Publishable version of Compendium on research results on agriculture and forest-biomass side-streams

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Bringing added value to agriculture and forest sectors by closing the research and innovation divide

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1. Executive summary

AGRIFORVALOR aims to close the research and innovation divide by connecting practitioners from agriculture and forestry to research and academia as well as with associations and clusters, bio-industry, policy makers; business support organisations, innovation agencies and technology transfer intermediaries in multi-actor innovation partnership networks. The focus of the project is on the transfer of know-how and information to enable and support farmers and foresters to exploit existing research results and facilitate the capture of grass root ideas for bio-industry development.

In the project, practitioners in the field of biomass side-streams are united in three Biomass Innovation Design Hubs, piloted in Spain (Andalucía), Hungary and Ireland. In each of these hubs, existing research results and good practices on valorisation of biomass side-streams from agro and forest will be shared and matched with the specific needs and potentials; new grass-roots ideas collected and developed; and dedicated innovation support applied to further deploy selected topics which are dealt with by multi-actor innovation partnership groups.

Research on the valorisation of these biomass side-streams is also increasing since some decades and since some important successful examples. Biomass production for energy production and for bio-based products has seriously stimulated this development. Many techniques are being researched. Some have already been successfully brought to the market (e.g. production of biogas and pyrolysis oil), others being researched in labs and test installations (e.g. production of functional materials/fine chemicals such as high purity lignin, plant sterols and peptides).

In literature and on the web, a vast number of research techniques can be found. An overview of techniques will be helpful to stakeholders dealing with biomass side-streams such as foresters, farmers, the biomass processing industries and the bio-energy sector.

This compendium on research results provides an overview of techniques based on side-stream valorisation in the production process. Through this, the compendium contributes to the deployment of the vast reservoir of existing scientific knowledge and an improved flow of information and knowledge between academia and practitioners in particular on agricultural and forestry practices and innovations.

Research results were collected from literature, the internet and research institutes, and were analysed on some important characteristics such as feedstock, output products, processing techniques and the technique readiness level (TRL). The hub partners supported

the search by using the following approach: As a first step, the Hubs completed a survey on types and quantities of biomass side-streams available through partners connected to the hubs. This provided information on the most relevant types of biomass side-streams. Secondly, valorisation techniques on these side-streams were sought out by search on the internet, through contacting research centres and on the web.

Different techniques are found to valorise biomass side streams. For agricultural related biomass side-streams digestion, extraction, fermentation and enzymatic fractionation seem promising techniques resulting in products for use in the food, (fine) chemical, functional materials and fuel sector.

For forestry related biomass side-streams, extraction, gasification, low NOx combustion, pyrolysis, organosolv fractionation, and torrefaction, in combination with pelletisation are techniques found to valorise woody side-streams into marketable products for food, (fine) chemicals, functional materials and fuel applications.

From these techniques collected, roughly five types of biomass side-stream valorisation can be distinguished

1) Production of functional materials, fine chemicals and food additives for food applications
2) Production of bio-energy and biofuels for energy production
3) Production of (fine) chemicals and functional materials for production of utensils
4) A combination of energy production, (fine) chemicals and/or functional materials
5) Production of fertilizers for improvement of soil fertility of agricultural land

The results show that mainly **agricultural biomass side streams** are used to produce products for food applications. This probably is due to the calorific value of this biomass and the economic costs of the techniques and biomass side-streams. From the 30 RTDs collected for agricultural related biomass side-streams, 15 techniques are producing products for Food applications, 11 techniques result in Functional material or Fine chemical products, 11 techniques produce Fuels, 6 techniques produce Fertilizers and 2 techniques produce Feed. 12 of the 30 techniques result in only one F category output product, while most (18) of the techniques result in two or more F category products.

For **combined agriculture and forestry biomass side-streams**, most of the techniques found (7 out of 10) result in products that can be classified as Fuel (e.g. biogas, heat, steam, bio-oil etc.). 5 techniques produce Fertilizers (mainly bio-char, compost and nutrients), and also 5 techniques produce Functional materials / Fine chemicals. Some techniques (5, mainly pyrolysis) produce more than one F-related output. From Table 2 it follows that RTDs

mainly aimed at fuel production have higher TRL levels than RTDs aimed at the other Fs like Fine chemicals, Functional materials and Fertilizers. No techniques for combined forestry and agriculture biomass-side-streams were found that produce products applicable for the food sector. Although this might be an option for some side-streams (especially for protein and sugar rich biomass) it seems that this usage is more applicable when using only agricultural biomass side-streams.

For **forestry related biomass side-streams,** 3 techniques found produce products used as Fuel (e.g. ethanol, heat, steam, biogas, pyrolysis oil). 4 techniques produce Functional materials/Fine chemicals like insulation material, active carbon, ethanol, lignin, and glucose. 2 techniques are producing Food additives. No technique is producing fertilizers.

Research techniques applied on woody biomass side-streams with a lower TRL level (3-4) are techniques producing functional materials, fine chemicals, and food, while techniques with higher TRL levels are mainly producing fuels for energy production.

Almost all biomass-side streams, both from agriculture and from forestry, can be used for energy production. However, in research, there is an increasing focus on techniques with a higher valorisation potential. This can be achieved by applying another technique resulting in another output product with a higher value. It can also be reached by applying a more advanced technique producing more than one output product. For instance pyrolysis techniques can produce fuel (biogas, pyrolysis oil), chemicals (e.g. ethanol) and fertilizer (bio-char) at the same time. Most used techniques for energy production are already in a further stage and close to the market; they need further fine-tuning and upscaling. The techniques used for the production of fuel are mainly digestion of crop residues resulting in biogas and fermentation or pyrolysis of woody biomass resulting in ethanol and bio-oil. Hence, in earlier research techniques (lower TRL), there is an increasing focus on techniques with a higher valorisation potential of biomass side-streams.

Also fertilizers are produced, but mainly as side product (e.g. bio-char) of a stepwise bio-refinery process. Only few techniques (composting, pyrolysis) are used for producing fertilizers as main product. Fertilizers are produced both out of agricultural and forestry biomass side-streams, separate and combined.

For the production of bioactive and chemical compounds, techniques as extraction, enzymatic fractionation, and organosolv fractionation are applied. The type of technique is depending on the quality of the biomass side-stream and on the compound to produce.

Pyrolysis and gasification are techniques resulting in a combination of energy production (e.g. heat, steam), fuels (e.g. pyrolysis oil, ethanol) and chemicals (e.g. acetic acid, lactic acid) and functional materials (e.g. high purity lignin, hemicellulose).

Research techniques producing food additives (e.g. colorants, fibres, sugar, proteins), functional materials and fine chemicals mostly have a lower TRL level (3-6) than techniques producing fuels for energy production (TRL 7-9). This can be explained because energy production techniques started (much) earlier than techniques producing chemicals and functional materials. The latter techniques are more complex, and need well developed knowledge on chemical processes and smart techniques to extract the chemical components with a high purity. This kind of science just seriously started some decades ago but now is increasing vast in number of researches and applications.

2. Results achieved

So far the consortium identified 30 research techniques applicable to agricultural related biomass side-streams, 10 research techniques applicable for combined agricultural and forestry related biomass side-streams and 8 research techniques applicable for forestry related biomass side-streams. Different techniques are found to valorise biomass side-streams as described in more detail in the following sections 2.1 to 2.3.

2.1 Research results of valorisation techniques for agricultural biomass side-streams

For **agricultural biomass** side-streams, liquefaction, fractionation, hydrolysis, steam explosion, extraction, coagulation, fermentation, digestion, bio-refinery, inverse osmosis, ultrafiltration and microbial transformation (e.g. by algae and bacteria) are promising techniques resulting in products for use in the food, feed, fertilizer, fine chemical / functional materials and fuel sector. An overview for agricultural biomass side-streams is given in table 1, indicating, the type of biomass side-stream used as feedstock, the country in which the technique is (being) applied/developed, the type of technique, and the indication of the output along to the 5Fs: Food, Feed, Fuel, Fertilizer, Functional material / Fine chemical, with this latter category including fine chemicals, performance materials, bulk and fermentation chemicals.

The table is sorted by the TRL-levels (low to high), and the techniques with the same level are sorted alphabetically based on the biomass side stream. The research results numbers 25, 26, and 28 are twofold, using different extraction techniques (Supercritical fluent extraction and solvent extraction). These results are from the same project that studies the valorisation potential of three different products: grapes, olives and tomatoes. The three products have different bioactive compounds. For all three products, cost calculations are available for the supercritical fluent extraction and the solvent extraction, explaining the separate treatment. The applications for food are mainly by usage of bioactive compounds through extraction or fermentation. The applications for fuel production mainly concern biogas production.

Table 1: Overview of valorisation techniques for agricultural biomass side-streams (sorted by TRL)

Research Results For Agriculture						
	Biomass side stream	**Applied in**	**Technique**	**Output**	**5Fs**	**TRL**
1	Brewer spent grain	Belgium	Extraction	Plant sterols	Food	3
2	Corn fibre	Hungary	chemical fractionation, enzymatic hydrolysis, biopurification, fermentation, purifications, separations	Xylitol Arabinose ethanol biomethane, digestion residue	Food, fine chemical, fuel, fertilizer	3
3	Manure and other organic waste	Hungary	Biodigestion - codigestion	biogas	Fuel	3
4	Olive biomass	Spain	Steam explosion	Antioxidant, sugars	Food and fine chemical	3
5	Olive prunings	Spain	Hydrolysis and fermentation	Ethanol, antioxidants, oligosaccharides, lignin-derived chemicals	Fuel and fine chemical	3
6	Sewage sludge and manure	Sweden	Anaerobic digestion and incineration	Energy, phosphate	Fuel and fertilizer	3
7	Yeast	Belgium	Extraction	Squaleen, Phospholipids	Food, fine chemical	3
8	Brewer spent grain	EU	Enzyme-aided fractionation	FAX, peptides	Food	4
9	Leek leaves	Belgium	Fermentation	Lactic Acid	Food	4
10	Olive crop residues	Spain	Isolation	New agrifood components	Food, feed, fine chemicals	4

11	Vegetable trimmings	EU	Liquefaction	Soluble colorant	Food and fine chemical	4
12	Agroindustrial waste water	Spain	Microalgae and bacteria	Biofertilizer and biogas	Fertilizer and fuel	4-5
13	Brewery wastes	Spain	Microalgae	nitrogen and phosphorous micro-algae biomass	Fertilizer and feed	4-5
14	Low value biogas	Spain	Purification	Valuable biomethane	Fuel	4-5
15	Rape, sugar-beet waste, other green plant biomass	Hungary	Acidification and gasification	Fermented biomass and energy	Fertilizer and fuel	5
16	Vegetables, corn	Hungary	Microbial fermentation	Lactic acid, ethanol, bio-energy	Fine chemical, fuel	6
17	Sugar beet, pig slurry and cow manure	Spain	Anaerobic digestion	Methane and fertilizer	Fuel and fertilizer	7
18	Vegetable waste	Spain	Green extraction	Food additives, biopolymers	Food, functional material	7
19	Vegetable waste	Spain	Green extraction	Bioactive compounds	Food, functional materials	7
20	Olive stones	Spain	Marine organisms	Proteins and enzymes	Food and feed	7
21	Orange skin and other agrifood byproducts	Spain	Dehydration and Pelletizing	Animal feeding	Feed	7
22	Blood (pigs, cows)	Italy	Sterilization, coagulation and separation	Recycled water and biogas	Fuel	8

23	Animal waste (bone)	Hungary	Anoxic heat treatment	Biochar	Fertilizer	8
24	Dairy serum	Spain	Inverse osmosis and ultrafiltration	Biogas, concentrate of proteins concentrate of lacteal whey, feed, food and supplements	Feed, Food, Fuel	9
25a	Grape pomace	Italy	Supercritical fluent extraction	Reserveratrol, anthocyanins, proantho-cyanidins, quercetin, grape seed oil	Food, fine chemical	9
25b	Grape pomace	Italy	Solvent extraction	Reserveratrol, antho-cyanins, proantho-cyanidins, quercetin, grape seed oil	Food, fine chemical	9
26a	Olive processing waste	Italy	Supercritical fluent extraction	Polyphenol, hydroxytyrosol Oleuropein	Food	9
26b	Olive processing waste	Italy	Solvent extraction	Polyphenol, hydroxy-tyrosol, Oleuropein	Food	9
27	Sewage sludge, green waste, production residue from the food industry, straw or animal excrement	Germany	Heating and condensation	electricity heat gas oil	Fuel, fertilizer, fine chemical	9

28a	Tomato pomace	Italy	Supercritical fluent extraction	Lycopeen, fibre, seed oil, enzymes	Food	9
28b	Tomato pomace	Italy	Solvent extraction	Lycopeen, fibre, seed oil, enzymes	Food	9
29	Olive mill waste	Spain	Anaerobic Digestion, Catalityc reforming and Use of proton exchange membrane fuel cells	Biogas, hidrogen, energy	Fuel	9
30	Vineyard waste, grape seed residue	Hungary	Special pretreatment of the residues (patented application)	Fertilizer	Fertilizer	9

Conclusions on the agricultural biomass side-stream valorisation techniques

When analysing all the data and literature gathered, it was noticed that a lot of attention is paid to techniques generating energy. However, the majority of these techniques are already operational. Most of the techniques concern fermentation of agricultural crop residues producing biogas (bio-methane) as output. When analysing the identified research results (TRL 3-9), it can be seen that the focus is shifting from techniques resulting in energy output to other techniques, with a higher valorisation potential. For example, extraction and fractionation to obtain different compounds with antioxidant capacity such as oleuropein, hydroxytyrosol and flavonoids (luteolin, apigenin) are increasingly applied. These compounds have great commercial interests in the food and pharmaceutical sectors due to the beneficial properties (food preservation, bioactive food, protection against different cancers, hypertension, diabetes, etc.) and the trend of using natural products to synthetic, by using for example biopolymers.

Also effects of specific regional available biomass side-streams can be seen. In Spain, for instance, we see a lot of research techniques about valorisation of olive biomass, which are mostly characterized by a low TRL-level (3-4).

From Table 1 it follows that 15 research techniques are producing products used in Food applications, 11 techniques result in Functional material or Fine chemical products, 11 techniques are producing Fuels, 6 techniques produce Fertilizers and 4 techniques produce Feed. 12 of the 30 techniques result in only one F category output product, while most (18) of the techniques result in two or more products. 4 techniques result in both Food and Fine chemical output products. And also 4 techniques result in both Fuel and Fertilizer output products.

2.2 Research results of valorisation techniques for agriculture/forestry biomass side-streams

An overview of Valorisation techniques found that are applicable for both **agriculture and forestry biomass** side-streams is presented in Table 3.

Table 2: Overview of valorisation techniques for agricultural/forestry biomass side-streams (sorted by TRL)

Research Results for Agriculture and Forestry						
	Biomass side stream	**Applied in**	**Technique**	**Output**	**5Fs**	**TRL**
1	Leguminous plants of high efficiency in biomass	Spain	Hydrolysis, combustion, gasification, pyrolysis for lignocellulosic material Composting for biomass residues	Biogas, Compost	Fuel, Fertilizer	3
2	Construction timber wastes, wood residues, sewage sludge, organic refuse	Ireland	Slow Pyrolysis	Bio-char	Fertilizer	4
3	Wood, straw, flax and cotton	Belgium & other countries	Bio-refinery	Sugar	Fine chemical	4
4	Wood, wood chips, Miscanthus	Ireland	Fast Pyrolysis	Bio-oil	Fuel, Functional materials	4
5	Wood chips, straw, other herbaceous plants	Netherlands	Pyrolysis	Biogas, bio-oil, bio-char	Fuel, functional material, fertilizer	5

6	Wood chips (willow) and straw	Netherlands	Organosolv fractionation	(hemi)cel-lulose and high purity lignin, ethanol, bio-oil, bio-char, heat	Functional materials	6
7	Wood residuals (also rice husk, bagasse, sludge, tobacco, energy crops, palm-oil residues, straw, olive stone residues, chicken manure were tested)	Netherlands	Pyrolysis	Pyrolysis-oil	Fuel	7
8	Wood waste and agricultural crop waste	Netherlands	Gasification	Electricity, Heat	Fuel	7
9	Fruits, vegetables, waste and sub-products from agro-food industry (broths, juices, pulps…), manure, slurry, sludges, forestry waste	Spain	Arthropods	Insect fat, Quitin, Hydrolysates	Feed, fine chemical, functional material, fuel, fertilizer	7

10	Wood residues, wood chips, agricultural crops (e.g. Miscanthus) and crop wastes (e.g. straw)	Netherlands	Torrefaction, pelletisation	Bio-pellets	Fuel	9

Conclusions on the agricultural/forestry biomass side-stream valorisation techniques

Most of the techniques found (7 out of 10) produce products that can be classified as Fuel (e.g. biogas, heat, steam, bio-oil etc.). 5 techniques produce fertilizers (mainly bio-char, compost and nutrients), and also 5 techniques produce Functional materials / Fine chemicals. Some techniques (5, mainly pyrolysis) produce more than one F-related output. From Table 2 it follows that RTDs mainly aimed at fuel production have higher TRL levels than RTDs aimed at the other Fs like Fine chemicals, Functional materials and Fertilizers. No techniques for combined forestry and agriculture biomass-side-streams were found that produce products applicable for the food sector. Although this might be an option for some side-streams (especially for protein and sugar rich biomass) it seems that this usage is more applicable when using only agricultural biomass side-streams.

2.3 Research results of valorisation techniques for forestry biomass side-streams

For **forestry biomass side-streams** pyrolysis, gasification, fractionation, fermentation and saccharification are the most applied techniques. Most applications of the woody based output products are for Functional materials (fibres, active carbon), Fine chemicals (e.g. ethanol, glucose, lignin), Fuel (e.g. pyrolysis oil) and Fertilizers (bio char) (Table 3).

Table 3: Overview of valorisation techniques for forestry biomass side-streams

Research Results For Forestry						
	Biomass side stream	**Applied in**	**Technique**	**Output**	**5Fs**	**TRL**

1	Tree bark	Hungary	Chipping	Bark chips for insulation	Functional materials	3
2	Kraft Birch Pulp	Finland	Ionic liquid extraction	Xylan	Food	4
3	Kraft Birch Pulp	Finland	Fibrillation	Fibrillated cellulose	Food	4
4	Acorns of Quercus ilex	India	Pyrolysis	Active carbon	Functional material	4
5	Waste paper sludge (paper industry)	Japan	Fermentation and Sacchari-fication	Bio-ethanol	Fuel / Functional materials/ Fine Chemicals	4
6	Wood residues (Beech xylem and Poplar Wood chips)	France	Transglycosi dation pretreatment and Concentrated acid and enzymatic sacchari-fication	Glucose and lignin	Functional materials / Fine Chemicals	4
7	Forestry Biomass	Spain	Chipping and pelletizing	Pellet and wood chip, Thermal energy	Fuel	9
8	Wood chips and peat	Finland	Fast pyrolysis	Electricity, heat, pyrolysis oil	Fuel	9

Conclusions on forestry biomass side-stream valorisation techniques

Of the RTDs presented in Table 3, 3 techniques produce products used as Fuel (e.g. ethanol, heat, steam, pyrolysis oil). 4 techniques produce Functional materials/Fine chemicals like insulation material, active carbon, ethanol, lignin, and glucose. No technique

is producing fertilizer, however the char produced by pyrolysis, now used as functional material, can also be used as fertilizer. 2 techniques produce Food additives.

From Table 3 follows that research techniques with a lower TRL level (3-4) are techniques producing functional materials, fine chemicals and food additives, while techniques with higher TRL levels are mainly producing fuels for energy production. This can be explained because energy production techniques started (much) earlier than techniques producing chemicals and functional materials, which are also more complex. The latter techniques need well developed knowledge on chemical processes and smart techniques to extract pure chemical components. This kind of science just seriously started some decades ago but now is increasing vast in number of researches and applications.

Hub Hungary

The focus of the Hungarian biomass side stream valorisation lays on valorisation of agricultural wastes such as crop residuals (e.g. corn, wheat, rape, sugar beet) and animal manure (e.g. poultry, rabbit). The biomass side-streams are mainly used to produce fuel (e.g. biogas, bio-oil). Little side-streams are used to produce fertilizers and functional materials or fine chemicals. No examples were mentioned for valorization as food or feed.

Hub Andalucía

Information from the Spanish hub shows that olive wastes (e.g. olive stones, , olive leaves, olive tree pruning) are used to produce all 5Fs. Several crop residues (e.g. vegetables, sugar beet, leguminous plants) are used for production of fuel, fertilizer and functional materials and fine chemicals. Animal manure (cows and pigs) and agricultural industrial waste water are used to produce fuel and fertilizers.

Hub Ireland

In the Irish hub, the focus of submitted information is on forestry biomass side-streams. Side-streams from the wood processing industries (e.g. sawdust, mill scrap, wood chips) are mainly used for fuel production. A higher level of valorisation is developed through side-streams usage for functional materials and fine chemicals (e.g. woodchips, wood residues and Miscanthus). Beside these side-stream usage, also agricultural biomass side-streams are available and used in Ireland. They, however, are mostly processed with techniques applicable for both agricultural and forestry side-streams. Techniques developed for the valorization of agricultural side-streams only were not identified in this project.

Table 4: Main biomass side-streams related RTD and predominant application fields per hub

5Fs	Hub			RTD
	Hungary	Spain	Ireland	
Food	corn fibre	Fruit and vegetable waste olive seeds, dairy serum, forestry waste		extraction isolation fractionation hydrolysis fermentation steam explosion, milling, inverse osmosis, filtration
Fuel	corn fibre, rape waste, sugar beet waste	sugar beet waste pig slurry cow manure agro industrial waste water olive stones olive tree pruning olive leaves brewery waste leguminous plant waste, dairy serum, fruit waste	Miscanthus wood residuals, wood chips	fermentation hydrolysis pyrolysis grinding
Feed		olive seeds brewery waste, fruit and vegetable waste, forestry waste		fermentation milling algae biomass growth
Fertilizer	corn fibre, vegetable waste, corn waste, slaughterhouse waste (bones)	sugar beet waste olive waste pig slurry cow manure agro industrial waste water brewery waste leguminous plants	sewage sludge construction timber wastes wood residuals organic waste	bio-extraction bio-refinery purification separation fermentation pyrolysis, arthropods

Functional material/ Fine chemical	vegetable waste corn waste tree bark	Fruit and vegetable waste olive stones olive seeds olive tree pruning olive leaves	Miscanthus wood residues wood chips	extraction fermentation chipping

3. Conclusions

To be resource efficient, industrial processes must be very efficient in process energy used as well as in use of the entire feedstock. Besides the main product, most industrial processes are also producing side-stream products. In the past, these side-streams were mostly seen as waste (e.g. sawmill scrap, crop residuals from agriculture etc.). To make the industrial processes more efficient, more profitable and more sustainable, valorisation of these side-streams is of great importance.

Increasingly, research is conducted focusing on bioactive and chemical substances. A transition in the chemical sector is visible from focus on fossil raw materials to bio-based/ renewable resources. Scientist see huge potential in this kind of research. There is a need for new bio refinery processes that valorise more constituents out of the side-streams such as proteins, lignin, fat, cellulose. Also the isolation of sugar out of biomass side-streams obtaining high degrees of lignocellulose could be applied for fermentation and chemical catalysis instead of fossil raw materials. In the food industry, phenols, colorants, peptides, sterols, lipids, fibres, enzymes, acids, etc. could be used as food supplements or neutraceuticals, to increase dietary fibre content, to increase anti-oxidant capacity, etc.

Therefore, AGRIFORVALOR has worked on the collection and analysing of data on available qualities of biomass side streams (See results section 2) and techniques that cover the range from lab to close to the market (from literature, other research projects, the internet and consultation of research centres and the hub managers) and which are still not fully known or tested by practitioners (Table 2, 3 and 4). The results will be disseminated to the hub partners of the project, to which biomass related stakeholders are connected. They will be further disseminated in hub launch meetings and RDI workshop of WP2. Also an internet application to demonstrate the results will be developed (side-stream-valley-tool). Through this, the results contribute to an improved flow of information and knowledge between academia and practitioners in particular on agricultural and forestry RTD results in order to deploy the vast reservoir of existing scientific knowledge and to further exploit existing knowledge.

So far, the consortium identified 30 research techniques applicable to agricultural related biomass side-streams, 10 research techniques applicable to both agricultural and forestry related biomass side-streams and 8 research techniques applicable to forestry related biomass side-streams. Different techniques are found to valorise biomass side-streams as described in sections 2.1 to 2.3.

All RTD techniques and related side-streams can be looked at in more detail from the sidestream valley tool, to be ready after 20.09.2016.

From these techniques collected, roughly five types of biomass side-stream valorisation can be distinguished:

1. Production of functional materials, fine chemicals and food additives for food applications
2. Production of bio-energy and biofuels for energy production
3. Production of (fine) chemicals and functional materials for production of utensils
4. A combination of energy production, (fine) chemicals and/or functional materials
5. Production of fertilizers for improvement of soil fertility of agricultural land

The results show that mainly agricultural biomass side streams are used to produce products for food applications. This probably is due to the calorific value of this biomass.

RTD results and related from agriculture related biomass side-streams

From the 30 RTDs collected for agricultural related biomass side-streams, 15 techniques are producing products for Food applications, 11 techniques result in Functional material or Fine chemical products, 11 techniques produce Fuels, 6 techniques produce Fertilizers and 2 techniques produce Feed. 12 of the 30 techniques result in only one F category output product, while most (18) of the techniques result in two or more F category products.

RTD results and related applications from combined agriculture and forestry related biomass side-streams For combined agriculture and forestry biomass side-streams, most of the techniques found (7 out of 10) result in products that can be classified as Fuel (e.g. biogas, heat, steam, bio-oil etc.). 5 techniques produce Fertilizers (mainly bio-char, compost and nutrients), and also 5 techniques produce Functional materials / Fine chemicals. Some techniques (5, mainly pyrolysis) produce more than one F-related output. From Table 2 it follows that RTDs mainly aimed at fuel production have higher TRL levels than RTDs aimed at the other Fs like Fine chemicals, Functional materials and Fertilizers. No techniques for combined forestry and agriculture biomass-side-streams were found that produce products applicable for the food sector. Although this might be an option for some side-streams (especially for protein and sugar rich biomass) it seems that this usage is more applicable when using only agricultural biomass side-streams.

RTD results and related applications from forestry related biomass side-streams

For forestry related biomass side-streams, 3 techniques found produce products used as Fuel (e.g. ethanol, heat, steam, biogas, pyrolysis oil). 4 techniques produce Functional

materials/Fine chemicals like insulation material, active carbon, ethanol, lignin, and glucose. 2 techniques are producing Food additives. No technique is producing fertilizers.

Research techniques applied on woody biomass side-streams with a lower TRL level (3-4) are techniques producing functional materials, fine chemicals, and food additives, while techniques with higher TRL levels are mainly producing fuels for energy production. This can possibly be explained because energy production techniques started (much) earlier than techniques producing chemicals, functional materials, and food which are also more complex.

General findings on output related research results (5Fs)

Fuel

Almost all biomass-side streams, both from agriculture and from forestry, can be used for energy production. Most used techniques for energy production have a higher TRL and hence are in a further development stage and close to the commercial market for upscaling. The techniques used for the production of fuel are mainly digestion of crop residues resulting in biogas and fermentation or pyrolysis of woody biomass resulting in ethanol and bio-oil. Hence, in earlier research techniques (lower TRL), there is an increasing focus on techniques with a higher valorisation potential of biomass side-streams.

Fertilizer

Also fertilizers are produced, but mainly as side product (e.g. bio-char) of a stepwise bio-refinery process or as a side-product of biogas or bio-oil production. Only few techniques (composting, pyrolysis) are used for producing fertilizers as main product. Fertilizers are produced both out of agricultural and forestry biomass side-streams, separate and combined.

Fine chemicals / functional materials

For the production of bioactive and chemical compounds, techniques as extraction, enzymatic fractionation, and organosolv fractionation are applied. The type of technique is depending on the quality of the biomass side-stream and on the compound to produce.

Pyrolysis and gasification are techniques resulting in a combination of energy production (e.g. heat, steam), fuels (e.g. pyrolysis oil, ethanol) and chemicals (e.g. acetic acid, lactic acid) and functional materials (e.g. high purity lignin, hemicellulose).

Food/Feed

Research techniques producing food additives (e.g. colorants, fibres, sugar, proteins), functional materials and fine chemicals mostly have a lower TRL level (3-6) than techniques producing fuels for energy production (TRL 7-9). This can be explained because energy production techniques started (much) earlier than techniques producing chemicals and functional materials. The latter techniques are more complex, and need well developed knowledge on chemical processes and smart techniques to extract the chemical components with a high purity. This kind of science just seriously started some decades ago but now is increasing vast in number of researches and applications.