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Bench-scale gasification tests at TRL4

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Abbreviations

AF	After filter
AR	After reformer
BFB	Bubbling fluidized bed
CFB	Circulating fluidized Bed
DFB	Dual fluidized bed
RWGS	Reverse water gas shift

Contents

Executive summary

Deliverable 3.1 “Bench-scale gasification tests at TRL4” is a public document of the BioSFerA project, delivered in the context of WP3 “Biological production of lipids from syngas at lab scale”.

The main objective of WP3 is to develop a two-stage biological gas-to-liquid process for the conversion of CO_2/CO/H_2 produced by gasification into medium (C_{14}) and long (C_{16-18}) chain triacylglycerides (TAGs) that will be upgraded to biofuels. VTT is leading Task 3.1 and focuses on syngas production. The aims of the task were:

- To enable gasification of different residue and waste feedstock for the BioSFerA process widening the available feedstock range
- Provide realistic water samples from the syngas process for the syngas fermentation tests in other tasks of the WP3
- Identify factors that might cause risks for piloting operations in WP4, in which the mobile gas fermentation unit is integrated into the syngas process at TRL5.
- Provide preliminary data and information for modeling and concept development work in WP2 and WP6.

Five different feedstocks were gasified and water samples were collected from the process and provided for partners who are responsible for syngas fermentation operations in the BioSFerA project. Based on the preliminary tests the syngas requires filtration and reforming before it is fed into the fermentation unit.

It is still unclear if the syngas impurities after the reforming unit (e.g. HCN, H_2S, benzene) can accumulate to levels where they inhibit the growth of microbes. In the next steps, these risks should be minimized by planning and modifying the downstream of the syngas process. More detailed definitions for syngas quality and possible recycling loops should be created together with the BioSFerA partners in the frame of WP3 activities.

1. Introduction to syngas process

Thermochemical conversion technologies such as gasification enable the recycling of biomass and plastic waste, helping replace fossil-based raw materials. They provide new solutions that enable converting low-value feedstocks to higher-value products such as marine and aviation fuels. VTT has several gasification-related process units and integrated processes available for piloting.

The syngas process which is used in the BioSFerA project contains several unit operations. The process chain will be modified and optimized for the gas fermentation process which will be connected and piloted at TRL5. The process at VTT contains the following units for producing clean syngas for elevated pressures:

- Gasifier
- Quench / Syngas cooler
- Hot-gas filter
- Reformer
- Syngas cleaning units
    - Condenser/water scrubber(s)
    - Adsorbers
    - Hydrolysis step for converting HCN and COS
- Guard bed
- Syngas compressor

The process chain is originally developed for Fischer-Tropsch production at medium scales 50 – 200 MWth. In the BioSFerA project, the syngas process will be integrated with BBEPP’s mobile syngas fermentation unit. The anticipated benefit of this integration is the minimization of the costs which are related to syngas processing. It is possible that certain cleaning units can be completely omitted as the microbes can potentially consume for example NH_3 as a source of nitrogen.

It is important that during WP3 and WP4, WP5, WP6 that the possibilities for process modifications, integrations, and recycling loops are well understood. Therefore, the following chapters will explain the main units and their purpose briefly.

1.1. Gasifier

A gasifier converts solid biomass to synthesis gas, which contains mainly hydrogen (H_2) and carbon monoxide (CO). Other gaseous components with higher concentrations are H_2O and CO_2. In addition to these, the non-processed syngas can contain H_2S, COS, NH_3, HCN, and different hydrocarbons such as alkanes (methane, ethane, etc.) and organic components like benzene and naphthalene which are commonly called as tars.

A gasifier is a reactor where oxidation reactions are carried out. Different gasification technologies exist, such as fixed bed updraft gasifiers and fluidizing bed gasifiers. The tests in WP3 were done in a bench-scale bubbling fluidized bed (BFB) gasifier. The main aim of the tests was to collect water samples from the process for producing realistic samples of different condensable and soluble impurities. Also, different feedstocks and their quality were studied in a gasification environment.

Different gasification agents can be used for conducting the partial oxidation reactions and for fluidizing the bed material and feedstock:

- Air blown gasification
- Oxygen blown gasification
- Steam gasification
- CO_2 gasification

Also, mixtures of different fluidizing agents can be used. It is important to notice that if the air is used as a gasification agent the syngas is diluted with nitrogen. Nitrogen acts as an inert component which leads to larger downstream equipment size. This should be acknowledged while designing the integration for piloting operations in WP4. Also, other components such as CH_4, C_2H_6, and CO_2 can act as inert and accumulate in the system if the gas fermentation unit has no ability to convert these components.

1.2. Quench / Syngas cooler

Normally the syngas is filtered for removing solid particles from the syngas. However, before syngas filtration, the syngas must be cooled down from around 800 °C down to 500 °C for allowing filtration of some metallic and inorganic impurities. The heat can be recovered from the cooler and used as process heat for various applications such as steam generation for the gasifier.

At lower temperatures, volatile metals such as sodium (Na) and potassium (K) forms solid particles that can be filtered. Without cooling, the volatile metals can penetrate through the filter and accumulate in the downstream units. At colder temperatures, also the formation of solid coke deposits is reduced on the filter surfaces. Although lower filtration temperature would improve the capture of volatile metals and minimize coke formation, on the other hand, the temperature of the filter should not be lower than 350 °C to avoid condensation of heavy tars (e.g., phenanthrene) which would plug the filter.

1.3. Hot-gas filter

The hot-gas filtration unit removes solid particles from the syngas. Normally, in the Fischer-Tropsch plant, the particles need to be removed to avoid plugging of subsequent equipment and catalyst inhibition. For example, ash and salts can inhibit reforming catalysts or slowly fill the fixed bed with solid particles causing blockages. These problems are anticipated to occur also in gas fermentation unit integration if the hot gas filter is omitted.

1.4. Reformer

A catalytic reformer reactor converts various organic tar components to syngas. Tars are organic molecules that easily condense in downstream equipment causing plugging of pipes and coating of surfaces. Tars would most probably accumulate also in the syngas fermentation unit and cause mechanical problems e.g. in compressor or completely inhibit the growth of syngas converting microbes. After reforming, the main condensable organic impurity is benzene (C_6H_6) which is the most stable organic component after methane.

The reformer is capable also to convert part of the NH_3 and HCN which is present in the syngas. The reforming reactions are endothermic and the reactor operates at around 900 °C under autothermal conditions. To maintain reactor operation stable, an oxidizing medium like pure oxygen is needed. The gas must be cooled down before it can be fed into the downstream units.

For minimizing the capital and operational costs in syngas processing it would be optimal if reformed syngas could be used without further purification in the gas fermentation unit. However, this approach possesses a risk of growth inhibition as the impurities can accumulate in the system in a long-term operation.

If ultra-cleaning is not needed in the BioSFerA-process, then the used syngas process in WP4 would only contain a gasifier, hot-gas filter, reformer, cooler/condenser, and syngas compressor with a gas buffer storage. The process is presented in Figure 1. For minimizing risks in the piloting phase, it is recommended that ultra-cleaning steps are added at least at the beginning of the piloting runs.

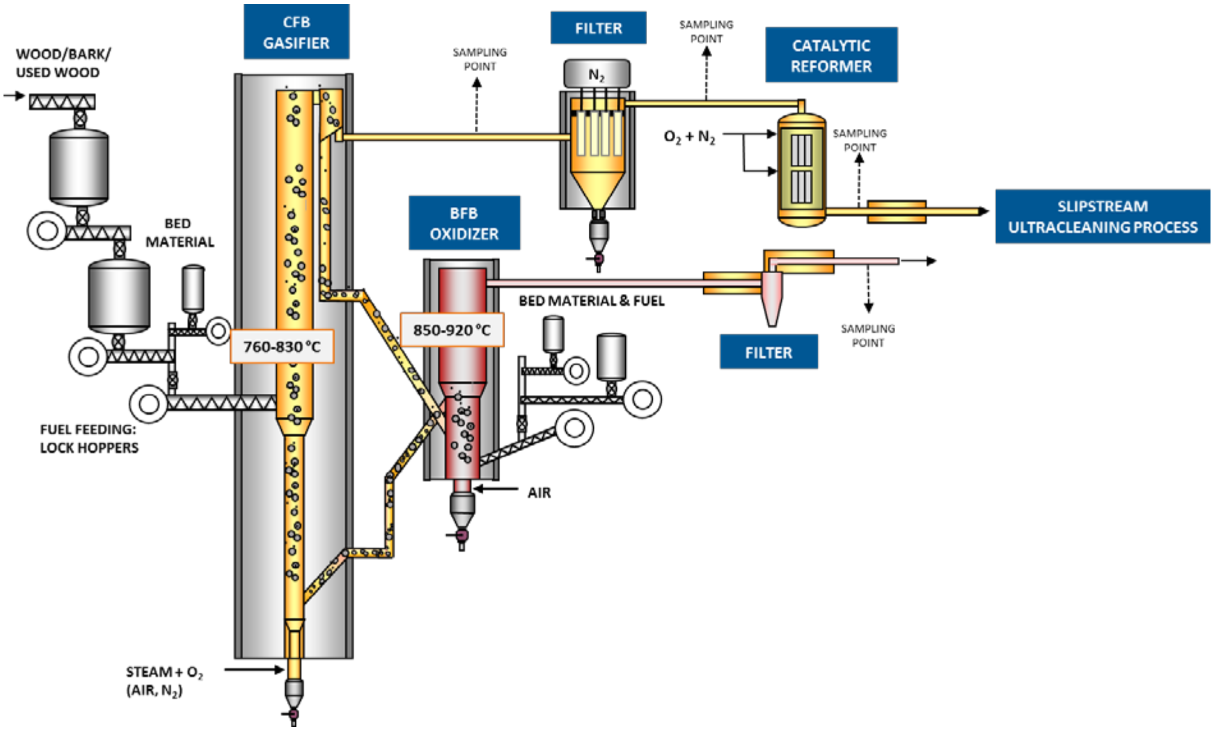

Figure 1 A syngas process consisting of a dual fluidized bed gasifier, hot-gas filter, and a reformer unit. Different arrangements between CFB and BFB reactors could be arranged if needed. At the moment (M12) the configuration is CFB + CFB at the piloting facility in Bioruukki.

1.5. Ultra-cleaning process

It is expected that the syngas contains inhibiting components such as HCN and benzene after reforming. These impurities might accumulate in the syngas fermentation unit in long-term operation and form soluble components such as metal cyanides. Therefore, additional cleaning steps such as scrubbers and adsorbers might be required in the process of removing the inhibiting components from the syngas down to a level where microbial growth is fast enough.

VTT has developed a syngas ultra-cleaning process that is capable to remove harmful components down below < 0.1 ppm levels. The ultra-cleaning process is developed for meeting the requirements of chemical synthesis processes such as Fischer-Tropsch reactors. As a presumption, it is expected that the gas fermentation can tolerate higher levels of impurities and therefore less complete syngas cleaning is needed. The following Figure 2 shows the syngas cleaning process which is currently used at VTT for producing Fischer-Tropsch fuels and is capable to remove > 99.9% of the impurities which are present in the syngas.

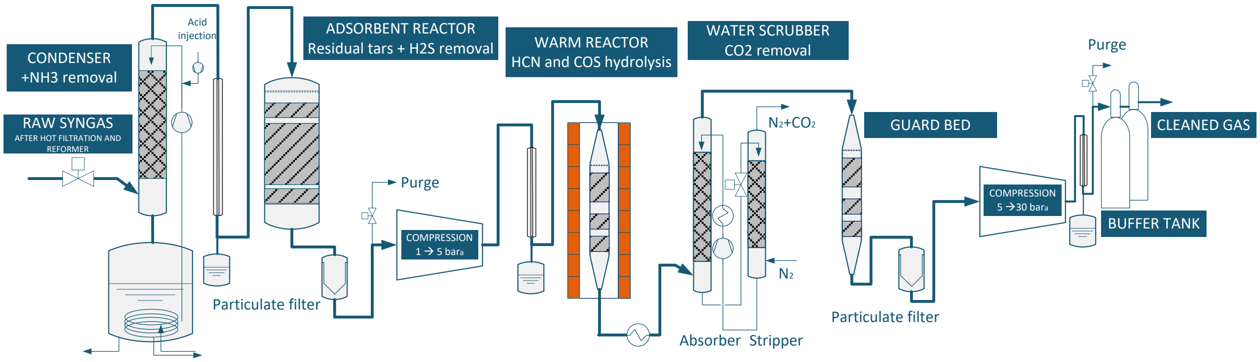

Figure 2 Ultra-cleaning process for producing clean synthesis gas.

In BioSFerA, different unit operations such as scrubbers and adsorbers can be used for removing target impurities selectively. Also, the CO_2 concentration of syngas can be decreased up to 50 - 60 % if high levels of CO_2 are found to be harmful for syngas fermentation e.g. due to decreasing pH or accumulation of inert components in the recycling loops. However, these cleaning steps increase operational and capital expenditures which easily leads to high production costs.

For optimizing the syngas process, more information is required about the maximum concentrations of different impurities including the optimal ratios between $H_2/CO/CO_2$ gasses. Optimal temperature and pressure levels would also need to be known before the piloting in runs in WP4 can start. The humidity level of syngas an influence on the gas fermentation and allowable humidity range should be defined.

2. Different feedstocks for gasification

The target in WP3 was to provide a wide range of different feedstocks which could be used in the BioSFerA-process for enabling feedstock flexibility. The feedstocks were selected in Task 2.3 of WP2 and the gasification tests were conducted in T3.1 for proving the quality of the selected feedstocks for minimizing operational risks in the piloting phase. The tested feedstocks in T3.1 were:

- Forest residue pellet
- Bark pellet
- Straw pellet
- Sunflower husk pellet
- Olive pruning pellet

These different feedstocks behave differently in the gasifier and produce different qualities of syngas. One of the most influencing properties of the feedstock is the sintering temperature of the ashes. Especially feedstock which has high potassium and sodium concentration can easily cause sintering of ashes which leads to defluidization in the gasifier or ash accumulation in the downstream (e.g. heat recovery unit).

Defluidization of the bed leads to poor conversion of the feedstock, which leads for example to larger tar formation and poor syngas production rate. Sunflower husk and olive pruning have high alkali content and therefore the gasification temperature is limited for avoiding sintering-related problems in the gasifier.

In addition to ash sintering, also sulfur and chloride content of the fuel can influence remarkably the syngas quality by deactivating reforming catalysts. Sulfur and chloride components of the feedstocks are partly converted to gaseous species (e.g. H_2S) which reacts with the catalyst material in the reformer causing deactivation. These deactivation reactions can lead to reversible and irreversible reforming catalyst deactivation. The catalyst deactivation increases the concentration of tars after the reformer and especially the concentration of benzene in the syngas. Concentrations of HCN and NH_3 can also increase if the reforming catalyst is deactivated.

Table 1 Analytical results of feedstock including heat value, moisture, proximate analysis, and ultimate analysis.

	Forest residue	Bark pellet	Straw pellet	Sunflower husk	Olive pruning
Heat value MJ/kg	19,7	18,9	17,3	17,8	18,9
Moisture, wt-%	8,1	8,4	8,1	9,8	5,9
Proximate analysis, wt-% d.b.					
Volatile matter	75,8	77,8	75,5	76,8	77,8
Fixed carbon	21,3	18,5	16,8	20,0	16,3
Ash 550 °C	2,6	3,7	6,3	3,2	5,9
Ultimate analysis, wt-% d.b.					
C	52,2	51,5	43,6	50,8	50,03
H	5,7	5,8	5,6	6,0	7,0
N	0,5	0,3	0,8	0,7	1,2
O - as difference	39,0	38,7	43,7	39,3	36,8
S	0,04	0,06	0,11	0,14	0,08
Cl	N/A	0,013	N/A	N/A	0,2

3. Test conditions and syngas quality

Syngas can be produced in many different ways. For example, the gasifier can process different feedstocks, gasification temperature, and pressure can be varied, different oxidizing and fluidizing media can be used, oxidizer reactor can combust char which is generated in a gasifier or the oxidizer can also combust off-gasses from syngas fermentation unit, also different bed materials such as sand or calcium carbonate can be used. All of these factors influence the syngas quality.

The target values which were used in the bench-scale tests are tabulated in Table 2. The parameters were chosen based on earlier experience and the parameters are not optimized for the BioSFerA process. The results represent preliminary design values which must be defined more accurately later in the project when more knowledge about the required conditions of syngas fermentation and the process concept is known.

Table 2 Process target parameters for the gasifier and reformer for each different feedstock.

	Forest residue	**Bark pellet**	**Straw pellet**	**Sunflower husk**	**Olive pruning**
Feed [kg/h]	4,0	4,0	3,7	3,9	3,7
Bed material	Sand + Dolomite	Sand + Dolomite	Sand + Dolomite	Sand + Dolomite	Sand + Dolomite
Gasification temperature [°C]	810	810	780	750	780
Pressure	1,05	1,05	1,05	1,05	1,05
Steam-to-feedstock [kg/kg]	1,0	1,0	1,1	1,1	1,1
Face velocity [m/s]	0,55	0,55	0,60	0,60	0,55
Filtration temperature [°C]	600	600	600	600	600
Reformer temperature [°C]	780-1020	780-1020	880-980	800-960	880-980
Feed gas to reformer O2/CO2	45 vol%$_{O2}$	45 vol%$_{O2}$	45 vol%$_{O2}$	45 vol%$_{O2}$	40 vol%$_{O2}$

3.1. Gasification and gas processing results

Bench-scale tests were conducted in a bubbling fluidized bed gasifier that does not have an oxidizer reactor. Feedstock, bed material (sand + dolomite), and gasification agents (H_2O and O_2) were fed continuously in the system. The gasification agent consisted of 93 vol% steam and 7 vol% oxygen. Steam to fuel ratios in the experiments were approximately 1 kg_{H2O}/kg_{fuel}.

Ash samples were removed from the bottom of the gasifier and from the filter unit semi-continuously. Gas quality was measured with different online and offline gas analysis methods after the hot-gas filter and reformer units. Additionally, a water scrubber after the reformer was tested for trace impurities removal for select feedstocks. The unit consists of a counter-flow packed-bed column with an open or closed-loop water circulation. The unit has a formic acid feeding for pH control. Separate analytical methods were employed for the post-scrubber gas, including continuous FTIR and FPD-GC for certain runs as well Dräger colorimetric tube analysis for HCN and H_2S.

Water samples containing different impurities were collected from two different points of the process: 1. after the hot-gas filter unit 2. and reformer unit. The water was collected by taking a small (10 dm^3/min) by-pass stream and by cooling and condensing the by-passed syngas. The water samples were collected for several hours. Approximately 0.25 dm^3 of condensed water together with condensable and soluble impurities were collected per hour.

Offline gas measurements measuring the concentration of NH3, HCN, and tars were measured after the filter (AR) and after the reformer (AR). Syngas after filter contains several organic impurities and normally higher concentrations of NH_3 and HCN.

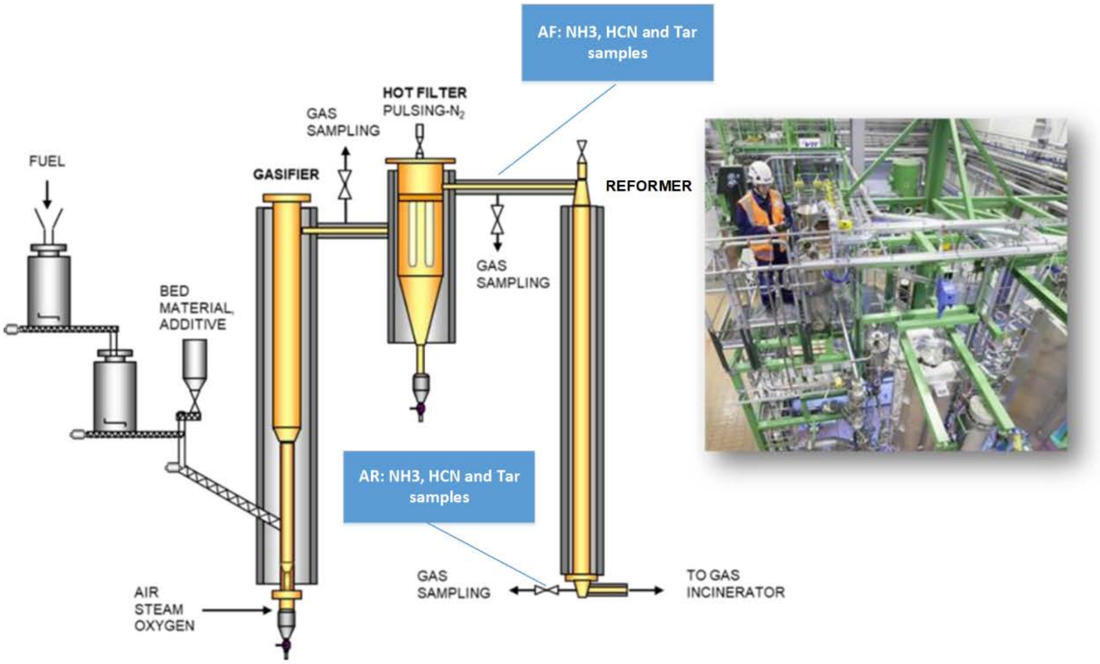

Figure 3 Bench-scale bubbling fluidized bed gasifier (BFB) system showing the sampling points for gas quality measurements and water sample collection points after the filter (AF) and after the reformer (AR).

Gasification and reforming temperature influence the gas composition. Also feed gasses (O_2, CO_2, H_2O, N_2) changes the composition of the gas which is delivered into the syngas fermentation unit. Therefore, accurate target gas composition cannot be defined before the process conditions such as feedstock and feed gasses are fixed.

The bench-scale test results cannot be directly used as design values for WP4, WP6, or WP7. However, the results give preliminary values for the gas composition which would be available for the syngas fermentation unit after each process unit. The following Figure 4 and Table 3 show the measured gas compositions and these values can be used as initial values for trying to emulate a more realistic gas mixture for the gas fermentation tests in WP3.

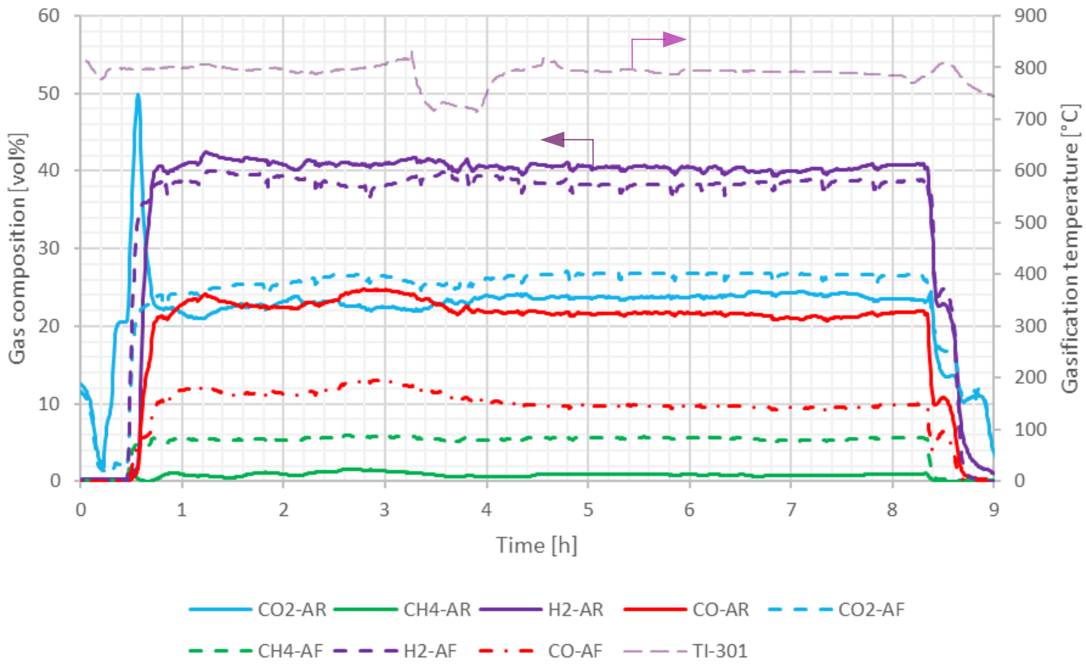

Figure 4 An example of gas composition measurement after the hot-gas-filter (AF, dashed line) and after reformer (AR, solid line) during an 8-hour run. Gasification temperature is shown on the secondary axis on the right. The concentration profiles were similar in all gasification tests during the measurement period.

Table 3 Average gas composition (d.b.) measured during an 8-hour test run with micro-GC after the filter (AF) and after reformer (AR) with three different feedstocks.

	Olive AF	**Olive AR**	**Straw AF**	**Straw AR**	**Sunflower AF**	**Sunflower AR**
H_2 [vol%]	37,4	38,8	39,6	36,6	34,99	38,3
CH_4 [vol%]	6,0	2,0	5,3	2,3	5,91	1,6
CO [vol%]	14,2	21,0	11,6	17,7	13,68	19,6
CO_2 [vol%]	20,3	18,0	26,2	21,1	25,62	23,6
N_2 [vol%]	19,2	18,4	15,2	21,0	16,97	15,2
O_2 [vol%]	0,00	0,47	0,05	0,46	0,00	0,47
Ethylene [vol%]	1,80	0	2,54	0	1,92	0
Ethane [vol%]	0,40	0	0,54	0	0,46	0
Acetylene [vol%]	0,05	0	0,11	0	0,05	0
Propane [vol%]	0,12	0	0,48	0	0,29	0
2-Butene [vol%]	0	0	0,01	0	0,00	0,06
N-Pentane [vol%]	0	0,005	0	0	0	0
1,3-Butadiene [vol%]	0,03	0,004	0,16	0,01	0	0,003

The reforming unit converts organic components such as benzene into syngas components (H_2, CO, CO_2, H_2O). The reforming unit can also convert CO_2 to CO via the RWGS reaction. In this way, higher concentrations and yields of H2 and CO can be achieved. The effect of these reactions on concentration can be seen in Table 4. It can also be seen that the feedstock has a relatively low influence on the syngas composition if the reformer unit is used. Residual benzene after the scrubber step was not measured, but it is known from prior that benzene solubility into water is low. After reformer, the oxygen content was measured to be 0.45 vol%. The high level of measured oxygen content is caused by a leakage in the gas analysis line or by other systematic error. The actual oxygen content in the syngas is much lower. However, even this lower oxygen concentration might influence on the anaerobic bacteria, and measures for guarantying low O_2 content in the syngas should be taken before piloting.

The reformer unit does not remove sulfur components from the syngas. H_2S and COS can react with the metal catalyst and deactivate the catalyst and therefore feedstocks with high sulfur content can produce lower quality syngas with high tar concentration.

In addition to these reactions, the reformer unit can convert HCN and NH_3. The measured conversion values after the filter and after reformer are tabulated in Tables 4, 5, and 6. In the bench-scale test, relatively high conversion rates were achieved. However, in the test, the catalyst bed was relatively large which might not economic on a larger scale. In commercial and pilot-scale operation the conversion rates are expected to be lower, which leads to higher HCN and NH3 concentration in downstream.

In the subsequent water scrubbing unit, the water pH affects which components are absorbed into the water. An acidic pH, by adding formic acid to the water, improves absorption of caustic gases such as ammonia. Ammonia is very soluble even in neutral water. Acid gases such as H_2S and HCN will dissolve in neutral pH, but full removal is unlikely. Table 5 gives hint that at small HCN concentrations neutral water scrubbing could be possible for full removal. Table 6 shows that low pH water is very effective at NH_3 removal, and still with neutral water almost complete NH_3 removal is achieved.

For the gasification campaigns, the water scrubber was either operated in normal mode, which is pH 3, intended for only ammonia removal. The other tested option was to operate it in non-circulating fresh water, pH ca 7.5-8. CO_2 in syngas naturally lowers the pH of a closed-loop solution, thus circulation could not be used. In an ideal scenario, a good compromise would be found for the pH level in the scrubbing step to simultaneously remove NH_3 and HCN. As for the sulfur removal, H_2S is partially removed, ca. 50 %, in the scrubbing step as can be seen from Table 7. Water scrubber at pH 3 generally is sour enough to not capture any H_2S according to our previous tests, thus it can be considered to be the same as the H_2S concentration after the reformer. COS concentration was a fraction of the H_2S, approaching the equilibrium. COS is perhaps the most non-reactive species of the aforementioned impurities, and therefore not affected by the water scrubbing at the tested pH levels. COS removal by for example catalytic hydrolysis or even adsorption by activated carbons could be possible.

Table 4 Concentration of tars and benzene after filter and reformer units and conversion of these components in the reformer.

	Wood residue	Bark pellet	Sunflower husk	Olive pruning	Straw pellet
Identified tars and benzene after filter [ppmv]	2845	4149	1814	5338	8097
Identified tars and benzene after reformer [ppmv]	0	2	16	19	51
Tar and benzene conversion in reformer	100 %	100 %	99,1 %	99,6 %	99,4 %

Table 5 Concentration of HCN after filter and reformer and scrubber units and conversion of HCN in the reformer.

	Sunflower husk	Olive pruning	Straw pellet
HCN after filter [ppmv]	11	50	727
HCN after reformer [ppmv]	2	7	5
HCN after water scrubber, neutral [ppmv]	0	N/A	N/A
HCN conversion in reformer	83 %	85 %	99 %

Table 6 Concentration of NH_3 after filter and reformer and scrubber units and conversion of NH_3 in the reformer.

	Wood residue	Bark pellet	Sunflower husk	Olive pruning	Straw pellet
NH_3 after filter [ppmv]	3 240	3 162	5 527	8 930	11 466
NH_3 after reformer [ppmv]	71	90	262	766	460
NH_3 after water scrubber, pH 3 [ppmv]	0	0	0	13/0[a]	25/0[a]
NH_3 conversion in reformer	98 %	97 %	95 %	91 %	96,0 %
Total NH_3 removal	100 %	100 %	100 %	99,9 %	99,8 %

[a] Tests conducted in neutral fresh water scrubbing and offline sampling and ammonia analysis showed a small breakthrough. With sour water scrubbing the continuous FTIR measurement did not detect NH3.

Table 7 Concentration of sulfur species after water scrubber.

	Sunflower husk	Olive pruning	Straw pellet
H_2S after water scrubber, pH 3 [ppmv]	300	170	N/A
H_2S after water scrubber, pH neutral [ppmv]	150	70	140
COS after water scrubber [ppmv]	N/A	9	14

3.2. Accumulation of impurities and toxins

Water samples have been collected for several hours during the bench-scale tests and sent to partners in WP3. This water collection method captures part of the impurities and produces more realistic conditions for lab-scale gas fermentation tests than with simulated impurities. According to the preliminary results, the syngas fermentation unit could possibly operate without problems by using reformed syngas as a feedstock without additional purification steps.

However, the syngas fermentation condition can differ remarkably in the piloting runs when the different impurities can accumulate in the system for hundreds of hours. Also, the aggressivity of the collected water samples is expected to decrease while the samples are stored and transported. The concentration of reactive syngas components decreases and forms less reactive components. This is expected to result in optimistic yields in syngas fermentation.

Aggressive components react during sample storing and transportation, which can influence the lab-scale syngas fermentation results and lead to different results in pilot scale operation, where the aggressive and possibly toxic components are directly transferred into the gas fermentation unit without a prolonged storage period.

The real environment in the pilot phase (TRL5) can be more aggressive for microbes and inhibit microbial growth.

3.3. Ultra-cleaning

Traces of impurities such as HCN and H_2S can be detrimental to microbial growth even at very low concentrations. BBEPP and CARTIF conducted tests with the water samples, which we collected after the filter and after the reformer. Based on these gas fermentation results with different microbial strains (*Clostridium ljungdahlii*, *Clostridium autoethanogenum* and *Morella thermoacetica*) it seems that the syngas after filter contains a too high level of impurities which strongly inhibits the growth of microbes. A similar test conducted in water collected after the reformer unit gave better results and the growth was only slightly inhibited in comparison to blank clean water tests.

At the moment it seems that microbes could grow in syngas which is coming from the reformer based on the short-term tests. It is still unclear if the soluble and condensable impurities accumulate in the system during a long-term operation and starts to inhibit the growth. Also, the effect of storing and transporting the samples in bottles is unknown. It is expected that the most aggressive chemical species react during the storing period and forms less aggressive and less inhibiting components.

To minimize operational risks in the piloting phase (WP4) additional syngas processing units could be added in the downstream. VTT has available different scrubber and adsorbent systems that could be modified for the BioSFerA-process after more knowledge of the allowed impurity concentrations (HCN, NH_3, COS, H_2S, benzene) is gained. The scrubbing step can be tailored to the desired pH for optimal removal of acid and caustic gases selectively or non-selectively. Trace impurities can be removed with activated carbon.

At this stage, it is already known that mere water scrubbing is not able to fully remove benzene and COS impurities, thus other removal solutions are required for these if removal of them is necessary. These modifications should be studied before finalizing the concept and before starting to integrate the syngas fermentation unit in WP4.

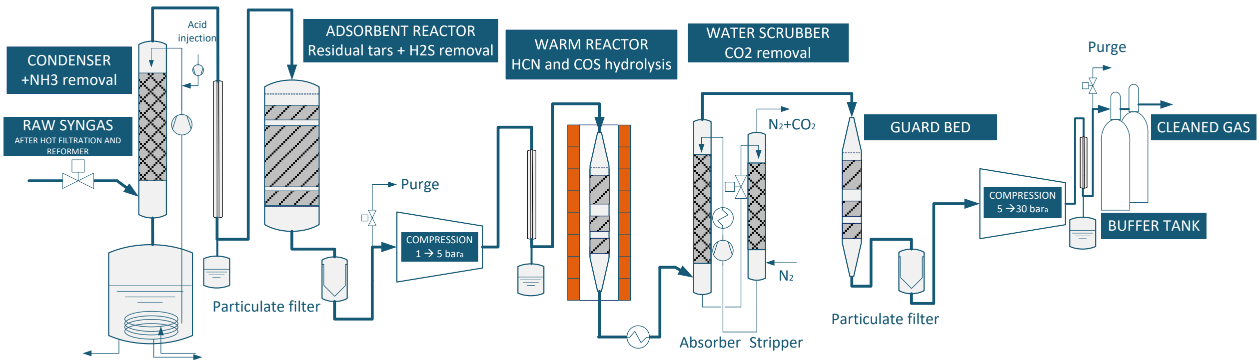

Figure 5 Current ultra-cleaning process which is optimized for small- and medium-scale Fischer-Tropsch production.

3.4. Integration of the mobile gas fermentation unit

During the piloting phase in WP4, the gas fermentation unit will be connected to the gasification process. Different integration possibilities exist and at the moment the most potential integrations are not known. For minimizing the risks with the inhibiting components, the piloting phase should be started with ultra-cleaned syngas. After target production rates of acetate are achieved some of the cleaning units could be removed and the influence of the increased impurity concentration on acetate generation could be monitored.

FILTERED SYNGAS	
Impurity	Concentration [ppm]
NH3	> 3000
H2S	20-400
COS	1-10
HCN	> 10
Benzene	1000-3000

REFORMED SYNGAS	
Impurity	Concentration [ppm]
NH3	250-500
H2S	20-400
COS	1-10
HCN	1-10
Benzene	10-200

SCRUBBED SYNGAS	
Impurity	Concentration [ppm]
NH3	50
H2S	20-400
COS	1-10
HCN	1-10
Benzene	10-200

ULTRA CLEANED SYNGAS	
Impurity	Concentration [ppm]
NH3	<0.1
H2S	<0.1
COS	<0.1
HCN	<0.1
Benzene	<0.1

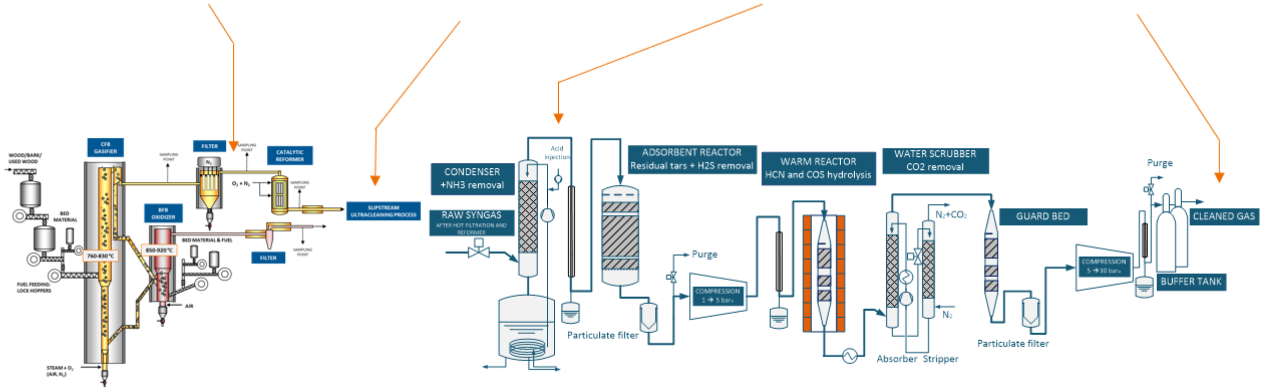

Figure 6 Approximate syngas impurity concentration after certain syngas processing units.

In the long-term tests in WP4, it is important to ensure that syngas is continuously available for the syngas fermentation at required quality levels. Different strategies for minimizing the risks for unforeseen shut down in the syngas production should be created e.g. by providing buffer capacity for the processed syngas.

4. Conclusions

Five different feedstocks were gasified and water samples were collected. Based on the results, syngas fermentation cannot be carried out with syngas without reforming due to the high concentration of inhibiting components. A reforming unit is required in the process of removing the harmful components.

Water collected after reforming the unit is relatively pure and microbial growth seemed to be high in the preliminary tests. However, the effect of impurities in long-term tests is still unknown as the impurities have more time to accumulate in the system.

After reforming, the gas composition is relatively similar with different feedstocks as the gas composition averages out in the reformer. Gasses that are fed into the gasifier and reformer (O_2, N_2, H_2O, CO_2) and their volume flow influence the syngas composition more than the selected feedstock.

Higher concentrations of H_2S, COS, HCN, and NH_3 are measured with feedstocks that have high sulfur (S) and nitrogen (N) content (e.g. straw, sunflower husk, olive prunings). This might lead to larger requirements for the gas cleaning in the downstream if these gaseous components inhibit the growth of microbes. Also, ash sintering can cause more operational problems in the gasifier if straw, sunflower husk, or olive prunings are used as a feedstock in WP4. Based on the bench-scale gasification tests all of the feedstocks could be potentially selected for the piloting runs. However, for minimizing the operational risks in the piloting operation, the wood residue pellet would be the most preferred feedstock.

In WP4 approximately 20 kg/h is planned to be fed into the gasifier. If the gasifier is operated for 300 hours during the piloting runs then approximately 6 000 kg of feedstock would be needed. Availability of the feedstock is one main criterion for selecting the feedstock.

5. Proposed next steps

For minimizing operational risks in the piloting phase more experimental data is required especially in the downstream part.

- Identification of the most critical impurities and purification steps after reforming e.g.:
  - Accumulation of impurities
  - Condensation in fermentation
  - Condensation in a scrubber system
  - Guard beds
  - Temperature and humidity control
- Fermentation tests with more realistic gas mixtures

For enabling smooth integration of the syngas production and syngas fermentation systems in WP4 and for enabling relevant data collection for modeling-based work in WP6 and WP7, several parameters and concept-related factors should be defined.

- Defining the amount of maximum allowable concentration of inert components (N_2, CH_4, CO_2)
- Maximum allowed concentration of oxygen in the syngas
- Fixing the process concept e.g.:
  - CO2 recycling to reformer
  - Pure O2 generation/availability for avoiding syngas dilution with nitrogen
  - Off-gas combustion in the oxidizer reactor

For widening the feedstock range and for providing feedstock flexibility for the BioSFerA process, tests to gasify SRF waste pellets are planned to be conducted later in 2021 when the feedstock is available for VTT.