging plastic, rubber or tires. Affected by the presence of inert materials.	Increase of heating value of the fuel its beneficial for the economics of the process
Ash content	Fillers from paper and cardboard, glossy paper Soil and minerals from construction waste Fine fractions	Particulate matter, fouling deposits, agglomeration, deposition



Moisture	Moisture content may increase due to the presence of foams, textiles and papers, which can absorb liquids if in contact with food waste or oils. Undried sewage sludge.	Reduction of final heating value, producer gas quality and fuel conversion
N content	Food waste, Polyurethane foams, acrylic fibers, wool, waste wood additives	Mainly transformed into NH <sub>3</sub> , HCN: influence in the sizing of gas cleaning sections
S content	Rubber and waste tires	Mainly transformed into H <sub>2</sub> S, COS: Interaction with alkali metals: emissions, deposits, corrosion Deactivation of downstream catalysts
Cl content	PVC hard plastics, certain kinds of paper, vinyl rubber, shoes, Kitchen waste	Mainly transformed into HCl, Cl <sub>2</sub> : Dioxides and furans emissions, corrosion, ash sintering
Other halogens	Brome from flame retardants Fluor for halogenated polymers	Production of undesired pollutants like HBr and HF
Si and P content	Paperboard, rubber	Inhibitory effect Agglomeration issues, erosion of equipment
K, Na content	Food residues	Catalytic effect, agglomeration issues, lowering of ash melting temperatures
Ca	Paper, cotton	Catalytic effect, increase of ash melting temperature
Hg content	Synthetic textiles, soft plastic, foam, electronic waste	Undesired emissions
Other heavy metals content	Tissue and plastic pigments, electronic waste, wires	Undesired emissions, ash disposal costs
Tar content	Favored by the presence of lignin, and plastics	Production of PAHs which result in equipment blockage, lower efficiency and increased maintenance

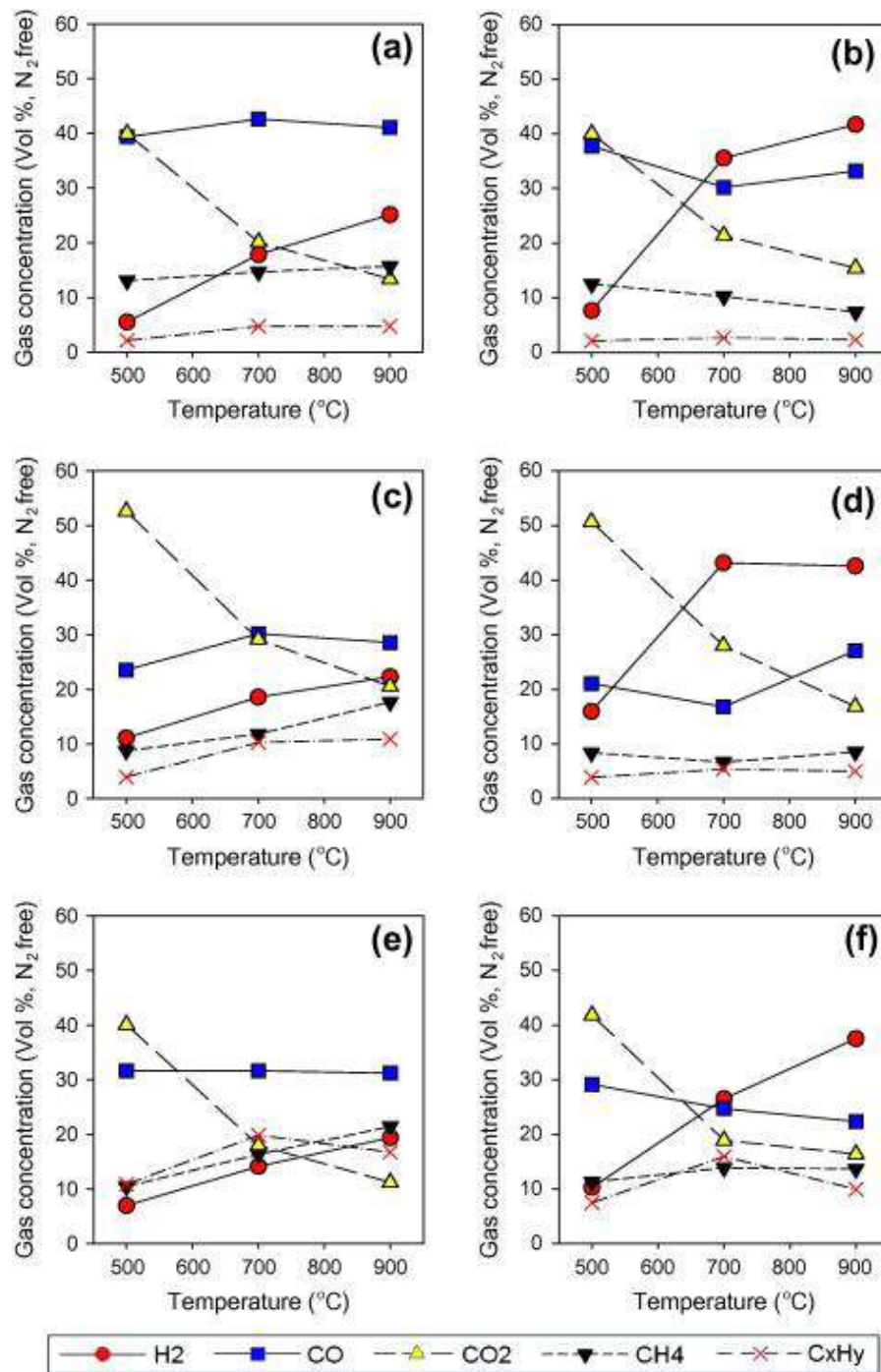


Figure 17: N<sub>2</sub> free gas composition obtained at different pyrolysis (on the left) and steam gasification (on the right) temperatures of (a) (b) wood, (c) (d) RDF, (e) (f) RPF (Hwang et al. 2014)

Another strategy investigated is SRF blending with biomass wastes as well as minerals additives for improvements. In this study (Pinto et al. 2014), olive and almond residues were used for co-gasification at pilot scale, it showed process performance improvement and helped decreasing SRF negative bearing and syngas inorganic pollutants, as shown Figure 18. Dolomite is particularly efficient as well as high temperature, or both combined, to reduce tars and inorganic pollutants content.

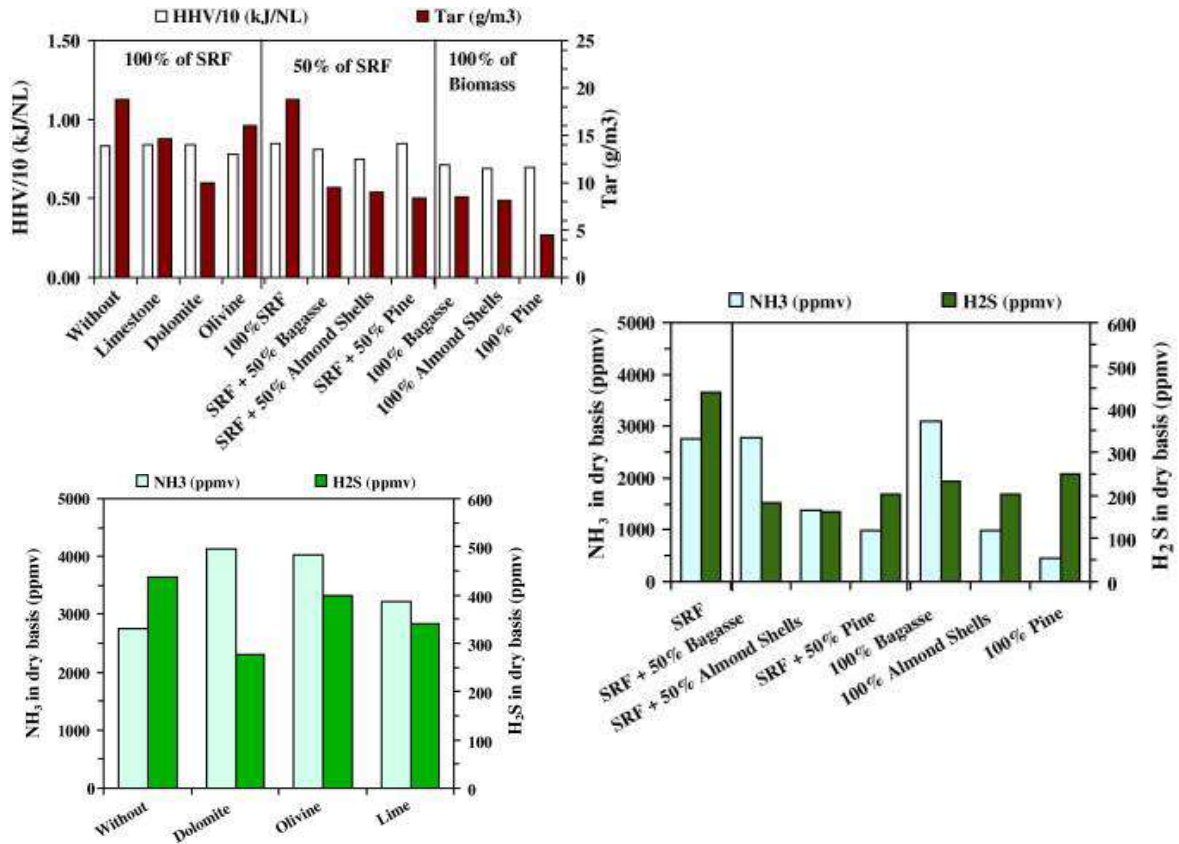


Figure 18: Influence of additive and feedstock blending type on syngas HHV, tars, NH<sub>3</sub> and H<sub>2</sub>S content in syngas (Pinto et al. 2014)

Tars concentration in syngas is mainly influenced by the presence of lignin and plastics in the feedstock, several studies compared wood and SRF fluidized bed gasification. SRF pellets gasification produces up to 1000 of g tars/Nm<sup>3</sup> of syngas at low temperature, which was expected higher than for woody biomass gasification in same conditions, Figure 19. These results were obtained in 1m high BFB but in batch conditions, this trend is still observed compared to wood at continuous pilot scale but in a lesser extent (less than 100 g/m<sup>3</sup>) (Valin et al. 2019). It was highlighted that tars concentration decrease with increasing temperature and steam addition (Valin et al. 2019), (Santamaria et al. 2021), as well as inorganic pollutants.

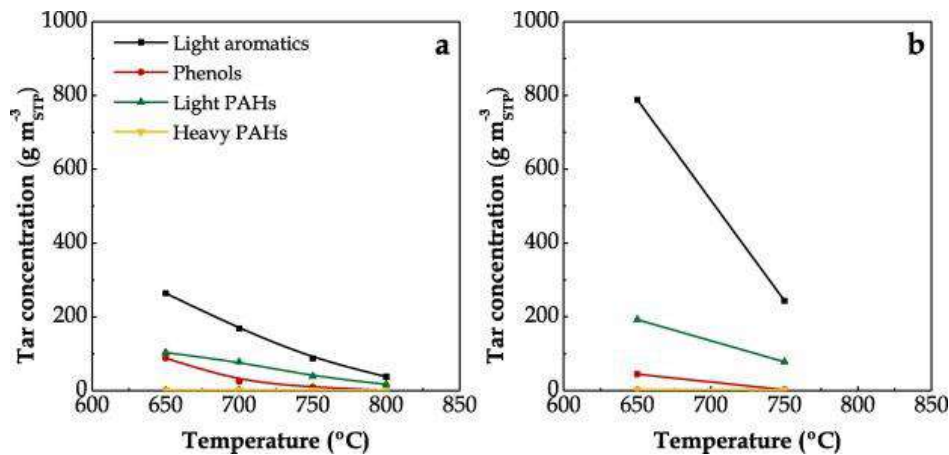


Figure 19: Tars composition and concentrations in syngas obtained from wood (left) and SRF (right) pellets gasification in a pilot scale BFB (Santamaria et al. 2021)

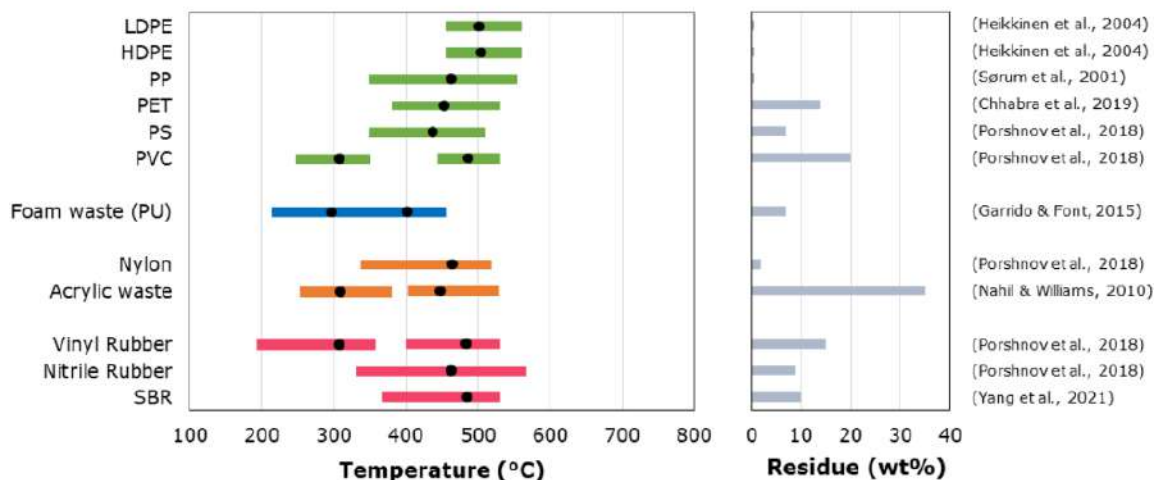


Figure 20: Thermal decomposition and char yields after pyrolysis of different plastics

**Plastic fraction** is the main SRF stream target of Fuels-C, thus, in this section, influence and properties of plastics on thermoconversion phenomenon will be presented.

Thermal decomposition and residue yields after pyrolysis of fossil based polymers is represented Figure 20 (Oscar Sosa Sabogal in 2022). The mass fraction of residue here is close to the sum of the fixed carbon and ash contents.

Several fractions of different plastics waste from separately collected materials were pelletized and tested in the BFB pilot scale used for the study of SRF air gasification already presented before (Arena et al. 2014), (Arena et al. 2010). Recycled polyolefins (GS3), PE, multi-layer food and beverage packaging (PDF), post-customer packaging containing ferrous materials (Neolite and Plasmix) were analyzed. Overall fractions presented a high Higher Heating Value (33 kJ/kg on an average) and a high carbon content (74% of dry matter on an average), relatively low ash amount and sufficient bulk density (>300 kg/m<sup>3</sup>). Major inorganic elements for all fractions were in a decreasing order Ca, Cl, Al, Fe, Na. Best results were obtained with PE and mixtures of recycled polyolefins and olivine or dolomite as bed material (ER = 0.3, bed temperature around 850°C), giving high CGE : 90%, as shown FX. This is a significant result especially because experimental conditions used in this study could be similar to the ones used at industrial scale. Tar content was very low and H<sub>2</sub>+CO represent more than 50% of the syngas produced, see Figure 21.

H<sub>2</sub>-rich syngas (up to 32%) production by fluidized bed gasification at pilot scale of biomass and plastic fuel (20% polyethylene) blend pellets was also reported (Ruoppolo et al. 2012). Increasing bed temperature leads to higher H<sub>2</sub> yield, as shown Figure 20, as well as higher total syngas yields. Comparison between biomass and plastic wastes, their mixing, are largely studied, such as for sewage sludge, to improve gasification performance and process feasibility. Within all types of plastics, PE and PET was more studied than others, especially pellets of PET, or PET mixed with wood (Robinson et al. 2016). Tar formation was reduced in during co-gasification, compared to PE and PET gasification alone. However, as shown Figure 22 CGE from wood-PE pellets does not exceed 0.4 in the tested conditions.

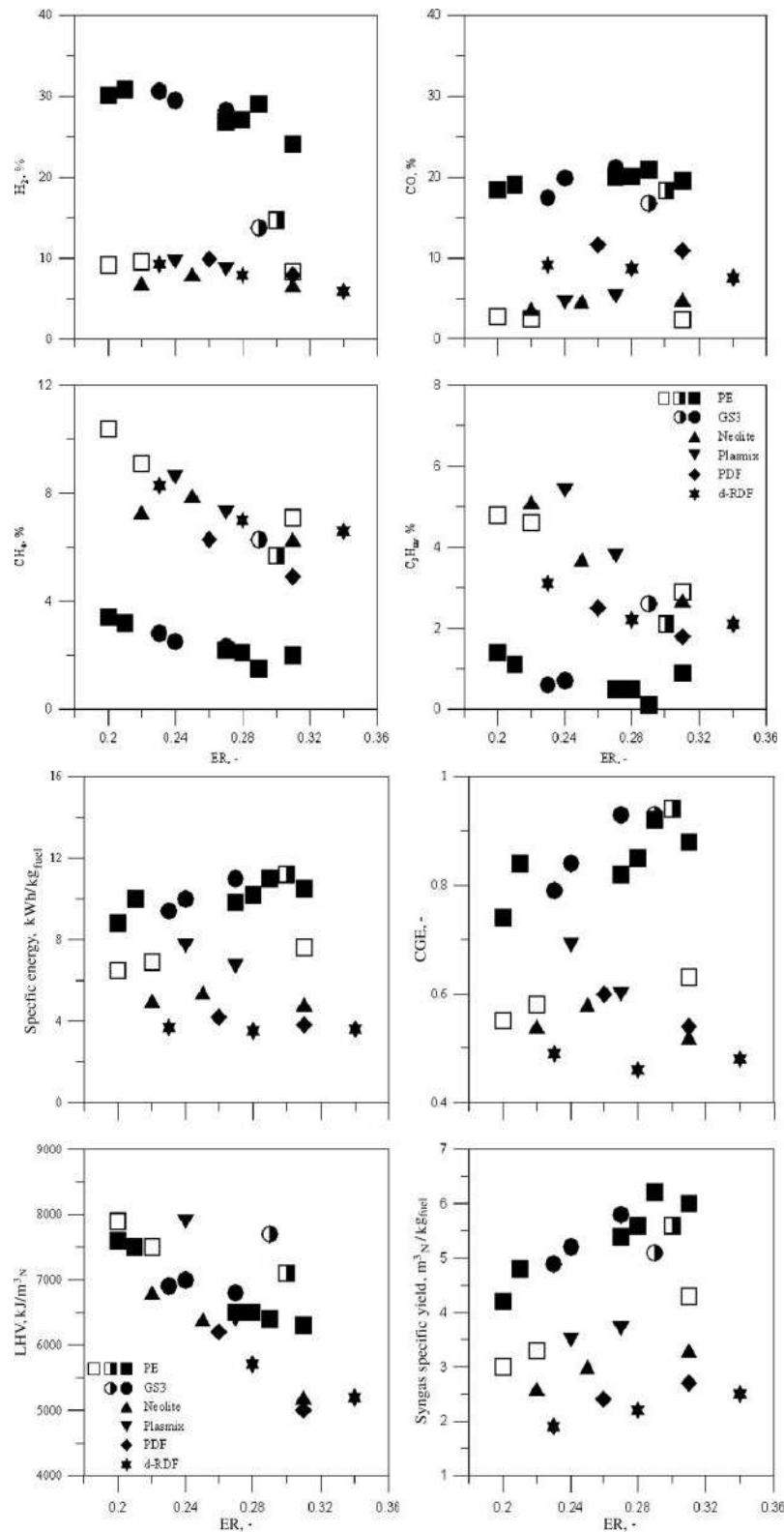


Figure 21: LHV, CGE, syngas yield and composition from GS3, PE, Neolite, Plasmix, PDF and densified Refused Derived Fuels from municipal waste (d-RDF) gasification. (shaded symbols = bed of olivine; open symbols = bed of quartz sand; half shaded symbols = bed of dolomite) (Arena et al. 2010)

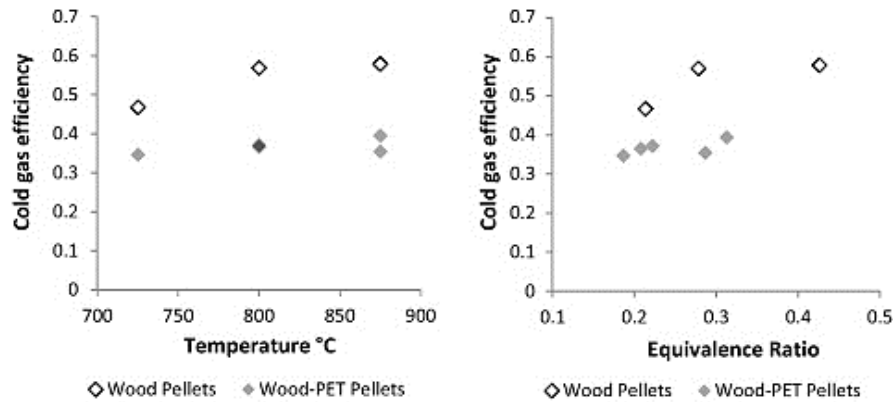


Figure 22: Influence of ER and temperature on CGE obtained from wood pellets and PET mixed with wood pellets gasification (Robinson et al. 2016)

(Lopez et al. 2018) gave an overview and summarized gasification behavior and efficiency of waste plastics. Figure 22, shows major trends of plastic waste gasification in different conditions, steam gasification, steam-oxygen and air gasification have been largely studied. Plastic and biomass waste co-gasification demonstrate higher gas yields with higher plastic fraction in feedstock, as well as H<sub>2</sub> yield and tars percentage in syngas (no major influence on LHV). Considering industrial operating conditions (ER 0.3, 800-900°C), corresponding syngas LHV and yields are presented in Figure 23.

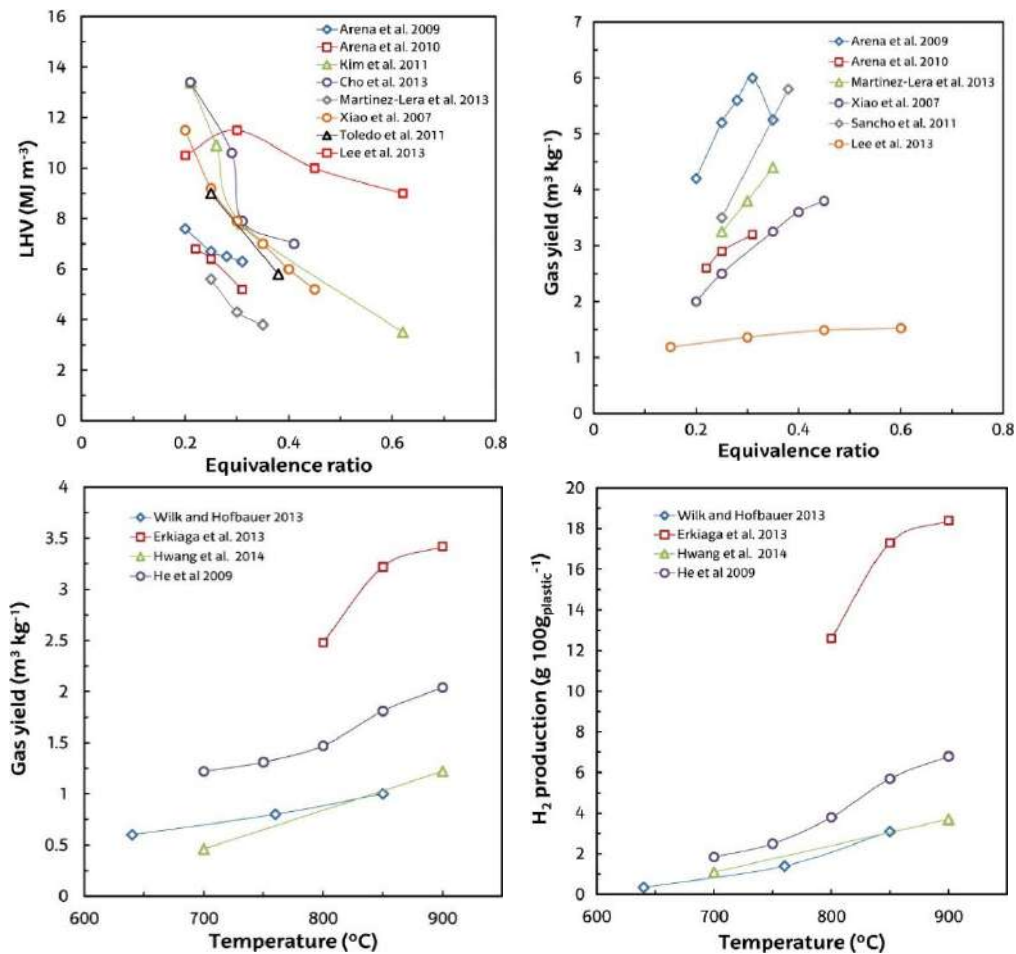


Figure 23: LHV, CGE, syngas yield and composition from GS3, PE, Neolite, Plasmix, PDF and densified Refused Derived Fuels from municipal waste (d-RDF) gasification. (shaded symbols = bed of olivine; open symbols = bed of quartz sand; half shaded symbols = bed of dolomite) (Arena et al. 2010)

## 6. Conclusions

As a conclusion, agricultural residues considered in Fuels-C project such as fruit tree pruning residues are biomass resources with the highest gasification potential, since their physico-chemical properties and gasification behavior are similar to that of hardwood. Solid recovered fuels and solid urban waste are highly available in Europe, it is composed of 50 to 70 %wt of biogenic wastes but also fossil materials (such as plastics) which can represent up to 40%, and thus cannot be considered as targeted biogenic waste in Fuels-C project. Digestates from municipal sewage sludges is an interesting biogenic waste if it is concentrated and already dried for gasification. However, its high water, and ash contents make it difficult to valorize from a process technological point of view. "Low LHV, CGE, CCE and tar content cause the problem of downstream utilization, for example, blocking of fuel lines in engines and lowered combustion quality in boilers" (Gao et al. 2020). This resource must undergo several energy consuming pretreatment to be valorized in gasification.

Major concerns about SRF and sludges :

- The variability of this resource over the year
- Inorganic pollutants release in gas phase and corrosion
- High plastic content triggers tar formation and represents non biogenic waste

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- Ash management and process operation difficulties

About pretreatment, the easiest resources is fruit tree pruning. Their sorting, grinding and/or pelletization are still less energy consuming than the drying of sludges and sorting of SRF. What is more, sludges present very high ash content, which is problematic from an industrial scale up process and gas cleaning point of views.

Gasification behavior of fruit tree pruning residues is well understood since this feedstock is similar to classic wood chips / sawdust, contrary to sewage sludge and even more solid recovered fuels. In terms of gasification performance, CCR, CGE and syngas yields, fruit tree pruning is a resource that is far more interesting. Overall studies converge towards a H<sub>2</sub>, CO<sub>2</sub>, CO rich syngas, with yields comprised between 1 and 2 Nm<sup>3</sup>/ dry feedstock.

High syngas and H<sub>2</sub>/CO yields can also be obtained from plastics waste or sewage sludge (non digested) in BFB/CFC fluidized bed reactors at pilot scale operating conditions, but with low CGE and CCR, even after several process parameters optimization. **Fuels-C objective of 70% CGE cannot be reached for SRF, urban solid waste, neither sewage sludge digestates.** Nevertheless, several papers show pollutants reducing efficiency and general process performance increased by mixing plastic waste/SRF/sewage sludges with clean biomass, this could be a path for the valorization of this type of fuels with gasification.

These three biomass types could be classified in terms of gasification ability (pretreatment steps, kinetics, ash behavior, gas yields, gas pollutants), it can be defined as follow:

- Woody fruit tree pruning residues
- Sewage sludge anaerobic digestate
- Plastic fraction of Solid Recovered Fuel

Results presented in Table 10 are summarizing properties and gasification performance of the three feedstocks chosen for Fuels-C (Arena et al., 2010; (Arena et al., 2014; (Gao et al. 2020; (Lopez et al., 2018; Picchi et al., 2018; Campoy et al., 2014; Nilsson et al., 2012, 2014, 2017), for ER between 0.25 and 0.35 and bed temperature around 850°C.

*Table 10: Composition and gasification performance of sewage sludge, fruit tree pruning and SRF*

Property	Unit	Sewage sludge	Fruit tree pruning	Solid Recovered Fuel
Moisture content	% tot	60 – 80	21	10
Organic matter	% dm	55 - 75	94 - 98	75 - 80
Ashes	% dm	27 - 44	2 - 6	7.5 - 30
LHV	MJ/kg dm	11 - 16	18 - 19	10 - 25
Volatiles	% dm	60 - 80	75 - 85	
C	% dm	35 - 40	48,0	55 - 68
H	% dm	5,8	7,2	7
O	% dm	16,7	43,0	20 - 30
N	% dm	4 - 8	0,4	3



# Fuels-C

S	% dm	1,6	0,1	1
F	% dm	0,001	0,001	1
Cl	% dm	0,0125	0,059	1
CCR	%	65 – 90 90 with additives	80 - 97	80 – 90
CGE	%	40 - 70	70-80	50 – 60 Only plastics with additives 90%
LHV of syngas	MJ/m <sup>3</sup>	4 - 7	4 - 10	4 - 7
Syngas tar content	g/Nm <sup>3</sup>	Up to 100	1 - 15	Up to 200 with only plastics

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