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Review

Analysis of the EU Secondary Biomass Availability and Conversion Processes to Produce Advanced Biofuels: Use of Existing Databases for Assessing a Metric Evaluation for the 2025 Perspective

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Abstract: Nowadays in Europe, the production of advanced biofuels represents a very important objective, given the strong interest in increasing sustainability throughout the transport sector. Production and availability of advanced biofuels are cited as a relevant issue in the most important international actions, such as the Sustainable Development Goals in UN Agenda 2030, EU RED II, and EU Mission Innovation 4, to cite a few of them. However, an important aspect to be considered is the prediction of feedstocks availability to produce advanced biofuel. The first aim of this paper is to assess the availability of European agricultural residues, forestry residues, and biogenic wastes in 2025. The data were collected through a deep review on open FAOSTAT and EUROSTAT databases and then elaborated by the authors. The analysis focuses on the fraction of feedstocks that can be used for advanced biofuels production, i.e., incorporating specific information on sustainable management practices, competitive uses, and environmental risks to preserve soil quality. An autoregressive model is developed to predict future availability, while also considering corrections due to the current pandemic. The results suggest that several European countries could produce enough sustainable advanced feedstocks to meet the European binding target. In particular, France, Germany, and Romania will have high production of agricultural feedstocks; while Austria, Finland, and Sweden will be rich of forestry residues; finally, Italy, France, and United Kingdom will have the highest availability of wastes. To complete the picture, a proper metric is introduced, aiming at generating a technology ranking of the examined alternative fuels, in terms of several relevant parameters such as biomass availability, Technology Readiness Level (TRL), quality of the biofuel, and costs. This analysis allows us to compare advanced biofuels and first-generation biofuels, whose utilization can impact the food market, while also contributing to the increase in the indirect land use change (ILUC). Although the first-generation biofuels remain the most common choice, the renewable (or green) diesel, pyrolysis bio-oil, green jet fuel, and the second-generation bioethanol are promising for different applications in the transport sector. Hydrotreated Vegetable Oils (HVO), Hydroprocessed Esters and Fatty Acids (HEFA), Anaerobic Digestion (AD), and transesterification from vegetable oil represent the most widespread and mature technologies. Thus, it seems mandatory that the transport sector will rely more and more on such fuels in the future. For such reason, a specific support for advanced biomass collection, as well as specific programs for conversion technologies development, are strongly suggested.

Keywords: advanced biofuels; prediction; sustainable feedstocks availability

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1. Introduction

In recent years, several EU policies introduced binding targets to be met by 2030, aiming at decarbonizing the European economy in many market segments, including the transport sector.

In 2009, the European Directive on the Promotion of Renewable Energy (2009/28/EC) (RES) [1] defined the objectives for the bioenergy development by 2020. The so-called "20–20–20" objectives set the reduction in greenhouse gases (GHG) emissions by 20% compared to those of 1990; the reduction in basic energy consumption by 20% and finally, the 20% as share of renewable energy (including bioenergy) in overall energy consumption. Additionally, the Directive endorsed a mandatory 10% minimum target for the share of renewable energy (mainly biofuels) in the transport energy consumption by 2020. From the point of view of the transport sector, practical and economic issues emerged, since the first-generation biofuels, directly related to a competition with edible biomass, showed severe drawbacks in terms of their impact on food crop prices, land use changes, and ecological damage. Then, new efforts were made to guarantee food security, health, energy, economic growth, and promotion of rural development, raised by UN Agenda 2030 for Sustainable Development [2].

Specific prescriptions were also introduced in the revised Renewable Energy Directive, (RED II) [3] which proposed binding targets, to limit first generation biofuels, and redirect public subsidies from crop-based to advanced biofuels that are produced by processing secondary biomasses like wastes, residual, or non-edible vegetables, as well as forestry products. According to the RED II, the contribution of advanced biofuels and biogas must reach a minimum threshold equal to 0.2% in 2022, 1% in 2025, and 3.5% in 2030 as a share of final energy consumption in the transport sector.

In recent years, many international events were summoned to discuss and support the most relevant aspects related to energy and environment, like the International Conference on Energy and Environment Research (ICEER). Among the main topics, there are just the advanced energy technologies, biomass, and bio-based products, as well as the efficient use of the resources, the ecology, and biodiversity conservation [4,5].

To ensure the fulfilment of these goals, European countries are assessing the economic impacts deriving from the introduction of such regulations aiming to support the reaching of the targets, even if the large-scale adoption of advanced biofuels remains largely uncertain.

The potential growth of the advanced biofuels, as well as their competitiveness, can be supported by the increase in crude oil prices and from technological progress in biofuels' production [6]. To encourage the transition toward the bioeconomy pathway, European Directives still provide subsidies (i.e., Horizon 2020 Program [7] and Horizon Europe to cite one of them) to support the development of the whole process, including feedstocks characterization, experimentation, and industrialization of the bioenergy industry. It is expected a reduction in the investment risk as well as the production costs thus supporting the use of advanced biofuels in place of fossil fuels.

Despite the mentioned critical issues, today, advanced biofuels represent a sustainable alternative to fossil fuel due to their properties similar to petroleum-derived fuels such as diesel, gasoline, or fuel oil [8]. This implies their direct use as fuels for on-road vehicles, industrial boilers, merchant vessels, trains, etc. On the other hand, it is very difficult to produce advanced bio-jet fuel with the proper quality [9] for the aviation sector.

In the field of advanced biofuels, the research activities are focused on assessing two main objectives: the future availability of sustainable biomass feedstocks, useful for reaching the targets, and the varying degrees of maturity and the costs of different technologies as reported in ref. [3].

Here, three categories of feedstocks, abundant in EU, are analysed: wastes, crops, and forestry residues. The available quantities are assessed, taking into account the quantity to be subtracted for guaranteeing the preservation of soil quality and other agricultural uses. To assess the future availability of feedstocks by 2025, a model based on auto-regressive methodology is presented and applied, also considering an ad-hoc correction accounting for the impact of the current pandemic situation on the development of the advanced biofuels for the transport sector. The outcome of the analysis could help understanding the existing trends in the residues' availability for advanced biofuels production and quantifying possible effects in terms of economic and technological improvements. Biofuel properties, like feedstock compositions and manufacturing processes [8], are reported and analysed. Then, the available technologies are assessed according to their Technology Readiness Level (TRL), which represents a widely accepted standard for ranking the maturity of the different solutions [10]. As a result, a metric for ranking the different solutions is proposed in order to detect the most appropriate technologies for advanced biofuel production.

2. Methodology

2.1. Databases

The study assessed the availability of sustainable feedstocks to produce advanced biofuels in the European Countries in 2025. As already mentioned, the feedstocks are divided into three main categories: Wastes, Crop, and Forestry residues, whose data were collected from EUROSTAT and FAOSTAT databases. In Table 1, each category is summarized indicating the source of dataset with its reference years, data format, location, and 2025 estimate.

Table 1. Summary of Categories, Datasets, Time Series and Locations, Provisional horizon implemented by the model.

Category	Dataset	Data Format	Past Interval	Location	Provisional Interval
Biogenic wastes	EUROSTAT [11]	Excel	2008, 2010, 2012, 2014, 2016	Europe/Europe List	By 2025
Agricultural residues	FAOSTAT [12]	Excel	2014–2018	Europe/Europe List	By 2025
Forestry residues	FAOSTAT [13]	Excel	2014–2018	Europe/Europe List	By 2025

Crops data were extracted by the FAOSTAT database [12] and twelve different crops were analysed: barley, oats, olives, corn, wheat, soybeans, rapeseed, sunflower, sugar beet, rice, rye, and triticale. These crops were chosen among the European most produced crops, mainly used in the bioenergetic sector. To determine their availability for the advanced biofuels production, data were manipulated by deducting the biomass main use (e.g., food) [14] i.e., by introducing residues to production ratio (RPR) and the residual part destined for competitive uses such as power, heat, or other (i.e., horticulture, feed or animal bedding). To preserve the soil quality, it is recommended that part of residues should be left on the fields. This percentage varies from country to country as illustrated in ref. [15].

Forestry production was estimated from FAOSTAT database [13]. Such products include wood fuels, saw logs and veneer logs, pulpwood (round and split), and other industrial roundwood coming from both coniferous and non-coniferous roundwood. These last categories differ for their density, whose values are shown in [16]. To assess the residual part, different residues to production ratios (RPR) are here considered according to the type of roundwood and location (Northern European and all the other European Countries) [15]. To compute the sustainable fraction of forestry residues, all competitive uses and environmental impacts should be hereby considered, such as the residual part left on soil to prevent ground erosion, and the use of heat and power for the industrial sector.

Finally, wastes availability data were taken from EUROSTAT [11], and they include all hazardous and non-hazardous wastes sent to landfill or disposed as reported in the disposal operations labelled with D1 to D7, D10, and D12 in ref. [17] and summarized in Table 2.

Table 2. Type of wastes and disposal operations selected from [17].

Category	Specific Disposal Operations [17]
Paper and cardboard wastes Household and similar wastes Animal and mixed food waste Vegetal wastes Animal faeces, urine and manure Wood wastes Sorting residues Common sludges	D 1 Deposit into or on to land (e.g., landfill, etc.) D 2 Land treatment (e.g., biodegradation of liquid or sludgy discards in soils, etc.) D 3 Deep injection (e.g., injection of pumpable discards into wells, salt domes or naturally occurring repositories, etc.) D 4 Surface impoundment (e.g., placement of liquid or sludgy discards into pits, ponds or lagoons, etc.) D 5 Specially engineered landfill (e.g., placement into lined discrete cells, which are capped and isolated from one another and the environment, etc.) D 6 Release into a water body except seas/oceans D 7 Release to seas/oceans including sea-bed insertion D 10 Incineration on land D 12 Permanent storage (e.g., emplacement of containers in a mine, etc.)

2.2. *The Autoregressive Model*

In the autoregressive model, future values of feedstocks availability are correlated with real past values and their evolution in time [18]. This allows us to predict the availability of feedstocks aiming at meeting the advanced biofuels production needed to fulfil the European binding targets. Feedstocks quantity $Q(t)$ is described by the additive model [19], i.e., through the sum of three components: trend $T(t)$, seasonality $S(t)$, and randomness $A(t)$, as shown below:

$$Q(t) = T(t) + S(t) + A(t) \tag{1}$$

The trend T describes feedstocks increasing or decreasing in the medium-long term. It is related to the systematic events occurred throughout the observation period. Trends can be constant, linear, polynomial, hyperbolic, exponential, or asymptotic [20]. In this study, the trend component is assumed to be linear, as illustrated in Equation (2) and in Figure 1a, since in the first instance, it is the simplest way to represent the behaviour of the recent data of feedstocks availability (Table 1):

$$T(t) = a + bt \tag{2}$$

The coefficient a and b are computed by the least square method [21], as reported in Equations (3) and (4), i.e., the trend line has to minimize the offset between the real values and those represented by the line itself.

$$a = \frac{\sum_i^{Np} Q(t_i)}{Np} = \overline{Q} \tag{3}$$

$$b = \frac{\sum_i^{Np} Q(t_i) \cdot t_i}{\sum_i^{Np} {t_i}^2} \tag{4}$$

The a and b coefficients are properly obtained by discretizing the time axis in Np. intervals (where i is the i-th interval) and positioning the time axis origin at the centre of the data. For completeness, the trend line, computed through the model, is illustrated in Figure 1a, only for the sunflower residues.

The seasonality represents data fluctuations around the trend line due to circumstances periodically appearing in each time interval. In this case, the time series is divided in periods with the same duration. Each period, in turn, is then divided in an equal number of intervals j with the same behaviour. For the j-th interval, the corresponding seasonality index S_j is computed as follows Equation (5):

$$S_j = \frac{\sum_1^N \Delta}{N} \left(\sum Sj = 0\right) \tag{5}$$

where $\Delta = Q(t_j) - T(t_j)$ and N is the number of period where there is seasonality. S_j. represents the average of the corresponding offset on the j-th interval. This process can be called seasonal adjustment of the time series [22]. By adding up the trend and the seasonality values, we get for example a behaviour illustrated in Figure 1b for sunflower residues.

Generally, the estimated feedstocks quantity $\widetilde{Q}(t)$, in terms of trend and seasonality $(T(t) + S(t))$, does not match the actual feedstocks quantity. There is a residual for each Np (period of observations) computed as follows Equation (6):

$$R(ti) = Q(t_i) - \widetilde{Q}(t_i) \tag{6}$$

Therefore, the performance indices as bias Equation (7) and root means square error Equation (8), deriving from the statistics, are introduced in the random component of the predictive model:

$$bias = \sum_{i=1}^{Np} \frac{R(t_i)}{Np} \tag{7}$$

$$\sigma_A = \sqrt{\sum_{i=1}^{Np} \frac{R(t_i)^2}{Np}}. \tag{8}$$

The bias sums all residues with their sign without filtering the compensation effects. Depending on whether the sign of bias is positive or negative, the quantity will be underestimated or overestimated, respectively. If bias has zero value, then the quantity is correctly estimated. The root means square error σ_A. measures the spread of data with respect to the average value of feedstocks quantity.

Assuming a Gaussian distribution of probability, the random component will be estimated as in Equation (9) and it is then added to the estimated quantity $\widetilde{Q}(t)$. By way of illustration, the estimated quantity is reported in Figure 1c,d for the sunflower residues according to different values of k.

$$A(t) = \text{bias} \pm \text{k}\sigma_A \tag{9}$$

where k is the confidence level of the distribution, whose values are reported in Table 3.

Table 3. Confidence levels k for the gaussian distribution of probability [23].

Confidence Level	80.0%	90.0%	95.0%	99.0%	99.9%
K	1.28	1.64	1.96	2.58	3.29

In the present analysis, k is chosen equal to 1.96, i.e., there is a 95% probability that the actual feedstocks availability falls inside the curve whose points represent the feedstocks availability estimated by the model (Figure 1d).

Based on these theoretical considerations, the model was developed, and all the collected data were implemented to assess the availability of advanced feedstocks in 2025.

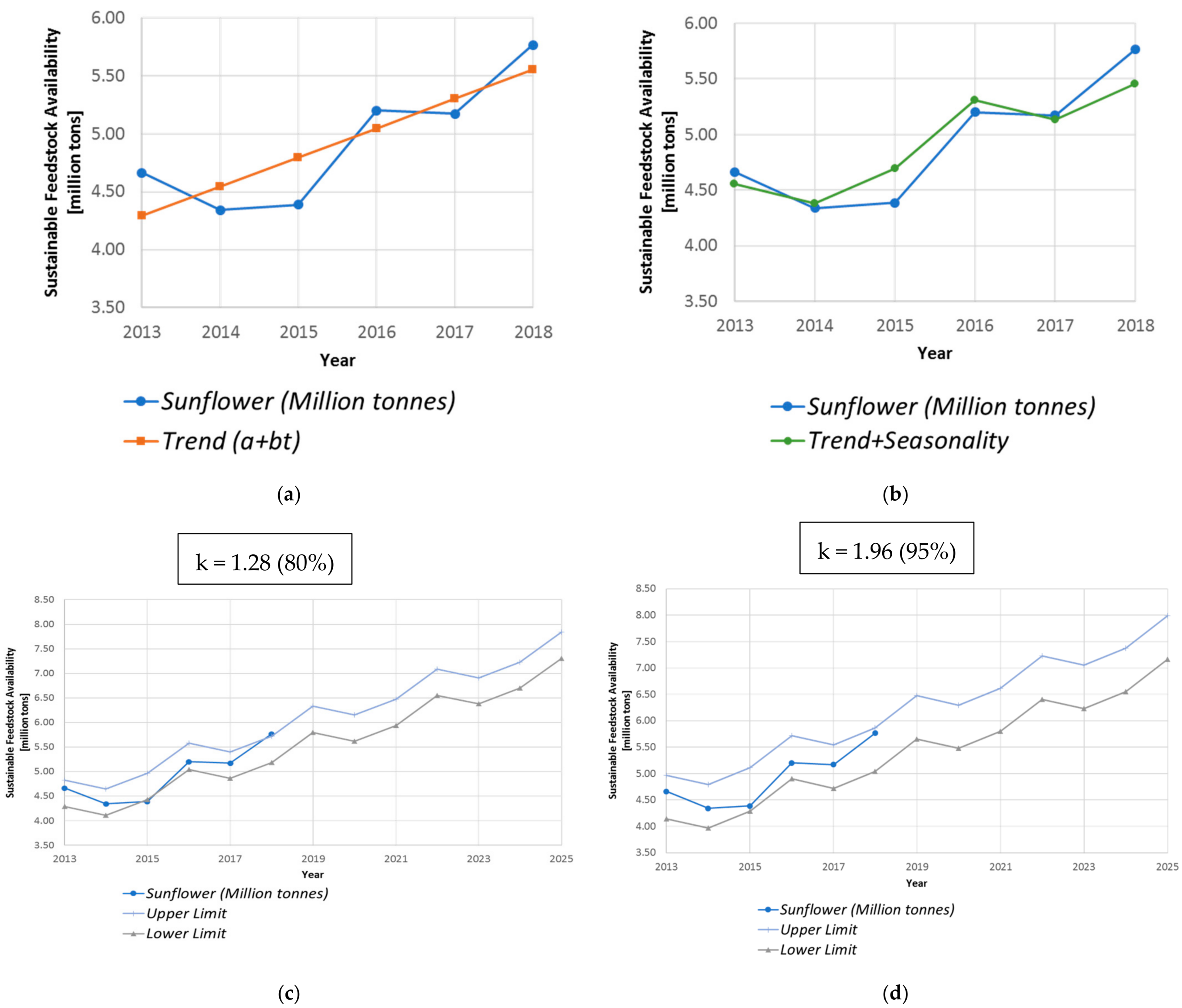

Figure 1. (**a**) Residues of sunflower seed and the trend line calculated by the model; (**b**) Residues of sunflower seed and the sum of the trend with the seasonality calculated by the model; (**c**) Residues of sunflower seed and the sum of trend, seasonality, and randomness for k = 1.28 calculated by the model; (**d**) Residues of sunflower seed and the sum of trend, seasonality, and randomness for k = 1.96 calculated by the model.

2.3. COVID-19 Related Correction of the Autoregressive Model

Lockdowns related to the spreading of COVID-19 pandemic, have altered all aspects of our lives from the basic necessities to the personal and professional interaction. In less than a year, the intensification of smart working led the daily commute to be upended. Thus, the impacts of the COVID-19 have been more readily apparent in the transport than in other energy sector all over the world. This involves the biofuels production for transport too. Indeed, although the global transport biofuels production reached 162 billion litres in 2019 (17.5 billion litres in Europe), to date the production is expected to be contracted for the next two years by 5% [24].

In Europe, IEA forecasts a 13% reduction in biodiesel and Hydrotreated Vegetable Oils (HVO) production and a 12% reduction in ethanol for 2020, due to significant reduction in demand across the continent [24]. Moreover, a lowering of crude oil prices has made biofuels less competitive with fossil transport fuels. Even if biofuel prices also fall to a lesser extent, the biofuels production will be an economic challenge for some plants [25].

To tackle the revenue losses and continue limiting greenhouse gases (GHG) emissions, local air pollution, noise, safety, and congestion issues, new strategical plans must be redesigned in terms of economic and political solutions. The real challenge will be to provide equitable and affordable access to safe mobility and to restore social inclusion and local economic development. As long as the transport biofuels consumption results are low due to Covid-19 crisis, the lowest affected sector is the transport of goods. Biorefining still remains one of the key strategies in the circular economy, essential to create or preserve jobs, as mentioned in current European facilities, which process residual biomasses.

Since this paper is analysing the sustainable lignocellulosic materials availability, rather than vegetable oils, whose utilization could be unsustainable and in competition with commercial oils production, only the percentage reduction in bioethanol is accounted for with the introduction of a correction in the prediction. Due to the high technological maturity, fermentation is the most used conversion process to produce bioethanol from lignocellulose. To determine the amount of fuel that can be produced from a given mass of biomass via sugar fermentation, mass ratio or biomass-to-fuel efficiency expressed as [kg/kg] is introduced Equation (10):

$$\eta_m = \frac{m_{bioethanol}}{m_{lignocellulose}} \tag{10}$$

Such value depends on feedstock's type and technological process [26]. As reported in [27], the theoretical maximum sugar fermentation efficiency from lignocellulosic materials is 325–530 L/dry ton (0.282–0.461 kg/dry kg [28]).

Therefore, the amount of corrected lignocellulosic feedstocks can be estimated as equal to:

$$m_{feedstock,\ corrected} = \frac{m_{bioethanol,old}\ (1 - 0.12)}{\eta_m} \tag{11}$$

where $m_{bioethanol,old}$ refers to the quantity of bioethanol produced without considering the COVID-19 effects. An example of application of the predictive model with and without correction is reported for sunflower in Figure 2.

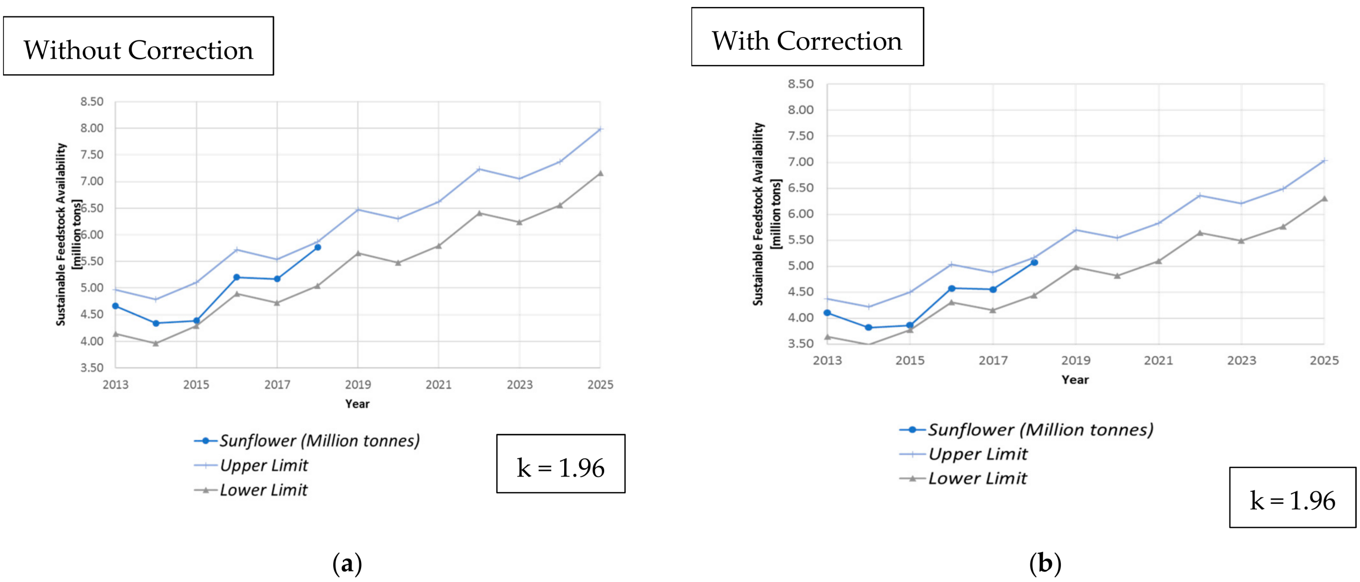

Figure 2. Availability of residues of sunflower without model correction: (**a**) residues of sunflower without the model correction, k = 1.96; (**b**) residues of sunflower the model correction, k = 1.96.

3. Results of the Implemented Model

3.1. Chemical Compositions and General Properties

Tables 4 and 5 show the agricultural residues characteristics relevant for biofuel production when considering biochemical and thermochemical conversion processes. Agricultural residues have high carbon and hydrogen content. This circumstance makes proper feedstocks for the gasification process, to get synthetic gas (e.g., syngas), that can be directly burned for cogeneration or further transformed in biofuels or valuable chemicals (e.g., through Fischer–Tropsch synthetic paraffinic kerosene SPK) [27].

Table 4. Ultimate endless of some crop residues chemical composition (% mass).

Crop Residues	Carbon (%)	Hydrogen (%)	Oxygen (%)	Nitrogen (%)	Sulphur (%)	Chlorine (%)
Wheat [29,30]	45.5–46.7	5.1–6.3	34.1–41.2	0.4	0.1	-
Rice (husks) [30]	37.9–44.6	4.82–5.6	33.7–49.3	0.43	0.17	-
Barley [31,32]	45	6.0	-	4.6	1.4	1.1
Maize [33]	45.5	6.2	47.0	1.3	-	-
Oats [31,32]	48	6.3	-	5.9	1.1	0.06
Rye (husk) [34]	75.6	-	18.9	-	1.3	-
Soybeans [35]	61.2	9.0	13.1	10.8	<0.1	-

Regarding biochemical processes, agricultural residues are the most interesting resource as they are rich in starch, sugar, and cellulose. Cellulose can be transformed in sugar, by enzymatic or acid hydrolysis, to eventually produce second generation ethanol [27]. The crops with higher cellulose share are wheat, barley, maize, and rice (Table 5). However, many feedstocks are rich of lignin, and they can be involved in further processes to get adhesives as co-product for applications like paper binding, medical tape, surgical glue, and engineered wood panels [27]. Finally, hemicellulose of herbaceous plants mainly contains xylan, which can be converted into solubilized monosaccharides (xylose) by hydrothermal liquefaction and upgraded to liquid fuels, platform compounds and valuable chemicals such as furfural, D-xylulose, glyceraldehyde, lactic acid, etc. [36].

Table 5. Cellulose, Hemicellulose and Lignin in the Crop Residues.

Crop Residues	Cellulose (%)	Hemicellulose (%)	Lignin (%)
Wheat (Straw) [30]	30–39.2	26.1–50.0	15–21.1
Sugar beet [37]	20	25	1–8
Barley (straw) [38]	31–45	27–38	14–19
Maize (straw) [39]	42.6	21.3	8.2
Oats (straw) [40,41]	26.6	21.3	24.8
Rice, paddy [42]	40.5	29	18.5
Rye [34]	26	16	13
Soybeans (hulls) [43]	33.49	17.15	9.88
Wheat (bran) [41]	32.2	28.0	5.2

The wood is characterized by 49% of Carbon [44], which makes it exploitable by both thermal and thermochemical processes to produce heat and power, as well as liquid and gaseous fuels, respectively. Nevertheless, no matter of the type of wood, there are high values of lignin (Table 6), which is a recalcitrant molecule that impedes polysaccharide accessibility and then its transformation into commercially significant products. In a biofuels production process, the removal of lignin is mandatory in the pretreatment phase [45].

Table 6. Cellulose, Hemicellulose and Lignin in the Forestry Residues [46].

Forestry Residues	Cellulose (%)	Hemicellulose (%)	Lignin (%)
Hardwood	40–44	15–35	18–25
Softwood	40–44	30–32	25–32

The available technologies for wastes belong to the class of the biochemical and thermochemical conversion processes according to wastes properties, recalled in Tables 7 and 8. High carbonaceous matter is favourably indicated for thermochemical processes like pyrolysis and gasification whose major products are the pyrolysis bio-oil, syngas, and ethanol, respectively. On the contrary, biological conversion processes, like the anaerobic digestion, produce biogas and biomethane as main fuels. However, high value chemicals are an economically viable and environmentally sustainable solution to recover valuable products from waste resources, since biorefinery platforms are mostly based on biofuels and chemicals too.

In this respect, main chemicals are manufacture lubricants, paints, inks, pharmaceuticals, and personal care products [27].

Some next-generation biological conversion processes can be applied on wastes to produce biohydrogen. These are dark and photo-fermentation, direct and indirect biophotolysis, microbial electrolysis cells, as well as microbial electro-hydrogenesis cells, as reported in ref. [47].

Table 7. Cellulose, Hemicellulose and Lignin content in various wastes [30].

Waste	Cellulose (%)	Hemicellulose (%)	Lignin (%)
Paper	85–99	0	0–15
Newspaper	40–55	25–40	18–30
Solid cattle manure	1.6–4.7	1.4–3.3	2.7–5.7
Wastepaper from chemical pulps	60–70	10–20	5–10

Table 8. Wastes chemical composition (% mass).

Waste	Carbon (%)	Hydrogen (%)	Oxygen (%)	Nitrogen (%)	Sulphur (%)	Chlorine (%)
Sewage Sludge (%) [48]	31	8.2	19.2	3.9	1.1	-
Paper (%) [49]	35.9	4.6	33.1	-	-	-
Garden Waste (%) [50]	26.8	3.3	22.5	0.56	0.06	0.10
Wood (%) [50]	46.0	5.9	41.3	0.20	0.03	0.04
Manure (%) [51]	35.4	4.7	57.5	2.4	-	-

3.2. Availability in Europe in 2025

Future values of agricultural residues for each European country are shown in Figure 3. The additive model, adopted here, allowed us to identify the upper and the lower limit of the crop residues availability at 2025.

France, Germany, and Romania showed the highest production of agricultural residues as they have the largest agricultural sector. Overall, the fraction of residues available for advanced biofuel production ranges between 10 and almost 25 Mt (2025 estimate). In view of the pandemic, the corrected values could be between 8.8 and almost 22 Mt in the same year. In recent years, Romania recorded increasing values of agricultural production, and it is assumed they will just keep increasing by 2038 until they will reach the Germany's level, as illustrated in ref. [52]. From this analysis, we can deduct that there are good opportunities to mobilize financial sources, locally or from external countries, intended for the growth of the advanced biofuels sector.

The remaining countries, with smaller production of sustainable crops, already use their collectable residues or they have the potential to witness a relevant growth in the next years, contributing at achieving the Renewable Energy Directive (RED II) targets [3] (like Hungary, Poland, Spain, and Italy).

The available forestry residues are very high in Finland, Austria e Sweden. The expected production ranges between 4 and 16 Mt in 2025, as reported in Figure 4. If we introduce the COVID-19 correction, the estimated availability 3.5 and 14 Mt.

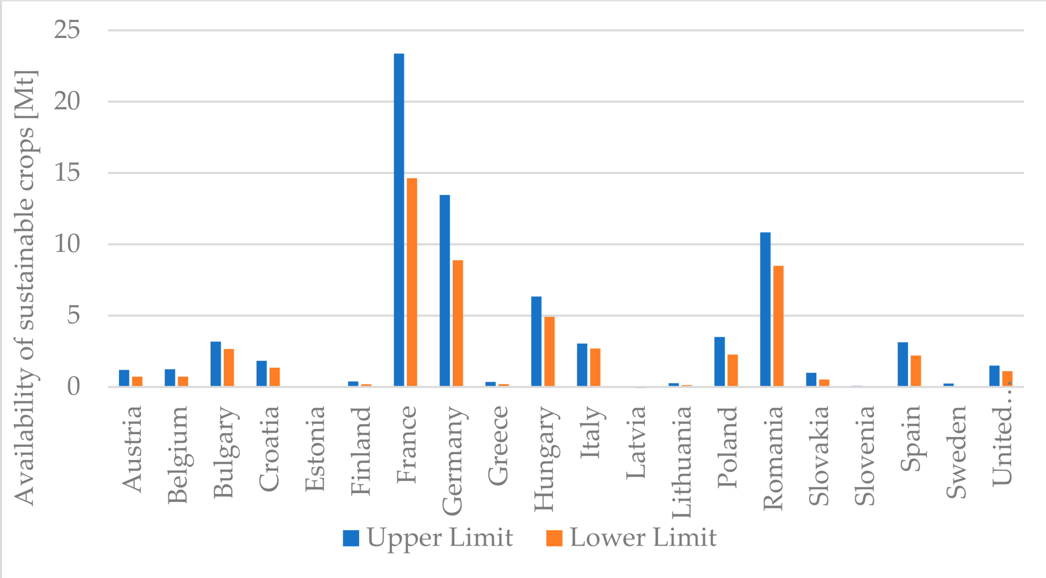

Figure 3. Agricultural Residues availability in Europe in 2025 in million tonnes per year.

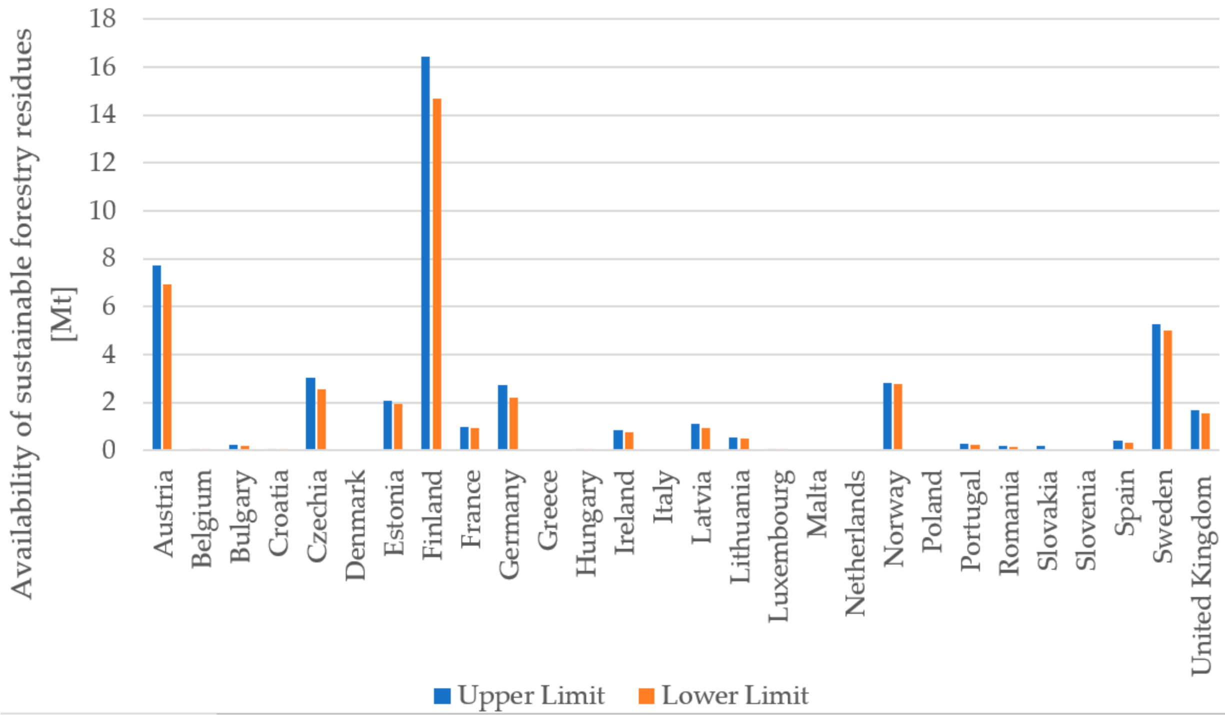

Figure 4. Forestry Residues availability in Europe in 2025 in million tonnes per year.

Austria has a long tradition in the use of forestry residues as well. With a forest coverage of 46% of the country [53], it is one of the most densely forested countries in Europe after Sweden, with its 55% productive forest land of the total land area [54], and Finland, with its 70% [55].

Finland and Sweden have vast forest resources supporting large wood production for industrial uses, energy supply, heat and power. This circumstance leads to an economic growth and social well-being [54,55]. However, part of these woody residues is used for the advanced biofuels production. Recent studies on the 2030 EU climate targets concluded that the most cost-efficient way to reduce emissions in Northern Europe is to invest in the production and uptake of advanced drop-in biofuels as they do not require changes to the vehicle fleet or fuel distribution system [56].

There are many European countries that will have a high availability of sustainable wastes like Italy, France, and United Kingdom, with values ranging between 2 and 7 Mt in 2025, as shown in Figure 5.

For that part of wastes, characterized by lignocellulosic material, such as paper and cardboard, vegetal and wood wastes, the corrected model suggests their overall availability will be approximately 1–1.7 Mt in 2025. However, even without any correction, the wastes availability is considerably lower than the crops residues. It is expected that waste generation and landfill will decrease in Europe by 2030, according to the European policies. These include the EU Waste Framework Directive (2008/98/EC) [57], the Landfill Directive (1999/31/EC) [58], and the Packaging and Packaging Waste Directive (94/62/EC) [59].

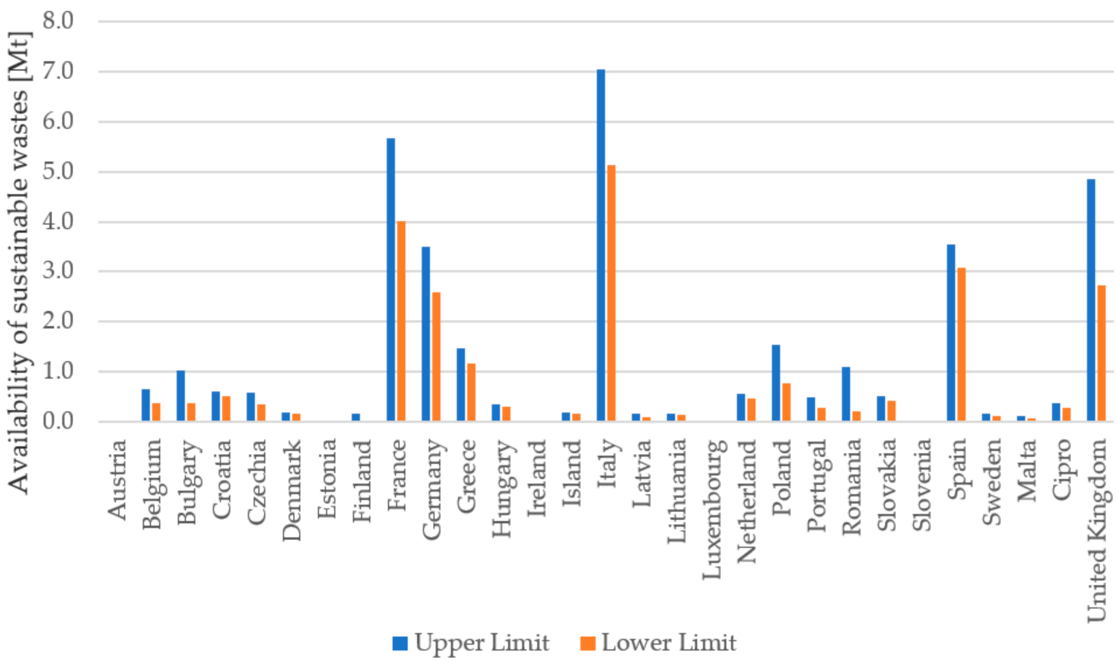

Figure 5. Wastes availability in Europe in 2025 in million tonnes per year.

For the sake of clarity, the results of the maximum and minimum availability of European feedstocks in 2025 are summarized in Table 9 according to the present autoregressive model:

Table 9. Summary of feedstocks availability in Europe in 2025 without Covid-19 effects.

Category	Without COVID-19 Correction		With COVID-19 Correction	
	Max Availability [Mt]	Min Availability [Mt]	Max Availability [Mt]	Min Availability [Mt]
Agricultural residues	74	51	65	49
Forestry residues	46	41	41	36
Wastes	35	24	31	21

3.3. Main European Facilities

3.3.1. Agricultural Residues

The most relevant technologies able to produce advanced liquid and gaseous biofuels from agricultural residues for the transport sector are described in an open database, available on [60], where it is possible to identify the major European industrial plants processing agricultural residues (Table 10).

As shown in Figure 3, France, Germany, and Romania have large availability of crop residues. Consequently, in these countries, there are several plants with well-developed technologies. In France, the operational IFP plant (Futurol project), produces second generation ethanol (or cellulosic ethanol) with the support of 11 project partners (ARD, IFP Energies nouvelles, INRA, Lesaffre, Office national des forêts, Tereos, Total, Vivescia, Crédit Agricole Nord Est, CGB, Unigrains) covering the entire process from the plant resource to the fuel tank [61]. With a budget of 76.4 million euros, including 29.9 million state funding (Bpifrance), IFP invested in advanced biofuels production, since it creates a solution for the maintenance of agricultural activities exploiting their widely availability of residues at moderate prices.

In Germany, there are already two operational plants: Global Bioenergies and Clariant. In the Global Bioenergies plant, the straw hydrolysates fermentation leads to the production of bio-isobutene [62]. The isobutene could eventually be transformed into isooctane fuel, as well as oligomers and polymers, by other chemical processes [62]. In the Clariant plant (Sunliquid project), an innovative process to convert agricultural residues in biofuel is employed. The plant uses optimized enzymes to convert cellulose and hemicellulose into ethanol. Since 2012, Clariant has produced up to 1000 metric tonnes of cellulosic ethanol every year [63], and in 2018, the same company also broke ground for its first-of-its-kind commercial-scale cellulosic ethanol production plant in Romania with an annual capacity of 50,000 tons of cellulosic ethanol production. Clariant is investing more than EUR 100 million in its first plant, receiving more than EUR 40 million funding from the European Union [64].

Table 10. Operational European facilities for the advanced biofuels production [43,60] from agricultural residues.

Owner	Name	Location
IFP	Futurol	France
Clariant	Sunliquid	Germany
Global Bioenergies	Isobutene demo	Germany
Clariant	Clariant Romania	Romania

3.3.2. Forestry Residues

According to the database on facilities [60], there are many operational facilities of the above-mentioned European Countries able to convert forestry residues and lignocellulosic materials into advanced biofuels. They are summarized in Table 11.

In Finland, the country with the highest availability of residues, there are several operational plants. Chempolis Ltd. developed an advanced technology (formico 3G biorefinery [65]) for bioethanol production. In 2012, Fortum invested €20 M to build the first industrial-scale integrated bio-oil plant [66]. More than 100 tonnes of bio-oil had been produced from sawdust and forest residues, and more than 40 tonnes of bio-oil had been combusted in Fortum’s 1.5 MW district heating plant [67]. Green Fuel Nordic based its business on innovative pyrolysis technology in the production of an advanced bio-oil. The annual production capacity of the refinery is 24,000 tons of bio-oil [68]. St1 produces about 10 million litres of advanced bioethanol through its St1 Cellunolix process optimized for softwood with an investment cost of €40 M [69]. The VTT Technical Research Centre of Finland Ltd. uses residual biomasses for the combined production of transport fuels, chemicals, and heat through gasification [70].

Table 11. Operational European facilities for the advanced biofuels production 60 from forestry residues.

Owner	Name	Location
Chempolis Ltd.	Chempolis Biorefining Plant	Finland
Fortum	Joensuu demo	
Green Fuel Nordic	Green Fuel Nordic	
St1	Cellunolix Kajaani	
VTT Technical Research Centre of Finland Ltd.	Dual fluidized-bed steam gasification pilot plant	
VTT Technical Research Centre of Finland Ltd.	Pressurized FB for synthesis gas production	
AustroCel Hallein	Biorefinery	Austria
RenFuel	RenFuel Backhammer	Sweden
SEKAB	Biorefinery Demo Plant	
Sodra	Sodra biomethanol	
SunPine	SunPine HVO 100 million litres	

In 2019, the Austrian AustroCel Hallein started the construction of a new plant, able to produce 30 million litres/year of bioethanol. The company also signed a multi-year agreement with integrated oil and gas major OMV AG for the supply of advanced ethanol for blending with gasoline [71].

In Sweden, the company RenFuel signed an agreement with the Swedish pulp producer Rottneros and the fuel company Preem to produce advanced biofuel (Lignol) from feedstocks rich of lignin with biological catalysts in a reactor without pressure and at a temperature below the boiling point. The catalytic process is patented and protected by RenFuel [72]. The process developed by Sekab E-Technology consists mainly of four steps: pre-treatment with acid and steam at 200 degrees; enzymatic hydrolysis to break down cellulose in sugar; fermentation and reprocessing. The final products are bioethanol, biogas, and chemicals (lignin) [73]. Sodra produces 5250 tonnes of biomethanol per year from wood raw material. The production begins with the sulphate pulp process at its mill. Wood chips are cooked with chemicals to separate the wood into its constituents, i.e., cellulose, hemicellulose (pulp), and lignin. Methanol is created when the wood and chemicals react. After cooking, the chemicals, lignin, and other residues are washed out of the pulp. They form black liquor, whose water content is then reduced by evaporation. What remains is a condensate of methanol, turpentine, and sulphur compounds. All the process is patented, and the company can produce 10 kg of biomethanol for every ton of pulp [74]. Finally, in 2019, SunPine produced 95 million litres of tall diesel, and new investments are being made to achieve a production volume of 150 million litres. Its diesel is then sold to Preem, which refines it into the world's only Nordic Swan eco-labelled diesel [75].

3.3.3. Wastes

Despite Italy and France being the European countries with the highest availability of wastes, according to [60] their facilities are not developed or operational yet. Therefore, in Table 12, the operational European plants are summarized. The Finnish St1 is focused on ethanol production that is the most used biofuel in the existing distribution networks. In addition, St1 generates fodder, energy, or heat as side products depending on the quality of the feedstock [76]. In 2019, St1 invested around 200 M€ in a new biorefinery in Sweden aiming at processing a wide range of feedstocks [77] by 2022. The main fuels will be HVO diesel, jet fuel, and naphtha.

Table 12. Operational European facilities for the advanced biofuels production [43,60] from wastes.

Owner	Name	Location
St1	Bionolix Hameenlinna	Finland
St1	Etanolix Jokioinen	
St1	Etanolix Vantaa	
St1	Etanolix Lahti	
St1	Etanolix Hamina	
Domsjo Fabriker	Domsjo Fabriker	Sweden
St1	Etanolix Gothenburg	
Advanced Biofuels Solutions Ltd. (ABSL)	Swindon Advanced Biofuels Plant	UK
Advanced Plasma Power Ltd.	BioSNG pilot plant	
Solena Fuels	Solena UK	

Domsjö Fabriker is a biorefinery whose recent businesses are the production of renewable fuels like bioethanol, bioDME, and biomethanol [78,79] from forestry wastes. The rest of residual products are used to produce heat, allowing a further energy recovery [78]. The production of second-generation bioethanol is delivered to SEKAB, which refines it further into car fuel.

Advanced Biofuels Solutions Ltd. (ABSL) are the licensors of the RadGas technology, which offers reliable, high efficiency conversion of waste and biomass residues into a clean syngas. In particular, the syngas is suitable for the conversion into fuels such as hydrogen, bioSNG, propane, methane, dimethyl ether, kerosene, or diesel [80].

Advanced Plasma Power (APP) is a UK-based sustainable energy company that has been operating for eleven years. During this time, it has developed its Gasplasma solution for converting municipal and commercial waste into advanced biofuels and electricity and has led the project development of several facilities based on its technology [81].

Solena Fuels Corporation is one step closer to produce sustainable 100% jet fuel purchased by British Airways at market competitive prices. The goal of the project is providing the gasification process that converts wastes into syngas and then in liquid biofuels (Integrated Biomass Gasification to Liquids (IBGTL)) [82].

4. Technological Maturity Level for Advanced Biofuels Production

Advanced biofuels have been considered a green alternative to fossil fuels for many decades, as clearly indicated in [83]. However, industrial technologies are a critical point in the bioeconomic value chain. In fact, there is still a gap between the bench scale and the higher production rates that would help these biofuels to become a commercial reality. To complete the picture, the technology readiness level (TRL) was employed to examine the development of the thermal, thermochemical, biochemical, and chemical conversion processes. The last three are the most widespread and strictly used to produce transport biofuels. For the sake of clarity, the definition of TRL is outlined in the following Table 13.

Among the chemical conversion processes, we consider Hydrotreated Vegetable Oils (HVO) or Hydroprocessed Esters and Fatty Acids (HEFA), Transesterification, and Bio-Derived synthetic paraffinic kerosene (Bio-SPK). All these can boast of being fully developed technologies, or nearly so, and be able to process vegetable or algal oils and animal fats to get the biodiesel fuel range or synthetic kerosene, used for the transport and aviation sector, respectively. As described in ref. [84], HVO is a mature technology, and it is already integrated in some existing oil refineries to co-process oil crops with fossil streams. For the same reasons, ref. [85] assigns TRL of 9 to both HVO and HEFA technologies. Transesterification is a competitive and currently in operation technology too. However, when algal oils are used as feedstocks, ref. [86] shows their conversion through transesterification is situated in a range from TRL 2 to 4–5. As a matter of fact, there are not developed industrial plants yet, but just advanced testing labs. Bio-SPK is a promising new solution for the global aviation industry, since its main product, named green jet fuel, has identical properties to jet fuel [87]. As appears from ref. [27], Bio-SPK is under assessment for commercial production (TRL 8).

Table 13. Technological Readiness Level (TRL) scale [83].

TRL	Definition	Description
0	Idea	Unproven concept, no testing has been performed
1	Basic research	Principles postulated and observed but no experimental proof available
2	Technology formulation	Concept and application have been formulated
3	Applied Research	First laboratory tests completed; proof of concept
4	Small scale prototype	Built in a laboratory environment
5	Large scale prototype	Tested in intended environment
6	Prototype system	Tested in intended environment close to expected performance
7	Demonstration system	Operating in operational environment at pre-commercial scale
8	First-of-a-kind commercial system	Manufacturing issues solved
9	Ready for commercialization	Technology available for consumers

In the class of biochemical conversion processes, the most mature technologies are alcohol fermentation, anaerobic digestion, and syngas fermentation. Alcohol fermentation converts sugars and starches from agricultural crops, producing conventional or first-generation ethanol used in gasoline engines. Lignocellulosic residues can also be used to produce advanced (or second-generation or cellulosic) ethanol. According to the different feedstocks, there is a change in the TRL assessment. In fact, ref. [85] distinguishes the two biofuels, conventional and cellulosic (or advanced) ethanol, by attributing them TRL 9 and 7, respectively. Generally, TRL 7 technologies, as that for advanced ethanol production, are for demonstration initiatives and not fully commercial. Anaerobic digestion is a widely used process to get mainly biomethane with a TRL 9. Its high technological maturity is due to a demonstrated use on a large variety of available feedstocks, such as organic waste fraction, industrial wastes, sewage and manure sludge, including energy crops, and crop residues [84]. Syngas Fermentation is an innovative process to produce ethanol. So, further technological improvements are needed to increase its maturity level. This justifies a TRL value limited to 6–7, as indicated in ref. [88]. It is also worth introducing Fischer–Tropsch synthesis (FTS) and Fischer–Tropsch synthetic paraffinic kerosene (FT-SPK). Both of these biochemical technologies may be integrated at the thermochemical pathway with the aim to convert syngas in drop-in fuel and green jet fuel, respectively. In recent years, Fischer–Tropsch processes have reached a higher maturity. FTS TRL is ranging from 5–9 [27], while TRL of 6–8 is attributed to FT-SPK [89].

Finally, in terms of thermochemical conversion, there are two widely used processes, thermal gasification and pyrolysis. During the gasification, both gaseous and liquid fuels can be produced from all the highlighted categories wastes, forestry, and agricultural residues. The gaseous biomethane and synthetic natural gas (SNG) is obtained via gasification with TRL 7, higher than the liquid fuel from lignocelluloses, whose technology has a TRL equal to 6. Similarly, pyrolysis is also a technology demonstrated in an industrially relevant environment with TRL 6. An overview of the mentioned TRL analysis is reported in Table 14.

Table 14. Assessment of the technological readiness level (TRL) for each mentioned technology.

Available Technology	TRL	Status
HVO or HEFA [85]	9	Commercial
Anaerobic Digestion [85]	9	Commercial
Fermentation for conventional ethanol [85]	9	Commercial
Fermentation for cellulosic ethanol [85]	7	Demonstration
Syngas Fermentation [88]	6–7	Demonstration
Thermal gasification for biomethane [85]	7	Demonstration
Thermal gasification for biomass to liquid (BTL) [85]	6	Demonstration
Pyrolysis [85]	6	Demonstration
Transesterification from vegetable oil [90]	9	Commercial
Transesterification from algal oil [86]	From 2 to 4–5	Research-Pilot
FTS [91]	5–9	Pilot-Commercial
FT-SPK [89]	6–8	Demonstration—First-of-a-kind commercial
Bio-SPK [27]	8	First-of-a-kind commercial

5. A Proposal for a Technology Ranking

The status and the reliability of the above-mentioned technologies to produce advanced biofuels depend on several factors. Here, some of them are considered to evaluate them and to obtain a comprehensive ranking, aiming at selecting the most promising advanced biofuels. In this study, five items are considered: process maturity, drop-in fuels quality, feedstocks, and biofuel production cost and finally, the feedstocks availability in 2025, according to the current analysis. All these parameters play a significant role in the ranking process, since they are responsible for determining affordability of advanced biofuels in the market development. The rank ranges between 1 and 3 for each of these items, assuming 1 as a poor, 2 as a medium-good, and 3 as a very good qualitative level, as illustrated in Table 15.

Table 15. Biofuel quality level for liquid biofuels.

Liquid Biofuel	Process Maturity	Drop-in Fuel	Feedstock Cost	Biofuels Production Cost	2025 Feedstocks Availability	Sum
First generation bioethanol	3	1	3	3	1	11
First generation biodiesel	3	2	2	2	2	11
Pyrolysis bio-oil	2	1	3	1	3	10
Second generation biodiesel	2	2	2	1	2	9
Renewable diesel (or green diesel)	3	3	2	1	2	11
Green jet fuel	2	3	1	1	2	9
Second generation bioethanol	2	1	3	1	3	10
Third generation biodiesel	1	2	2	1	1	7
Drop-in biofuel	1	3	2	1	1	8

The process maturity is well represented by the TRL. A lower process maturity requires a higher number of development steps, thus making the technological supply chain complex and expensive. Therefore, if the TRL of the corresponding technologies is 8 or 9, a value of 3 is assigned, if TRL is between 6 and 7 then the rank will be 2, and finally, for all the TRLs lower than 4–5, the rank will be 1.

When a liquid biofuel is drop-in, it is considered as an added value since it is fully compatible with the existing petroleum infrastructures, as reported in ref. [92]. In this ranking, if the fuel is drop-in, then the rank will be maximum (i.e., 3). If it is semi drop-in fuel, the rank will be 2, otherwise it will be 1.

Feedstock and production costs strongly influence the final biofuel ranking as they should satisfy the growing demand of the advanced biofuels in the current and future market. When the feedstocks cost is lower than 34 EUR/MWh, the rank is 3, if it is ranging from 34 and 60 EUR/MWh, the value is 2, and for all the feedstocks costs greater than 60 EUR/MWh, the rank is 1. Similarly, if the production cost is lower than 85 EUR/MWh, the rank is 3, if it is included between 85 and 94 EUR/MWh, the rank is 2, and when it is greater than 94 EUR/MWh, the rank is 1. Such division was made on the basis of costs given in ref. [84].

Finally, the feedstocks availability could also help to understand and quantify the ecological boundaries of the bioeconomy from wastes, agriculture, and forestry residues. If the fuel comes from crop or forestry residues that are all lignocellulosic sources, the rank will be 3, if it is obtained by oil coming from wastes, the rank will be 2, otherwise all the fuels achieved by vegetable or algae oils (whose availability analysis is not reported in this paper) will be valued with the minimum rank, i.e., 1.

Table 15 shows that the second-generation biofuels with the highest scores are the biodiesel fuels.

As previously illustrated in Table 14, the technologies with the highest TRL are fermentation for conventional ethanol, HVO/HEFA, anaerobic digestion for biogas and transesterification from vegetable oils for biodiesel. However, although all the technologies are mature, only the last four are significant for the advanced biofuels production. With reference to these technologies, feedstock and production costs (as reported in ref. [84]), are summarized on average in the following Table 16, showing the lowest costs for biogas production and comparable values for the alternatives considered biofuels.

Table 16. Feedstocks and production costs for Technologies with the highest TRL according to ref. [84].

TRL 9 Technologies	Feedstock Cost [EUR/MWh]	Production Cost [EUR/MWh]	Total [EUR/MWh]
HVO or HEFA	50	78	128
Anaerobic Digestion	18.5	80	98.5
Transesterification from vegetable oil	60	95	155

6. Conclusions

This study estimated the amount of wastes, agricultural, and forestry residues by 2025 that can be sustainably used to produce advanced biofuels without neglecting aspects related to the environmental impact and other existing competitive uses.

Residues from the agriculture and forestry sector will be the most abundant in 2025 in Europe, since wastes should be limited by European policies, as illustrated previously, as well as they are considered the most promising feedstocks for various types of advanced biofuels used as energy supply in the European transport sector. As suggested by ref. [93], the potential of biomass from agricultural sector cannot be considered as a constant value over time because of some changes such as the amount of available agricultural land or the structure of cultivated crops. However, it stands to reason that, by 2025, there will be not large variations in respect of the present results for both the smallness of the estimated time interval and the considerations of all the aspects related to the biodiversity and the environment.

Despite the pandemic emergency, advanced biofuel demand is expected to continue growing over the next decades and relying heavily on the current and future technologies. According to the present ranking of different technologies, HVO or HEFA are the most used, thanks to their maturity level (TRL equal to 9) and optimized costs. Nevertheless, technological improvements are expected to produce biofuels with even higher efficiencies. In this regard, promising technologies with lower TRL are fermentation for cellulosic ethanol and syngas fermentation, due to high values of agricultural and forestry residues, as emerged in the current paper. Although the first-generation biofuels remain the most common choice from the metric in Table 15, the renewable (or green) diesel is promising for different applications in the transport sector. It is followed by the green jet fuel applied in the aviation sector and the second generation of bioethanol (or cellulosic ethanol), whose technological efforts are still challenging.

By building new biorefineries, the bio-based value chain, based on secondary biomasses, will be established in Europe, providing a tangible example for a successful circular economy approach. These plants lay the foundation for a wide-scale implementation of advanced biofuels production worldwide and for a more sustainable energy supply in the European transport sector.

In this critical financial situation, the support of the biorefineries is essential to preserve and create jobs, and to avoid service degradation. This is indispensable for realizing the true potential of circular economy and to address the concerns of residues and wastes management and alternative energy generation.

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