





LISTA DE LUCRĂRI ȘTIINȚIFICE RELEVANTE

10 lucrări

1. **Moiceanu G.**, Paraschiv G., Voicu G., Dinca M., Negoita O., Chitoiu M., Tudor P., Energy Consumption at Size Reduction of Lignocellulose Biomass for Bioenergy, SUSTAINABILITY, Volume: 11 Issue: 9, May 2019, DOI: 10.3390/su11092477, Publisher MDPI, ST ALBAN-ANLAGE 66, CH-4052 BASEL, SWITZERLAND ISSN: 2071-1050, **Impact Factor 2.592**, WOS:000469518700025
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Article

Energy Consumption at Size Reduction of Lignocellulose Biomass for Bioenergy

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Abstract: In order to obtain bioenergy (biogas, biofuel) or pellets, different types of lignocellulosic biomass are subjected to a mechanical pretreatment, first by size reduction, then by separating, and ultimately by fracturing or bio-refining. Biomass processing mainly refers to a grinding process that occurs until reaching certain limits. The size reduction process, such as grinding, is an operation that is executed with different levels of energy consumption, considering biomass mechanical characteristics and the necessary grinding level. This paper, illustrates a comparative analysis of experimental results obtained by grinding multiple types of vegetal biomass (*Miscanthus*, corn stalks, alfalfa, willow) used in the process of bio-refining and bio-fracturing. Experiments were realized using both a laboratory knife mill Grindomix GM200 (Retsch GmbH, Haan, Germany), and a 22 kW articulated hammer mill, using different grinding system speeds and different hammer mill sieves. Results have shown that biomass mechanical pre-processing grinding leads to supplementary costs in the overall process through bio-refining or bio-fracturing in order to obtain bio-products or bio-energy. So, specific energy consumption for grinding using a hammer mill can reach 50–65 kJ/kg for harvested *Miscanthus* biomass, and 35–50 kJ/kg for dried energetic willow, using a 10 mm orifice sieve, values which increase processing costs.

Keywords: biomass; size reduction; hammers mill; energy consumption; *Miscanthus*

1. Introduction

Sustainable development of human society implies, among many other things, the use of renewable energy resources based primarily on biomass, which reduces the conventional fuel pollution in general. Due to sale versatility, the renewable nature, and the low impact on the environment, lignocellulosic biomass is an attractive source for producing fuels and chemicals. The biomass conversion perspectives are special, as it can be processed and transformed, especially in biofuels, meaning ethanol, butanol, biogas, biohydrogen, biodiesel, syn-gas, but also many other products, can be produced [1].

It must be said that the lignocellulosic biomass category includes energy plants such as *Miscanthus x giganteus*, willow, poplar, acacia, paulownia, which are all plants grown in Romania. The *Miscanthus x giganteus* plant belongs to the C4 plant category, being a perennial plant with a calorific value of about 15.8 MJ·kg⁻¹ in ground form or briquettes.

Approximately 2.3 kg of *Miscanthus* with a 14% moisture content is equivalent to one liter of diesel fuel. In a chopped state, the volumetric mass of the *Miscanthus* is about 130 kg·m⁻³ [2]. Moreover, the ash content of *Miscanthus* plant is about 1.5%, carbon content 48.7%, nitrogen content 0.47%, sulfur content 0.07%, cellulose content 49.22%, and lignin content 29.25%, [3].

The willow is a fast-growing plant (3.0–3.5 cm/day) that is cultivated as a short rotation energy culture and has a calorific value of about $18.7 \text{ MJ} \cdot \text{kg}^{-1}$ [4] and a yield of $6.5\text{--}24 \text{ t} \cdot \text{ha}^{-1}$ per year, depending on variety, agro-technical methods, natural conditions, and other factors. The acacia shoots strongly after the first year of plantation, and the amount of biomass obtained doubles from $8\text{--}9 \text{ t} \cdot \text{ha}^{-1}$ after the second planting year to about $20 \text{ t} \cdot \text{ha}^{-1}$ from the third year of plantation.

Durable and economical utilization of biomass resources for producing bio-energy can be enhanced through bio-refineries, a concept that includes a wide range of technologies through which biomass is separated into its chemical components (proteins, carbs, etc.). These can later be transformed in products with added value into chemical substances and biofuels. A biorefinery integrates biomass conversion processes and equipment to produce biofuels, energy, and chemicals from biomass [5,6]. Through bio-refining, all types of biomass from agricultural, forestry, food industry waste, like agricultural plant stems, wood and wood residue, organic residue (vegetal and animal), forestry residue, etc. can be produced [5]. Depending on the type of utilized biomass it is possible to obtain both biofuels as well as chemical substances that can be obtained with added value, mainly energy (electrical or thermal) but also auxiliary materials, according to the type of utilized biomass.

It should be noted that economic and environmental considerations have always led to a continuous improvement of biomass bio-refining process. In this context, fractions that could be separated from biomass during bio-refining or fractioning (food, fodder, chemical products, fuel) could generate added profits which overcome their calorific value [5].

Also, it must be said that biogas (as a product of the conversion of biomass into bioenergy) can be produced from virtually any type of biomass, although the largest resource used for obtaining biogas is farmyard manure, with a percentage of approximately 65% out of the total quantity of biomass used for biogas production. So, even if farmyard manure represents a very high percentage of raw material used for producing biogas, energy crops can also be taken into consideration as material for biogas production, [7,8].

Analyzed from the point of view of energetic potential in biogas production, perennial *Miscanthus*, switchgrass and annual maize presented a significantly lower energetic potential compared with fossil resources. At the same time these perennial crops present a higher ecological performance regarding biogas production and a lower impact on the environment, thus perennial grasses and *Miscanthus* presented the potential to improve sustainability in the biogas area [9].

The ecological performance of energy crops (*Miscanthus*, switchgrass, and maize biomass) has been analyzed by the authors [9] both from the perspective of contributing to climate change and eutrophication of freshwater and marine water, as well as acidification of agricultural soil or the replacement of fossil fuels. All stages of biomass production have been considered, up until the fermented residues are discharged from the biogas plant.

Disregarding the type of end products that are needed to be developed from lignocellulosic biomass, an initial mechanical processing is needed, which is finalized through a corresponding grinding of biomass stems and fragments.

In general, mechanical pre-treatment is considered the most important and promising preliminary stage for treating and transforming biomass into bio-fuel before passing to the next pre-treatment processes [10].

Size reduction of biomass, before all, must be a technological process through which easy transformation of biomass components into different types of matter is facilitated and that can be used in different domains (food industry, bio-fuels, chemical industry, fodder, etc.) The usual methods of biomass grinding include chopping, milling (dry or moist), and crushing through compression.

Without providing an adequate grinding degree, biomass cannot be processed efficiently. Still, biomass grinding is an energy consuming process and if the most adequate grinding equipment and the most favorable process parameters are not used, the process of transforming biomass into useful components will be inefficient or have a low efficiency [11,12].

For example, the energy consumption for biomass densification is influenced by the equipment used, the material properties, particle size/distribution, and also the lignocellulose composition, but is mainly influenced by the extrusion through the mold. An approximate value of the energy consumption of the sawdust extrusion process in order to obtain pellets is $130\text{--}135 \text{ MJ}\cdot\text{t}^{-1}$, thus, obtaining a density of about $1000 \text{ kg}\cdot\text{m}^{-3}$ [13].

Energy consumption for biomass grinding depends on the grinding machine variables, the feeding flow and the material properties, including initial particle dimensions [14–16]. Practically, size reduction can be achieved through dividing or shearing with sharp knives, in which the particle geometry is altered due to impact or compression [10–12].

Considering that excessive heating during the grinding operation and contamination of the initial biomass are factors that can negatively influence the material properties subjected to grinding, many studies attested that the process of reducing particle size dimension need to be done without affecting the material. Thus, Mani S. et.al. [17], conducted tests with a hammer mill using materials such as wheat and barley straws, corn, and switchgrass stalks. Tests had shown that switchgrass had the highest specific energy consumption for every sieve used, and also for all the moisture contents, unlike the other ground plants. For wheat straws with a moisture content between 4–7% and sieves dimensions of 0.8, 1.6, and 3.2 mm, the specific energy consumption was $185.8 \text{ MJ}\cdot\text{t}^{-1}$, $133.2 \text{ MJ}\cdot\text{t}^{-1}$, and $41.0 \text{ MJ}\cdot\text{t}^{-1}$. For the corn stalk comminution process with a moisture content of 12% and a 3.2 mm sieve orifice dimension (of the hammer mill), the energy consumption recorded was $11 \text{ Wh}\cdot\text{t}^{-1}$. It could be concluded that if the sieve orifice dimensions were smaller, the comminution specific energy consumption was higher.

Tavakoli et.al [18] measured the grinding power demand for wheat stalks using three different revolutions (400 , 540 , and 800 min^{-1}), a straw thresher machine, two different evacuation sieve orifice dimensions (2.5 and 4 cm), and two different blades on the drum (88 and 176 blades respectively, on four or eight rows). Based on the results obtained, it was concluded that the grinding power demand increased in correlation to the blade drum revolution and the decrease of sieve orifice dimensions and the drum number of blades. The maximum power consumption (5.377 kW) was registered for a sieve orifice dimension of 2.5 cm and a revolution of 800 min^{-1} , with four lines of blades, while the minimum power consumption was registered for a sieve orifice dimension of 4 cm and a revolution of 400 min^{-1} , with eight lines of blades on the drum.

Researchers Gil et. al. [19] designed pilot biomass grinding equipment in order to conduct a large number of experiments on different types of biomass and different ground particle dimensions. Using corn stalk and biomass residues with different moisture contents and different ground particle dimensions, it could be observed a decrease of the plants moisture content of about 3–5% occurred after the grinding process for each type of biomass, which should be considered when the drying process is evaluated. Results confirmed a smaller energy consumption and a fine grain of ground particles for corn stalk regarding biomass residues.

Miao et. al. [20] conducted experiments regarding mechanical size reduction of *Miscanthus* (*Miscanthus x giganteus*), switchgrass (*Panicum virgatum*), willow (*Salix babylonica*), and energy cane (*Saccharum spp.*) using a commercial hammer mill, a knife mill, and a hammer mill Retsch SK100 (Retsch GmbH, Haan, Germany). The results showed that the specific energy consumption of biomass comminution and the aperture sizes of the milling screens were related in power-law forms. Biomass moisture content significantly influenced the grinding energy consumption, mainly for smaller dimensions of the ground material. It was possible to observe the inversely proportional variation of the size of the particles with their bulk density for all four energy plants used in the experiments. Also, the comminution ratio, obtained from the ratio of the final mean particle size and the original mean particle size, was proportional to the energy consumption for all four energy crops.

Shastri et. al. [21] confirms the importance of the grinding material process and conducts its experiments in order to determine the necessary energy for *Miscanthus* and switch grass particle size reduction to dimensions between $1\text{--}25.4 \text{ mm}$ for which the densification pressure in 1.2 MPa .

Thus, in order to develop adequate machines, designers and manufacturers of grinding equipment must have at their disposal data regarding the scope and utilized material in order to identify the most adequate technological flux for processing.

In this respect, this paper presents an analysis of the grinding behavior of certain types of lignocellulosic biomass and the experimental highlighting of the grinding energy consumption using first a GM200 laboratory mill with two fixed knives and then a universal hammer mill. The analysis considered the rotor speed of the mill and the sieve orifice dimensions with which the hammer mill is equipped.

An analysis of granulometric determinations results was conducted for the ground material with the laboratory mill and their correlation to energy consumption for three types of agricultural biomass (grass, maize, alfalfa).

Ground material can be used both for pellet and briquette production through densification as well as for bioenergy (biofuel, biodiesel, biohydrogen), or bio-products (bio-food, fodder, chemical products, etc.) through biorefining process.

2. Materials and Methods

In order to present the influence of the types of biomass on energy consumption for the mechanical process of geometric size reduction, three types of biomass were used—corn stalks, alfalfa, and mountain grass, with initial particle dimensions of approximately 30–50 mm.

Initially, a laboratory mill Grindomix GM200 (Figure 1) was used, equipped with a tray and steel knives, and a 900 W motor with 2000–10,000 min^{−1} adjustable speed.

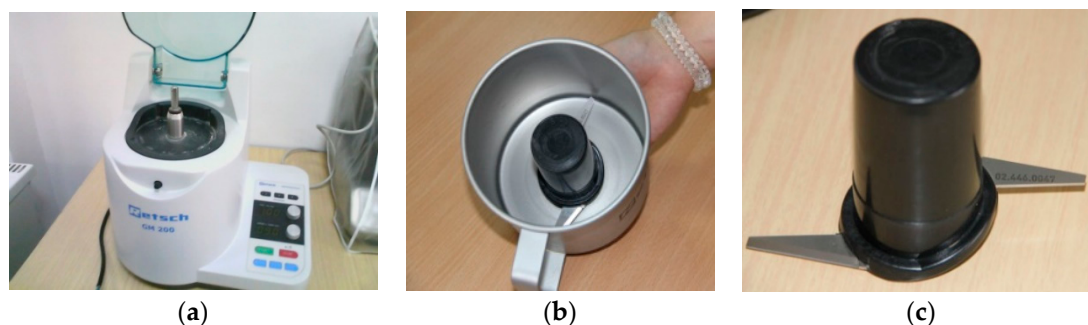


Figure 1. Lab mill GRINDOMIX GM 200, [16]. Note: general view of lab mill (a); Mills steel box (b); Mills knife drum (c).

Samples of 20 grams of material were used, which were subjected to the grinding process for 60 seconds, and the consumed power was recorded through measuring the electric current with an ampermetric pleyer Extech (both average values, as well as maximum values—see Table 1). Knife rotor speed values were 3000, 4500, 6000, 7500, and 9000 min^{−1}. Plant humidity was relatively low, all types of biomass having humidity content below 14%.

The resulting material after grinding was subjected to a granulometric analysis using a sieve shaker. model Analysette 3 Spartan (Fritsch, Idar-Oberstein, Germany) for 180 seconds, in order to determine the grinding degree [22,23]. Dimensions of the sieve orifices being used and the material percentage remaining on each of the classifier sieves are presented in Table 2, for each of the three types of lignocellulosic biomass subjected to experiments.

Grinding degree was derived through the equivalent dimension of the ground material particles, calculated with the Equation (1):

$$d_m = \frac{\sum_i p_i l_i}{100} \text{ (mm)} \quad (1)$$

where:

p_i (%) represents the material, percentage remaining on the sieve i ;

l_i (mm)—medium orifice dimensions which come under each material fraction on the sieve i ; 100—the total percentage of material (sum of all fractions).

For the last sieve we considered that above it exists another sieve with 4 mm orifice dimensions (through which we assumed all the particles passed).

Physical pre-treatment of lignocellulosic biomass or reducing its dimensions is a mandatory condition for chemical or bio-chemical processing in biomass bio-refining. Still, wood particle size reduction is very intensive, which differentiates wood biomass from grass biomass or from lignocellulosic stems for bio-refining [24].

In general, energy consumption for *Miscanthus* plant harvesting is situated between 13.5–18.5 kJ/kg, with some exceptions due to the angle of cutting knives [25] and to plant humidity, thus, continuous grinding until reaching the required dimensions is needed.

If harvested biomass is subjected to grinding with the help of hammer mills, energy consumption for mechanical pre-treatment before the fracturing process or bio-refining increases even more. So, this research continued with the determination of energy consumption of harvested biomass grinding (*Miscanthus* and energetic willow) using a hammer mill MC-22 from INMA Bucharest Romania (Figure 2). Determinations were realized in different working conditions regarding both the size of sieve orifices from the hammer mill and hammer construction. In this paper the results obtained from using some hammers with edges of one side, and sieves with circular orifices of 16 mm or 10 mm, are presented (the 16 mm sieve was mounted first and afterwards the 100 mm sieve)

Miscanthus particles had average sizes of 123–127 mm, while energetic willow particles had dimensions between 24–47 mm (over 85% of material). *Miscanthus* biomass humidity was between 10.02–11.39%, and in the energetic willow between 8.89–11.97%.

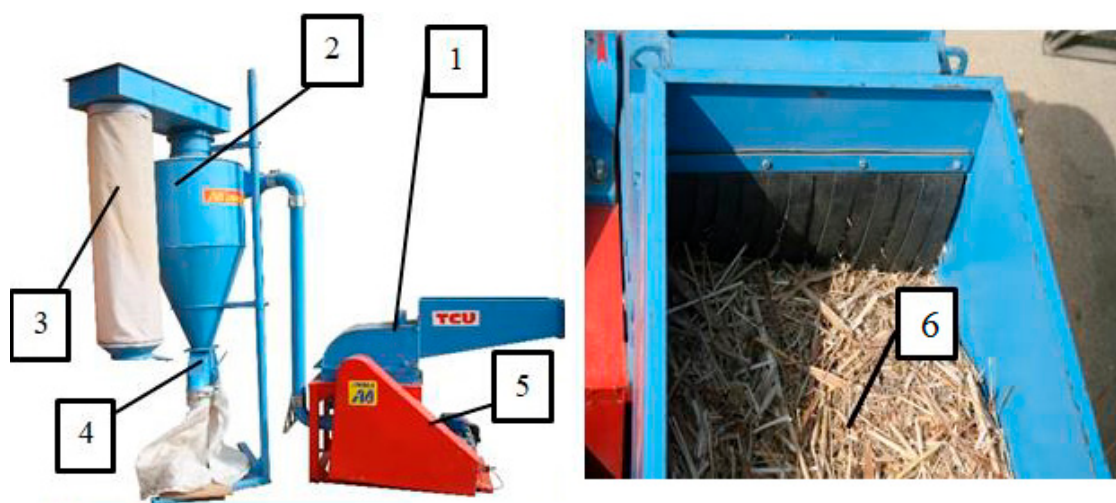


Figure 2. Hammer mill MC-22 (22 kW): 1. hammer mill; 2. vent; 3. support cyclone and bag for dust collecting; 4. evacuation chamber for ground material; 5. electric motor; 6. *Miscanthus* biomass before grinding.

3. Results and Discussions

Shastri et. al. [21] confirms the importance of grinding process and conducts its experiments in order to determine the necessary energy for *Miscanthus* and switchgrass particle size reduction to dimensions between 1–25.4 mm for which the densification pressure is 1.2 MPa.

Thus, the values for grinding power and the specific energy consumption from this research are presented in Table 1 for all three types of biomass at each of the five values of speed revolutions. In order to calculate the specific energy consumption, the medium value of the grinding power along with the type of sample and the weight of each material probe subjected to grinding were taken into consideration.

Table 1. Energy markers for grinding alfalfa, corn stalks, and mountain grass biomass.

Speed of Revolution, min ⁻¹	Necessary Grinding Power, W						Specific Energy Consumption, MJ·kg ⁻¹		
	Alfalfa		Corn Stalk		Mountain Grass		Alfalfa	Corn Stalk	Mountain Grass
	Mean	Max.	Mean	Max.	Mean	Max.			
3000	480	610	770	1850	480	580	1.44	2.31	1.44
4500	460	620	560	1900	440	600	1.38	1.68	1.32
6000	420	625	480	2000	420	650	1.26	1.44	1.26
7500	410	630	420	2150	420	670	1.23	1.26	1.26
9000	410	640	390	2200	410	690	1.23	1.17	1.23

Based on the results obtained for the grinding power of biomass, medium and maximum power curves were drawn, which were recorded by the equipment and were dependent on knife drum revolution. Curves were drawn using computer regression analysis with MS Office Excel (Microsoft Office, Bucharest, Romania) using the experimental points recorded for each type of biomass at each of the five values of the knife drum revolution. These curves are graphically presented in Figure 3.

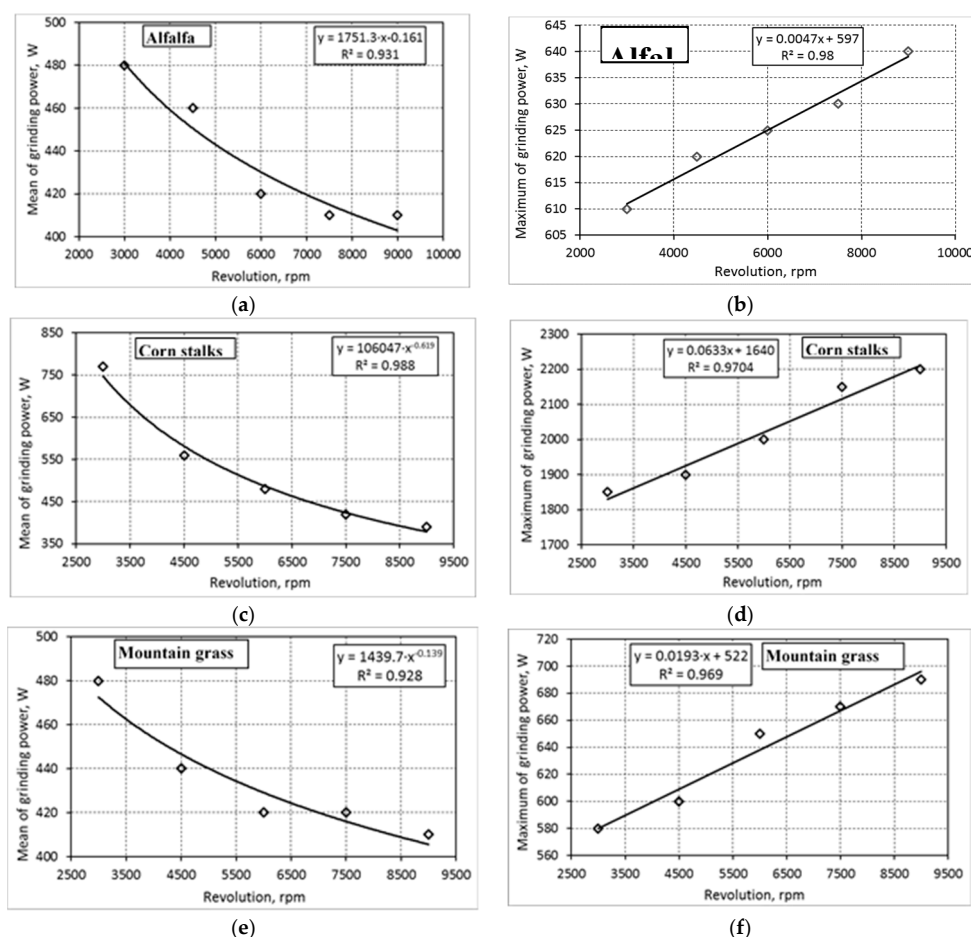


Figure 3. Mean and maximum power variation for grinding process considering the mill drum speed of revolution. Note: mean power variation graph for alfalfa (a); maximum power variation graph for alfalfa (b); mean power variation graph for corn stalks (c); maximum power variation graph for corn stalks (d); mean power variation graph for mountain grass (e); maximum power variation graph for mountain grass (f).

The necessary average power for grinding biomass had a decreasing variation with the rotor speed, while the maximum power had an increasing tendency. If we think about the initial shock on the hammers, at each level of rotor speed, it is normal for the maximum power to be higher at

higher speeds, meanwhile, as the material is grinded, the necessary power decreases as the speed increases. Variation of consumed average power for grinding versus rotor speed followed a power type distribution, with a correlation coefficient R^2 of over 0.969 for all types of biomass (see Figure 3b,d,f).

In Figure 4, the variation of consumed specific energy for grinding, in relation to the mill rotor speed, is presented for all types of biomass.

From analyzing Figure 4, smaller values of necessary energy can be seen for grinding alfalfa plants, together with mountain grass, at the majority of mill rotor speeds. Also, it was observed that corn stalks required higher values of consumed energy, especially at lower rotor speeds, even if at high speeds (over 8000 min^{-1}) the energy values were of the same size order as the ones recorded for alfalfa and mountain grass.

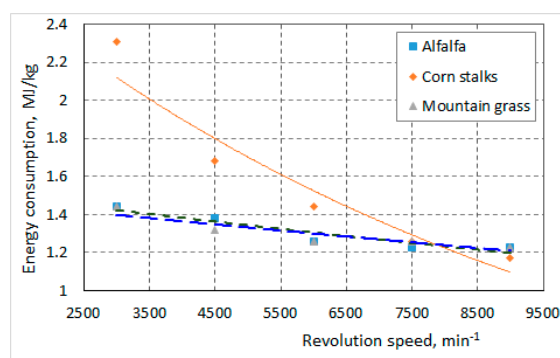


Figure 4. Variation of average power necessary for grinding for all types of experimental biomass.

Even if the initial shock felt by the knife rotor was far greater when grinding corn stalks (consumed power reaching 2200 W at 9000 min^{-1}), still, the average value of necessary power for grinding, at the same speed, was significantly lower, this being the case in all types of biomass. In the case of corn stalks, however, the difference was greater than in the alfalfa or mountain grass. Also, in paper [26] the specific energy necessary for grinding presented a variation approximately exponentially decreasing along with the increase of mill sieve orifice dimensions from 1 to 12.7 mm for different types of lignocellulose biomass among which were *Miscanthus*, *Salix viminalis*, and switchgrass.

It could be said that in the case of corn stalks, which have a thicker exterior wall and a larger diameter compared to alfalfa or mountain grass, the initial shock was normally greater, but as the plants were grinded, the consumed power decreased constantly. Supporting this claim, the exterior/core ratio of stalks should also be considered, which is far greater in corn stalks than in alfalfa stems, or mountain grass.

If the differences between the maximum value of requested power for turning the mill rotor and the average value of consumed power were recorded when grinding, alfalfa stems were situated in the interval 130–230 W, mountain grass between 100–280 W, and in the corn stalks case, this difference was far greater, respectively between 1080–1810 W for speeds between 3000 min^{-1} to 9000 min^{-1} .

In paper [27] scientists found that when the mill hammers have straight corners (90 °C), the total specific grinding energy increases up to 45% if the hammer mill rotor speed of revolution increases from 2000 to 3600 min^{-1} for grinding corn stalks.

In conclusion, it can be said that, when the mill rotor requires using low power, especially at the beginning of the grinding process, an adequate pre-grinding of biomass stalks would be necessary, before starting the actual grinding process.

For determining the grinding degree of alfalfa, mountain grass, and corn stalks, after passing them through the hammer mill GM200, the grinded material was subjected to a granulometric analysis with a laboratory classifier, using five superposed sieves with wire sieve surfaces and orifice sizes of 2.8 mm, 2.0 mm, 1.4 mm, 1.0 mm and 0.71 mm, starting from the largest to the smallest, from top to bottom [15].

Percent values of the ground material that remained on each of the classifier sieves are presented in Table 2, together with the equivalent average dimension values of material particles, calculated with Equation (1).

It can be seen that for the top situated classifier sieve (mesh 2.8 mm) the material percentage on the sieve decreased with the mill rotor speed, closing on the value zero, and that the percentage of material that passed through the bottom sieve (mesh 9.71 mm) increased, from a speed of 3000 min^{-1} to a speed of 9000 min^{-1} .

Table 2. Experimental results in the granulometric analysis test.

Material	Sieve Orifice, mm	Knife Rotor Speed, min^{-1}				
		3000	4500	6000	7500	9000
Alfalfa	0.00	7.5	23.0	46.0	53.0	58.5
	0.71	3.0	13.0	22.5	25.5	28.0
	1.00	2.5	9.0	11.5	14.0	12.5
	1.40	1.0	1.5	3.0	2.5	0.5
	2.00	22.5	26.5	15.0	5.0	0.5
	2.80	63.5	27.0	2.0	0.0	0.0
	dm, mm	2.80	1.88	0.97	0.74	0.62
Corn stalks	0.00	4.5	15.0	28.5	38.0	40.5
	0.71	1.5	6.5	14.0	19.5	20.5
	1.00	1.5	5.5	9.0	10.5	12.0
	1.40	0.5	1.0	1.5	1.5	2.0
	2.00	8.0	12.5	18.0	20.0	21.0
	2.80	84.0	59.5	29.0	10.5	4.0
	dm, mm	3.10	2.51	1.77	1.29	1.14
Mountain grass	0.00	8.0	16.0	21.5	41.0	54.0
	0.71	6.0	11.5	12.5	23.0	25.0
	1.00	5.5	6.5	7.0	9.5	13.5
	1.40	1.5	1.5	2.5	2.5	3.5
	2.00	19.5	22.0	20.5	20.5	4.0
	2.80	59.5	42.5	36.0	3.5	0.0
	dm, mm	2.66	2.23	2.03	1.11	0.72

The top sieve was the only sieve in which the same phenomenon took place, although it sometimes occurred for the 2 mm sieve, but only in the case of alfalfa and mountain grass (for which the variation is relatively non-uniform). In the case of all other sieves, variation of the percentage of material remaining on the sieves increased with the rise of mill rotor speed.

It must be outlined that, indeed, the percentage of material remaining on the top sieve was relatively greater at low speeds of the mill rotor GM200, and the percentage of material that passed through the last sieve was very small, which leads to the conclusion that for obtaining a high grinding degree (for the GM200 mill, and probably for all mills of this type), greater values of mill rotor speeds are required.

Taking into consideration the results from the paper [9], at a mill rotor speed of 3000 min^{-1} , peripheral speeds of knives are between the interval 8.4–20 $\text{m}\cdot\text{s}^{-1}$, values that are insufficient for disintegrating lignocellulosic stalks (mainly corn stalks), while at the knife rotor speed of 9000 min^{-1} , velocities (interior and exterior) have values three times greater.

In Figure 5, the variation of material particle equivalent dimensions is presented, for each of the three types of vegetal dried biomass, in relation to the mill rotor speed.

As seen in Figure 5 the average equivalent dimension (calculated with Equation (1)) had greater values at reduced knife rotor speeds, decreasing as the speed increased, in all types of biomass subjected to experimental determinations. This variation was approximately linear, the correlation coefficient R^2 , determined through regression analysis on the computer, had relatively high values (over 0.88).

It resulted that as the GM200 mill rotor speed increased, the material was ground more extensively, but the grinding energy also increased.

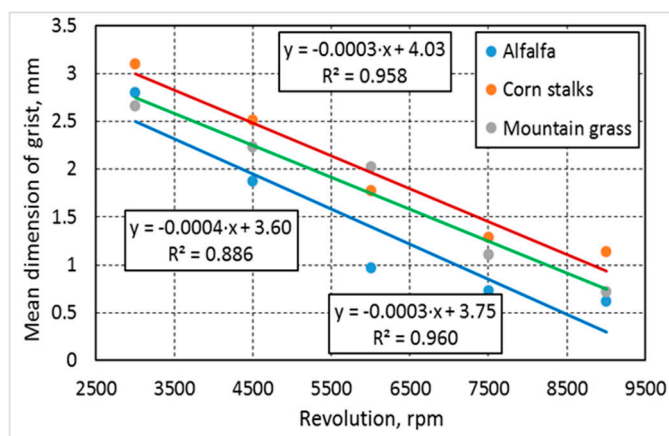


Figure 5. Variation of ground material equivalent dimensions, according to mill rotor speed.

For wood biomass of willow and lignocellulosic biomass of *Miscanthus*, both having moisture content founder 12%, grinded with a hammer mill, variation of the energy consumption versus mill rotor speed is graphically presented in Figures 6 and 7. It must be mentioned that willow biomass had the same initial particle dimensions as those that resulted from harvesting (meaning under 50 mm), but its humidity content decreased under normal conditions following storage in a dry chamber for 6 months.

From analyzing the graphical data from Figures 6 and 7, the general tendency of a decrease in specific consumed energy was observed, for grinding both types of biomass, as the mill rotor speed increased, even if the experimental determined values present random variations. Moreover, for using a sieve with smaller circular orifice size (10 mm instead of 16 mm), the necessary energy for grinding increased, for both types of biomass. Graphical data showed smaller values for grinding willow biomass, but it must be taken into consideration the fact that initial particle dimensions for willow were far smaller compared to the ones from the *Miscanthus* biomass.

In the given conditions, costs for pre-processing lignocellulosic and wood biomass increase if the grinding equipment is not chosen correctly, as well as parameters of working regimes of these types of equipment. Fracturing and bio-refining biomass for obtaining bio-products and bio-fuels also includes costs for pre-treating and mechanical pre-processing, like biomass grinding.

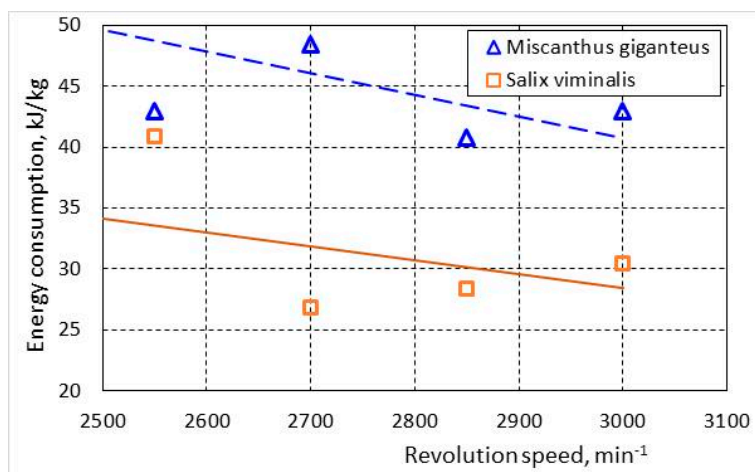


Figure 6. Variation of the energy consumption when grinding willow and *Miscanthus* biomass using a hammer mill and a 16 mm orifice sieve.

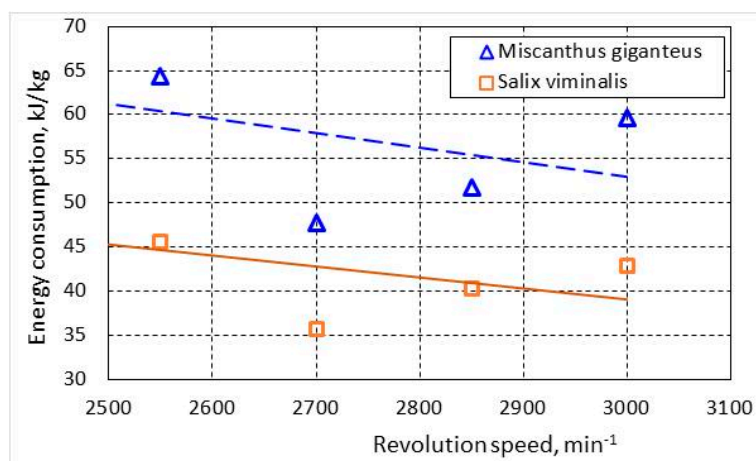


Figure 7. Variation of the energy consumption when grinding willow and *Miscanthus* biomass using a hammer mill and a 10 mm orifice sieve.

4. Conclusions

This paper presents experimental results regarding energy consumption, respective to the power necessity, for grinding some types of dried vegetal biomass, including alfalfa, mountain grass, and corn stalks, using a hammer mill with fixed knives, as well as obtained results for grinding *Miscanthus* and willow biomass using an articulated hammer mill.

From the experiments realized using the laboratory mill GM200, it was found that mountain grass and alfalfa require the smallest values of grinding power, compared to the corn stalks, more so for higher mill rotor speeds. Thus, the average necessary power for grinding alfalfa and mountain grass was between the limits of 480–410 W, for the mill rotor speeds from 3000 min⁻¹ to 9000 min⁻¹. For corn stalks the average necessary power for grinding was between 750–390 W, at the same speeds of the mill rotor.

Also, specific energy consumption was between the limits of 0.40–0.34 kWh·kg⁻¹ for alfalfa stalks and mountain grass, while for corn stalks this energy consumption was between the limits of 0.65–0.32 kWh·kg⁻¹, in the speed interval 3000–9000 min⁻¹.

It was observed that for the same speeds of the mill rotor, corn stalks were ground less than the other two types of biomass, while alfalfa obtained the highest level of grinding, especially at speeds of over 6000 min⁻¹.

When using mills with articulated hammers, specific energy consumption reached 14–18 kWh·t⁻¹ for harvested *Miscanthus* biomass, and 10–14 kWh·t⁻¹ for dried energetic willow biomass, while using a sieve with 10 mm orifices. For bio-refining and fracturing, biomass particle dimensions must be relatively reduced, and grinding should be continued until reaching the desired dimensions. These consumption values actually mean 14–18 kWh/Mg for *Miscanthus* biomass, and approximately 10–14 kWh/mg for energetic willow biomass.

If a kWh of electrical energy costs approximately 10 euro cents for industrial consumers or even more, then for processing large quantities of biomass, just the biomass grinding process (or mechanical pre-processing) has relatively high costs.

Obtained results should be used for choosing the mechanical pre-processing equipment for biomass, but also the working regimes, mainly when they are used for transforming biomass into bio-fuel or bio-products, through bio-refining or chemical fracturing.

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Influence of Different Types of Substrate on the Anaerobic Fermentation Process

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Abstract

*With the growing prices on fossil fuels and the negative impact that they have on the environment it can see the necessity to integrate renewable source energy for consumption. One of these that stand forward is biogas produced from anaerobic fermentation process. This type of energy diminishes the impact on the environment by reducing greenhouse gases and is useful for producing electrical and thermal energy. Anaerobe fermentation process is regarded as a good solution because of two aspects: producing energy and giving a solution to rising quantities of junk. Biomass used in order to obtain biogas can be formed from urban solid and liquid garbage, animal and vegetal mass dejections. In the case of animal dejections they are being mixed with energetic plants or agricultural residue. The processing is realized by anaerobic fermentation process. The mix used for producing biogas was formed from animal dejections (bovine and pork) with energetic plant grind (*Miscanthus giganteus*) with different dimensions. Production of biomass expressed after 22 days of anaerobic fermentation showed the influence of energetic plants on the process of anaerobic fermentation. The three recipes used in the present paper were composed out of bovine dejections and *Miscanthus* green leaves mix of different dimensions (between 2-9cm), production of biomass being recorded for each type of recipe being tested, and the percentages that compose the biogas were recorded (CH₄ % v/v, H₂S % v/v and CO₂ % v/v). Results showed that the largest production of biogas with highest concentration of methane was obtained for the recipe in which green leaves of *Miscanthus* with dimensions of 2 to 5 cm were added.*

Keywords: biogas composition, animal manure, renewable energy, *Miscanthus x giganteus*

1. Introduction

In present time there are seven procedures of recuperation energy from organic agricultural residue: anaerobic fermentation at ambient environment temperature, anaerobic fermentation at high temperatures, thermophilic anaerobic discomposure, distillation, composting, incineration and heat transfer [1]. The highest potential comes from anaerobe fermentation, this being considered as one of the most attractive solutions to produce renewable energy from biomass. On average, at a fermentation plant out of a tone of residue mix can be obtain about 400-600 Nm³ of biogas out of which 50-70% methane [2]. Also, this represents an optimum treatment for vegetal and animal residue giving the fact that the substrate is transformed into renewable energy and fertilizer for agriculture [3]. As substrates for producing biogas can be used different varieties of substrate between which could outline

stable residue and secondary agricultural products, organic residues digestible from food industry and agro-industries (vegetal and animal), organic fraction and home residue and catering (vegetal and animal), sewage sludge, energetic cultures (corn, Chinese cane, clover) or adequate residue for biogas production [3]. The final result from the anaerobic fermentation process is biogas that represents a mixture of methane (CH_4) and carbon dioxide (CO_2), on which it can be seen traces of hydrogen sulfide and water vapors (S. KARELLAS & al. [4]). The process of biogas forming, anaerobic fermentation, takes place at temperatures between $20\text{--}45^\circ\text{C}$, in the presence of two species of bacteria: *Bacillus cellulosae methanicus*, responsible for methane yield and *bacillus cellulosae hydrogenicus*, responsible for hydrogen forming. After that, these two species have been reunited under the common name of methano-bacteria [1]. The four phases for anaerobic fermentation process are hydrolysis, acidogenesis, acetogenesis and methanogenesis (C. PARK & al. [5]).

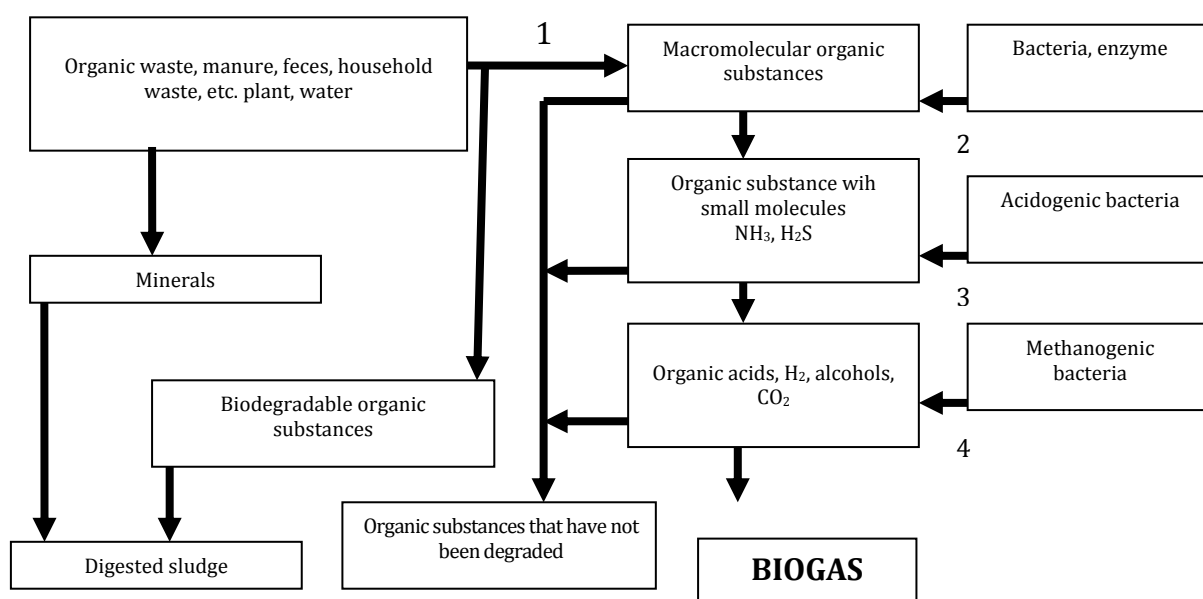


Figure 1. Biogas production scheme and presentation of anaerobic fermentation stages [6]

In order for the anaerobic fermentation to be made in a proper environment for development of microorganisms it is necessary that the material being used to favor this fact. So, the used substrate pH must be neutral and also it must not contain substances that inhibit the process of anaerobic fermentation as well as the C/N relation, it must have values between 15 and 25 (P. DOBRE & al. [7]). Due to a lack in adequate concentration of solids of animal dejections (smaller than 8%) although they contain necessary nutrients, in general are mixed with different types of agricultural or energetic residues (L. REGUEIRO & al. [8]). An optimum C/N relation can be obtained through fermenting matter that is rich in nitrogen together with lignocellulosic biomass (M. SEPPALA & al. [9]). The substrate being used must have a structure that permits liquid circulation through the entire solid mass. This is why high degree compacting matter is not used, as cow feces, or, if they are used, must be mixed with matter that will give texture and aeration, for liquid circulation (milled straws, vegetal substrate, etc.) [10]. The most used energetic culture both in agriculture as well as biogas production is corn culture. Starting from this fact in the moment of evaluating different substrates used in biogas production it was compared with corn biogas production in the process of anaerobic fermentation dejections [11]. Experimental researches in which corn was

used as co-substrate are most common in Germany (W. BRITZ & R. DELZEIT [12]). Taking into consideration the ongoing preoccupation for alimentary safety, it was necessary that the corn substrate to be exchanged with other types of culture, researchers attention being pointed to agricultural residues, alimentary residues as well as energetic cultures (*Miscanthus*, energetic plant, etc.), (H. UELLEND AHL & al. [13]). Perennial culture of *Miscanthus X Giganteus* can be used for biogas yielding but in mixture with other vegetal mass types. Due to its character this type of energetic plant can be harvested on polluted soil, without affecting the annual dry matter production (A. E. DARABAN & al. [14]). Thus experiments using *Miscanthus* as substrate in biogas yielding was used. In paper [15] the authors followed defining the quantity and biogas composition obtained as a result of using *Miscanthus* in experiments. Giant *Miscanthus* is a C-4 photosynthetic plant and, therefore it is characterised by greater carbon dioxide (CO₂) absorption. It grows very fast and due to plantation longevity (15–20 years) as well as big biomass productivity, it is recognised as a valuable, alternative source of energy (Sørensen et al. 2008 [16], Zawadzka et al. 2010, [17]). Comparing the results obtained by the authors with other researchers results it could be conclude that it is a viable culture for biomass yield through the process of anaerobe fermentation process as well as the fact that it can replace corn cultures used more often. During a similar experiment the quantity of biogas obtained was of 0.30 dm³/g with a 50.4% methane (Grala et al. 2011 [18], J. KAZIMIEROWICZ et al. [15]). Other experiments have showed that the use of *Miscanthus* culture is the best alternative to corn in the process of anaerobe fermentation, registering a biogas yield of $5.5 \pm 1 \times 10^3 \text{ m}^3 \text{ ha}^{-1}$, comparative to $5.3 \pm 1 \times 10^3 \text{ m}^3 \text{ ha}^{-1}$, obtained in the case of corn (F. MAYER & al. [19]). In the present paper the influence of different types of substrate was studied on the process of anaerobic fermentation. Returned parameters were evaluated following the process of anaerobic fermentation (CH₄, H₂S, CO₂) as well as the quantity of biogas being obtained for each type of substrate.

2. Materials and methods

1.1. Preparation of feed material and experimental set-up

During presented experimental researches in this paper fresh bovine dejections were used, obtained in June 2015 from a farm in Teleorman County, in mixture with energetic plant *Miscanthus giganteus* a perennial plant, sterile hybrid, harvested in the vegetation period from The National Institute of Agricultural Machinery, INMA Bucharest. So, bovine dejections were used in mixture with green leaves from the *Miscanthus* plant cut in different dimensions in three categories (2-5cm, 5-7cm, respectively 7-9cm). Leaves have been cut with the help of a special equipment for grinding vegetal material in INMA Bucharest. Experimental researches were carried out in a stainless steel bioreactor of 60l, thermal isolated, reaction environment being controlled with an electric boiler charged by photovoltaic panels. Through the command panel connected at the biogas installation pH and temperature of the fermenter were recorded. For the substrate to be homogenized, the fermenter was equipped with a palette agitator. This started automatically every 30 minutes being activated by an electric motor. Every 30 minutes the substrate was homogenized for 3 minutes. In order to measure the inside pressure from the inside of the reactor a low pressure sensing device with 0-3 bar was used, type HONEYWELL – MLH 010BGC14B. Experimental data obtained for the duration of fermentation process were recorded.

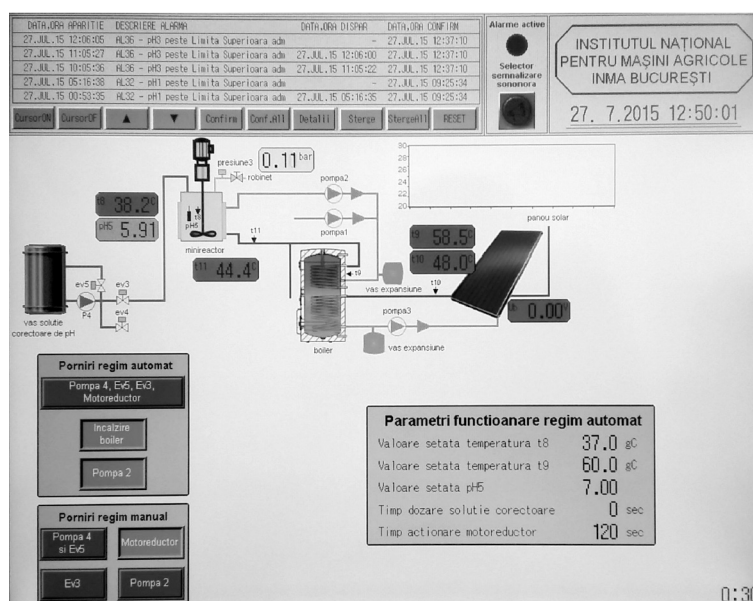


Figure 2. Biogas yield scheme and presentation of the anaerobic fermentation stages

Bovine dejections were mixed with *Miscanthus Giganteus* leaves and water, in quantities represented in table 1:

Taking in consideration the data from speciality literature, the C/N ratio of the mixture must have values of 20-30, in order for the anaerobic fermentation process to take place in optimum conditions. Also, this relation was calculated in accordance with proposed method by T. VINTILĂ and V. NICOLIK [20], having the value of 25.4 for used quantities.

Experimental researches have been achieved in Mesophilic conditions, temperature being raised to $37 \pm 1.5^{\circ}\text{C}$. This value of the temperature was maintained until the end of each experiment.

For all experiments, the value of pH was maintained in the optimum methanogenic bacteria optimal growth range (6.8-7.2) for the duration of the anaerobic fermentation process.

Duration of an experiment was 22 days, after which the biogas yield was insignificant.

Table 1. Tested substrate for biogas yield

Substrate	Quantity (kg)	C/N Ratio	Moisture content (%)
Substrate type 1			
Bovine dejections	16.5	25 [15]	86 [15]
<i>Miscanthus x giganteus</i> (leaf) 2-5 cm	3	26 [16]	85 [17]
Tap water	14	-	-
Substrate type 2			
Bovine dejections	16	25 [15]	86 [15]
<i>Miscanthus x giganteus</i> (leaf) 5-7 cm	2.5	26 [16]	85 [17]
Tap water	15	-	-
Substrate type 3			
Bovine dejections	16	25 [15]	86 [15]
<i>Miscanthus x giganteus</i> (leaf) 7-9 cm	2.5	26 [16]	85 [17]
Tap water	15	-	-

1.2 Analytical methods

Influence of different types of substrate on the process of anaerobic fermentation was realized through analysis and interpretation of the following values: v/v percentage of CH₄, H₂S, CO₂ as well as the biogas volume obtained for each of the three cases. Daily the volume of biogas was measured with a gas meter Sacofgas Milano, fitted with a pulse counter, 1 pulse = 0.01 m³. Biomass composition was measured with a portable gas analyzer Mentor/CombIR Series, equipped with methane sensors, carbon dioxide and hydrogen sulfide.

For the duration of biosynthesis, the sugar content and soluble protein from the filtrate it was determined, taking samples from the inferior part of the reactor thus determining the concentration ratio. Another analyzed parameter outlines the relation between soluble protein and sugars. In days 1, 4, 7, 14, 18, 22 mixture probes were taken from the bioreactor. The soluble protein was determined using Lowry method [21], as a benchmark for the analysis bovine serum albumin being used (Sigma Co) and the sugar concentration from the probes, we used the method that uses acid 3,5- dinitrosalicylic (DNS), [22]. Absorbance were measured with a spectrophotometer T92+UV VIS, PG Instruments.

3. Results and discussion

Results obtained for experimental determinations in a biogas small capacity installation are presented in tables 2 and 3. Based on the presented results in these tables methane variation, hydrogen sulfide variation, carbon dioxide variation and the biogas volume have been graphically drawn. The specific methane percentage in biogas for each type of tested substrate is shown in Figure 2. Methane is the most important component of biogas. The biogas heating power depends on its percentage in biogas production. It can be seen that the methane production on the first day of anaerobic digestion process was almost zero, in all cases; this fact could be attributed to the small amount of methanogenic bacteria present in bioreactor in initial phase.

Table 2. Methane, hydrogen sulfide and carbon dioxide variation during 22 days of experiments

Day	Substrate type 1			Substrate type 2			Substrate type 3		
	CH ₄ % (v/v)	H ₂ S% (v/v)	CO ₂ % (v/v)	CH ₄ % (v/v)	H ₂ S% (v/v)	CO ₂ % (v/v)	CH ₄ % (v/v)	H ₂ S% (v/v)	CO ₂ % (v/v)
1	0.00	0.84	13.00	1.20	0.81	11.50	2.40	0.79	10.00
2	2.40	1.82	27.33	9.20	1.81	23.17	16.00	1.80	19.00
3	12.80	2.89	35.67	17.60	2.92	35.33	22.40	2.95	35.00
4	24.53	3.67	44.67	24.27	3.68	44.33	24.00	3.70	44.00
5	33.07	3.78	50.67	30.13	3.72	51.83	27.20	3.65	53.00
6	38.93	3.27	44.33	34.67	3.33	46.17	30.40	3.38	48.00
7	43.47	2.74	35.33	37.73	2.93	39.67	32.00	3.12	44.00
8	46.67	2.16	30.67	40.53	2.40	36.33	34.40	2.64	42.00
9	50.13	1.92	28.00	43.47	2.19	34.00	36.80	2.46	40.00
10	52.53	1.69	27.00	45.87	1.92	31.00	39.20	2.16	35.00
11	54.13	1.42	25.67	47.87	1.70	28.83	41.60	1.98	32.00
12	57.33	1.20	23.00	50.67	1.55	25.50	44.00	1.89	28.00
13	58.93	0.97	17.33	52.27	1.25	21.67	45.60	1.54	26.00

14	58.40	0.82	15.33	53.60	0.98	19.17	48.80	1.14	23.00
15	53.60	0.78	13.33	54.40	0.81	16.17	55.20	0.84	19.00
16	46.93	0.62	12.67	51.87	0.68	15.33	56.80	0.75	18.00
17	38.40	0.50	9.67	43.60	0.58	12.33	48.80	0.66	15.00
18	32.27	0.44	9.00	34.13	0.48	11.00	36.00	0.53	13.00
19	29.33	0.40	7.67	30.67	0.44	9.83	32.00	0.48	12.00
20	28.27	0.35	7.00	28.93	0.42	9.50	29.60	0.48	12.00
21	24.53	0.35	6.00	25.07	0.40	8.00	25.60	0.44	10.00
22	23.20	0.31	6.00	22.80	0.35	7.50	22.40	0.40	9.00

Table 3. Biogas volume variation obtained during the 22 days (m³)

Day	1	2	3	4	5	6	7	8	9	10	11	12
Substrate type 1	0.000	0.019	0.043	0.073	0.098	0.141	0.169	0.189	0.191	0.209	0.221	0.206
Substrate type 2	0.00	0.02	0.04	0.06	0.08	0.11	0.14	0.15	0.17	0.18	0.19	0.18
Substrate type 3	0.000	0.012	0.028	0.047	0.068	0.086	0.102	0.117	0.139	0.151	0.157	0.162
Day	13	14	15	16	17	18	19	20	21	22	TOTAL	
Substrate type 1	0.186	0.161	0.121	0.101	0.095	0.087	0.071	0.056	0.049	0.035	2.521	
Substrate type 2	0.17	0.16	0.14	0.12	0.11	0.10	0.08	0.06	0.05	0.03	2.326	
Substrate type 3	0.160	0.155	0.149	0.138	0.125	0.103	0.086	0.070	0.050	0.026	2.131	

After about 6 days, the CH₄ concentration of the produced biogas for all three types of substrate was in the range of 32–43% (v/v). As expected, the dimensions of Miscanthus leaves fragments presented a moderate influence on the volume and yielded biogas composition, determining a rise of the CH₄ percentage out of the total biogas volume obtained. Different values of the methane concentration represents a rise of 9% towards CH₄ for the case of using substrate 2, considered a reference, for which the volume of CH₄ was minimum. The highest methane concentration of about 59% v/v was recorded on day 13 in the case of substrate type 1 where was used cow manure mixed with miscanthus leaves of 2-5 cm unlike the case of substrate type 3 where was used cow manure with miscanthus leaves of 7-9 cm when the highest value of methane concentration, about 57 % v/v was recorded on day 16.

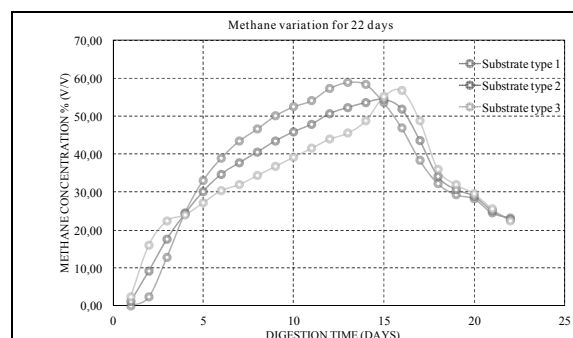


Figure 2. Variation of methane concentration % (v/v) during 22 days of experiment

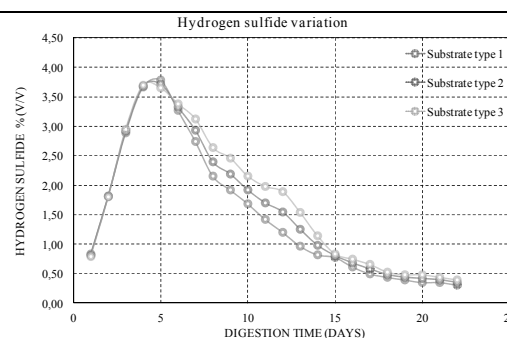


Figure 3. Variation of hydrogen sulfide concentration % (v/v) during 22 days of experiment

In the case of CO₂ and H₂S synthesis the results were similar, the size of leaf fragments having insignificant influence. Variations of CO₂ and H₂S is presented in figures 3 and 4.

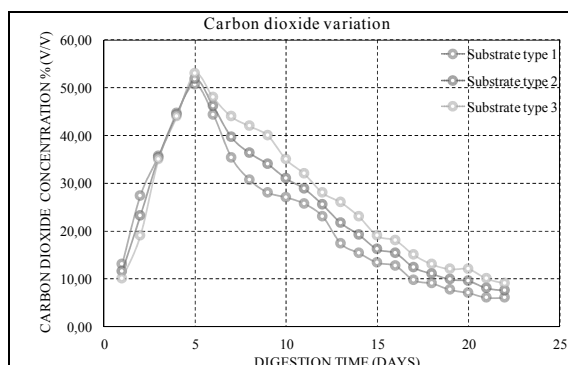


Figure 4. Concentration of carbon dioxide for all types of substrate

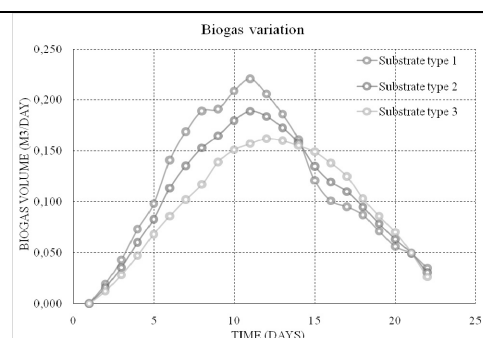


Figure 5. Biogas volume obtained for each day of experiments

Regarding biogas production curve (Figure 5), it could be observed that the highest total biogas yield was obtained from the substrate type 1 that contains cow manure and miscanthus leaves of 2-5 cm. The maximum value of total biogas production during the 22 days of anaerobic digestion was about 2.53 m³. From all types of substrate, it can be seen a delayed start of biogas production, this phenomenon being due to the lag phase of bacterial growth, required for adaptation of cells to the new culture conditions. In the case of using substrate 1 containing Miscanthus leaves with 2-5 cm in dimension it was observed that the biogas total volume is larger by 7.7%, than in the case of substrate 2 and with 15.4% higher than the obtained volume from substrate 3. With all this, the growth of the CH₄ percentage and the biogas total volume should be correlated with the energy consumption necessary for grinding the leaves into smaller fragments for a proper evaluation of the treatment energy efficiency. It is possible that the influence of the grinding degree on the biogas production to be minimal knowing that the rise of foliar fragment is not significant. In this case of Miscanthus leaf geometry, the sacking of surface of fermentescible fragment and so the transfer of nutrients from the foliar tissue towards the fermentation environment are minimal. Also, referring to the soluble protein and sugar ratio the fact that the greater ratio on 0,207 was registered in the case of substrate 1 must be mentioned, which evidences the way in which the used recipe (miscanthus particle dimension) influenced all the analyzed parameters during this paper, including this relation.

Table 4. Soluble protein and sugar concentrations

		Protein content (mg/ml)	Sugar concentration (mg/ml)	Ratio soluble protein/sugar
Substrate type 1	Day 1	0.6	3.80	0.157895
	Day 22	0.54	2.6	0.207692
Substrate type 2	Day 1	0.65	4.3	0.151163
	Day 22	0.51	3	0.17
Substrate type 3	Day 1	0.7	4.80	0.145833
	Day 22	0.47	2.60	0.180769

Researches will be continued using different substrates and also with different dimensions of vegetal material. Results are in correlation with the data in literature but an economic analysis for the processes should be made.

2. Conclusions

In this paper production of biogas and methane concentration was evaluated, as well as time variation of the animal dejection substrate in mixture with the *Miscanthus X giganteus* energetic plant, using a low capacity installation for biogas yield at 35(±1)°C, neutral pH and intermittent mixing. The installation worked for 22 days, time necessary for a complete cycle of anaerobic fermentation for the used substrate. Evaluating the potential for obtaining biogas from the *Miscanthus* energetic plant is very important, because in our current times there is a constant rise in interest for finding biomass harvests with a high energy content, low production costs and minimal effects on the environment). The results presented in this paper show that the use of *Miscanthus x giganteus* mixed with cow manure for biogas production is a challenging process and that the substrate composition has a great influence on the anaerobic digestion process performance. The maximum value of total biogas production during the 22 days of anaerobic digestion of animal manure and *Miscanthus x giganteus* was about 2.131m³ for 33.5 kg mixture containing recipe no 1.

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Article

Digital Twin and Smart Manufacturing in Industries: A Bibliometric Analysis with a Focus on Industry 4.0

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Abstract: Technology is being used in our society in all areas, mostly in industry, and generates the most interest in current research since it is a part of day-to-day activities. The main objective of this research was to use bibliometric analysis to analyze the production of scientific literature on digital twin and smart manufacturing with a focus on Industry 4.0, using information from the Web of Science database. To conduct the study, the keywords necessary for data selection were chosen, and then analyzed based on different variables such as author productivity, citations, most productive institutions, publishers with the highest number of publications, scientific document classification, countries with the highest number of publications, and a network analysis using VOSviewer. The results showed Tao F. and Soderberg R. were the main authors, that China was the country with the highest knowledge, and Elsevier was the main publisher. Although the subject has only been in publication for five years, digital twin will constitute an important part of future technologies due to its rapid ascension, proof of this being its yearly productivity (2020 producing the highest number of materials). Papers published in 2021 were excluded, but the difference between the numbers of materials found and those analyzed shows that 2021 will be even more productive than 2020.

Keywords: digital twin; smart manufacturing; Industry 4.0; bibliometric analysis



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1. Introduction

Technology expansion and consolidation are key components of all activities, whether concerning natural science or industry. New challenges facing competitive markets impose a new approach, thus digitalization is seen as an opportunity for industries, because using digitalization in manufacturing can achieve higher productivity [1]. Taking advantage of the new technologies in constant development will ensure companies from different industries maintain their competitive edge in an increasingly competitive market.

Since the advent of the first computers, the first element of technology, people have tried to abstractly model the different problems they were facing, with the intention of finding answers using processing power. In recent times, industries have focused on the new concept of digital twin [2]. According to research, digital twin offers professional products and services and a partnership responsible for the total digitization of design and manufacturing processes [3–6]. Digital twins are currently being developed for every process, product, or service in a company, in order to simulate all kinds of scenarios before their commencement in the physical world.

Due to exponential technological advance, highlighted by storage capacity and processing power, applications have contributed to the development of the fourth technology revolution known as Industry 4.0 (a set of technological principles aimed at taking full advantage of the new technologies). This allowed for an easy and rapid connection between people, assembly lines, machines, robots, and processes, etc., [7].

According to [8], the number of publications on digital twin show a rapid growth from around 2016, then a doubling of growth every year.

Smart manufacturing could optimize manufacturing procedure and the entire business process in terms of achieving higher productivity, while lowering costs and waste material [9]. The once-known process of manufacturing, making goods to be sold and bought, human labor, tools, equipment, etc., is now a smart process due to the digital transformation of manufacturing. The implication of “smart” technologies is aligned with the principles of the fourth industrial revolution [10]. Additionally, integration of the manufacturing system both on a vertical and horizontal level is smart manufacturing from the facility level [11]. To classify the smart manufacturing system, scientists use sustainability and asset utilization [12]. Since the use of smart manufacturing can be applied in various industries, a series of elements such as technologies, factors and characteristics need to be known. Even though smart manufacturing is a huge leap forward for companies, specially tailored methodologies are constantly being developed for many industries, allowing even greater optimization to take place.

When connecting the terms digital twin and smart manufacturing, it is observed that digital twin is an important part of smart manufacturing innovation [13]. The merger of digital twin and smart manufacturing services could make important changes in the usage, product design, and other types of processes [9,14–17]. Data streams are constantly being analyzed through digital twin, thus, the results may present trends in the actual performance of the manufacturing process. The comparative analysis that can be performed can help optimize the manufacturing process in the real world [18]. Virtual models of physical objects created using digital twin can help simulate their behavior, thus understanding of their state, and estimating and analyzing the dynamic changes [17,19,20]. In this way, constant optimizations in the design phase, in a virtual environment, eventually lead to the direct production of the target product, without discovering mistakes later in the production phase that otherwise would cost enormous quantities of money.

By adding the term Industry 4.0 to the database search of publications and scientific data, it can be observed that the appearance of Industry 4.0 and technical resource possibilities have enabled the progress of digital twin, and thus smart manufacturing [21].

This is a normal process, because of a single factor: disruption coming from new companies. Industry 4.0 can help start-ups leverage the advantage of traditional original equipment manufacturer (OEMs), by directly implementing the concepts of digitalization, cloud, smart factory, and smart manufacturing [22–27]. Industry 4.0 closed the gap between these large companies and newcomers, so that every company in every industry moves towards these concepts, to maintain their competitive edge, but more importantly, secure their future in their respective market.

The end users are receiving the best from both worlds: they receive optimized products to best fit the market’s needs, while procuring them at a cheaper price due to competition, and companies achieve cost savings by producing error-free products.

The construction industry is heavily affected by challenges due to low productivity and poor technology adoption. The authors of [28] analyzed the current state of DT concept and adoption in the construction industry, showing that there is a high potential for the use of digital twins to solve numerous challenges in the construction industry.

The use of digital twins is heavily increasing within smart cities, due to the rapid development of connectivity and internet of things (IoT). A growing number of cities are becoming “smart”, thus communities benefit from the use of smart city digital twins. Another benefit is that the use of digital twins will determine research for advanced AI algorithms [29].

The importance of digital twins in the construction industry was also described by [30], who noted that while digital twins enable the bi-directional flow of data between digital and physical entities and consequently change each other, digital shadows represent a physical model with only one-way data flow. Despite particular challenges, digital twin technologies

are gaining popularity in various sectors, and the greatest pull for this technology is coming from industry [31,32].

Smart buildings require expensive operation and maintenance, outlining the need for digital twins, created from building intelligent management systems to improve these operations [33]. This can lead to beneficial interactions between users, the digital twin and the application framework, with the purpose of lowering maintenance costs.

Digital twins and smart manufacturing have also begun to make an impact in smart prognostics and health management systems [34]. Interconnectivity and the large gathering of data helps to detect faults. The use of smart prognostics and health management systems applies to any manufacturing operation across industry. Data acquisition, preparation and analysis, and modeling lead to better predictions and deployment.

The issue of health diagnosis and the benefits of digital twin have also been researched by [35], outlining the need for an intelligent health diagnosis and maintenance method for smart manufacturing, enabling maintenance personnel to identify significant influencing factors without knowing the health degradation of the equipment.

The authors researched the use of digital twin on the prognosis and health management of a proton exchange membrane fuel cell, reaching a high prediction accuracy, despite limited measurement data [36].

Even though smart manufacturing is being successfully implemented in different industries, research regarding the new 5G connectivity and its benefits are limited, according to [37]. In their paper they outlined the importance of Industry 4.0 and digital twin in reaching the potential of 5G networks.

Another research conducted a survey for the shipbuilding industry, investigating the adoption level of smart manufacturing and digital twins in eight shipyards from South Korea, proposing a new framework for smart shipyard maturity level assessment. Their results showed that adopting smart technologies for smart manufacturing led to better results than conventional methods [38].

Also the way DT and Industry 4.0 is changing the shipbuilding industry was discussed by researchers. Many issues that this industry faces generate losses, such as quality requirements, market fluctuations, and safety [39]. Therefore, in their research, scientists designed an implementation mode using different tools (CAD, 3D tools, PLM, simulation charts, simulation modeling tools, decision making methods, etc.) to create a model that they proposed to apply for a creation shipyard [39]. Researchers in [40], with the aim of connecting the Industry 4.0 technologies to the supply chain, showed that the shipbuilding supply chain should be lean and green, both very important paradigms.

Automotive manufacturers are constantly faced with difficulties in delivering to an on-time schedule due to constant changes in orders and requirements from their customers. Researches proposed a web-based cyber-physical system based on digital twin for abnormal scenarios in automotive industry production lines, and its capability was tested via experiments [41]. Their conclusions were very promising, reaching an average prediction performance of 94% for the production plant, thus confirming that it could be a solution to predicting whether production was possible according to the production plan.

With the exception of using DT for the manufacturing process, there is concern within the automotive industry regarding privacy, because DT in smart cars can collect data—starting from the manufacturing process, through the operational driving stage, the decision-making stage which is based on measurements and historical data, and in the final reporting stage. Considering this, scientists have analyzed the automotive ecosystem from the point of view of privacy problems/anomalies with the intention of reducing risk [42].

Another important area where digital twin can bring considerable improvement is in the energy sector. As the electricity sector is one of the main polluters when it comes to greenhouse gas emissions, it is necessary to assess the situation and see how digital twin and smart manufacturing can bring value [43]. By using digital twin to create a way to monitor the energy system, the industry can achieve a better view of the entire process—

from modeling a service to customer behavior—which will allow it to achieve a pattern that will lead to a reduction in energy consumption [44].

Regarding the renewable energy sector, the authors of [45] tested digital modeling with the generative power system, with the aim of solving some problems. They used a hybrid renewable energy system that was useful in updating DT in the energy sector, concluding that the components of the architecture were very important for the design of future power systems. Additionally, in [46] the author presented the application of Industry 4.0 for the integration of distributed energy resource applications using a predictive analysis model.

Another area where digital twin is recording impressive results is in the retail industry, where it is being used to improve product delivery and customer service by better analyzing customer behaviors and feelings, products, and other elements. Using proper tools allows retailers to have an overview of the process, exploring the materials, products, customer feedback, sales (local, regional, national, or international), costs, and—not to be forgotten—production time [47].

Creating new revenues and answering strategic questions are the main values that can be created with digital twin. Questions that once had no answer or could not be answered may find a solution using the applications of digital twin.

The main objective of this study was to perform a bibliometric analysis of the articles published in the Web of Science (WoS) database on digital twin and smart manufacturing, and then to determine the extent to which these keywords were in correlation with Industry 4.0. Therefore, the general search focused on digital twin and smart manufacturing, and the specific search focused on digital twin and smart manufacturing and Industry 4.0. For this purpose, the following questions guided this research:

Q1. How did the publications on digital twin and smart manufacturing evolve? How did they evolve for digital twin and smart manufacturing and Industry 4.0?

Q2. Which authors have published the highest number of publications on the subject, and which authors have the highest number of citations?

Q3. Which institutions, publishers and countries focused most of their attention on digital twin, smart manufacturing, and Industry 4.0?

Q4. What type of documents are most frequently published?

Q5. What citation nodes are the most influential in the network map?

The results showed that the number of published articles has significantly increased in the last two years (2019 and 2020). The author analysis revealed that Tao F. was the author with the highest influence among the scientific community with regard to digital twin and smart manufacturing, but Soderberg R. was the author that most presented the relation between digital twin, smart manufacturing, and Industry 4.0. As we can see from both analyses conducted, it is only in recent times that the subjects have increased in publication, and are rapidly becoming of interest, which can only mean that technologies implemented in the future will be part of these areas. There are some clusters of collaboration between authors, with other clusters still developing, and soon they will all form a network of data and information useful both for the academic community and for the socio-economic environment.

In order to answer all the research questions and achieve the desired objectives, the article is divided into two sections, one for the general search using digital twin and smart manufacturing, and the other for the specific search which included Industry 4.0. The framework is presented, the method of the study is presented, and the results and discussions on the bibliometric analysis are then presented. Additionally, the limitations of the study and some future lines of research are presented, with the article ending with conclusions on the results found.

2. Materials and Methods

The researchers considered the structure of bibliometric studies, where a topic is being studied and evaluated, for this paper's structure and presentation.

To conduct the study, the literature search took place during September 2021 using the Web of Science database. This database was selected as the source of data collection because for researchers and university professors in Romania, this is the platform with the highest degree of stringency and most prestigious work, and its prestige is international. As Web of Science contains the best scientific productions in various fields and the papers from this database have a high impact factor, which is a very important indicator in Romania then this is one of the reasons of choosing it. It also offers, most recently, many features that can be used in searching, selecting and gathering information.

In order to obtain the final samples to analyze, we first began by choosing the keywords needed to conduct the search in the platform ISI Web of Science. The keywords chosen were digital twin and smart manufacturing. In the search field we used "digital twin" AND "smart manufacturing", thus obtaining 397 documents. Second, since we wanted to focus also on Industry 4.0, we added a more specific search where we used the three keywords connected by "AND". This search yielded 173 results.

To refine these results, we used some inclusion and exclusion criteria that led us to the samples used for the bibliometric analysis. These criteria were:

- a. The inclusion criteria:
 - Use of "digital twin" AND "smart manufacturing" for the general bibliometric analysis;
 - Use of "digital twin" AND "smart manufacturing" AND "Industry 4.0" for the specific bibliometric analysis;
 - Production of materials up to 2020;
 - Web of Science collection;
- b. The exclusion criteria:
 - Material published in 2021, due to the fact that the year was not yet complete;
 - Other scientific databases.

After applying these criteria, we obtained 276 materials out of 397 materials for the more general search, and 121 materials out of 173 for the focus of the article. The flowchart regarding the methodology is presented in Figure 1.

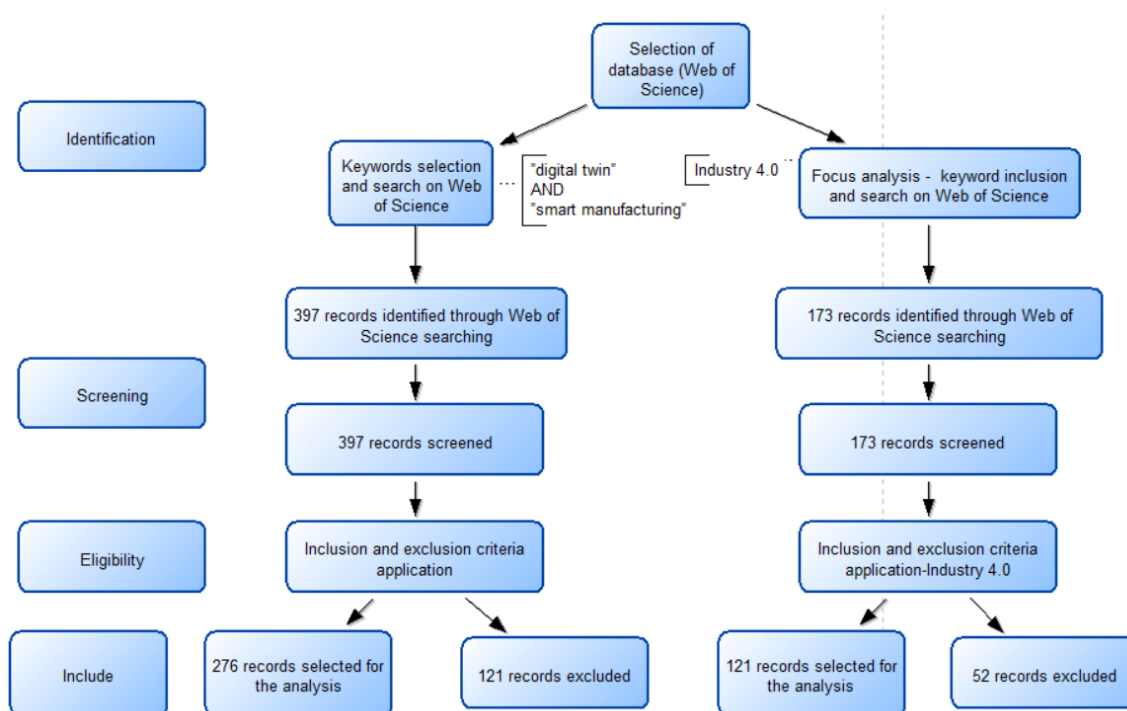


Figure 1. PRISMA flowchart that shows the step-by-step process of the application of inclusion and exclusion criteria that generated the final number of studies for analysis.

The next step was to download all the records in plain text with all the information given: publication type, authors, author keywords, abstract, researcher IDs, times cited, publication date, etc. After this, the downloaded database was verified to see whether it contained duplicate records that needed to be deleted in order to conduct the bibliometric analysis.

To have a bibliometric analysis that is both qualitative and quantitative, we also analyzed the journals in which the materials were published.

The general bibliometric analysis was conducted in the following order: first, the yearly productivity of publications on the subject; second, determination of the most productive authors, with affiliations, citations and impact index in all three areas; third, the most productive institutions; fourth, the publishers with the highest number of publications; fifth, an analysis of the classification of scientific documents; sixth, the countries with the highest number of publications; and then we created the network of citation analysis, using the authors as a unit, with the help of VOSviewer.

3. Results

This section presents the results obtained, firstly from the general bibliometric search (digital twin and smart manufacturing), and then the results for the specific search (digital twin and smart manufacturing and Industry 4.0).

3.1. General Search: Digital Twin and Smart Manufacturing

As mentioned previously, a total of 276 articles, published in journals, written by 898 authors from 393 institutions and 49 countries, were found. Therefore, the basic bibliometric indicators such as year of publication, most productive authors, journal, institutions and countries, and the connection between descriptors, is presented.

Figure 2 presents how literature has been distributed since the initial presentation of the topic in a material in 2016, until 2020. It can be observed that the last two years, 2019 and 2020, constitute 78.63% of the total scientific production of these five years. This increase demonstrates the interest that digital twin is garnering in industry, and the strong connection to smart manufacturing. The trend seems to indicate a continuous growth in the number of materials published.



Figure 2. Diachronic productivity of digital twin and smart manufacturing materials published in Web of Science since 2016.

A total of 898 authors contributed to publishing at least one article on the subject analyzed. Among them were some researchers that had high productivity in the field such as Tao F. with 12 materials, followed by Soderberg R. with eight materials published, and then five authors with seven materials. These authors and others are presented in Table 1. Additionally, the impact index column in Table 1 shows that Tao F. was not the author with the highest value; that author was Qi Q. L. with 179.5, compared with Tao's 137.08.

Table 1. Most productive authors (≥ 6 papers), with affiliations, citations and impact index in digital twin and smart manufacturing.

Author	No. Doc	%	Citations in WoS Core	Impact Index	Affiliations
Tao F.	12	0.4348	1645	137.08	Beihang University
Soderberg R.	8	0.0289	196	24.5	Chalmers University of Technology
Leng J. W.	7	0.0253	423	60.43	Guangdong University of Technology
Liu Q.	7	0.0253	423	60.43	Guangdong University of Technology
Parlikad A. K.	7	0.0253	54	7.71	University Cambridge
Warmefjord K.	7	0.0253	194	27.71	Chalmers University of Technology
Xie X.	7	0.0253	42	6	University Cambridge
Lu Q. C.	6	0.0217	54	9	UCL
Noh S. D.	6	0.0217	66	11	Sungkyunkwan University
Qi Q. L.	6	0.0217	1077	179.5	Beihang University
Zheng P.	6	0.0217	212	35.33	Nanyang Technology University
6 researchers	5	-	-	-	-
10 researchers	4	-	-	-	-
22 researchers	3	-	-	-	-
104 researchers	2	-	-	-	-
745 researchers	1	-	-	-	-

There was a total of 393 institutions, but just five of them stood out in terms of most numerous scientific production, with more than seven publications (65 institutions had six publications, respectively). The institution in the first place was Beihang University with 13 publications, followed by Chalmers University of Technology with 12 publications, and third, Guangdong University of Technology with 10 publications. If we analyze the first 70 universities, we can see that they mostly were from countries such as China and USA. The institutions with the highest number of publications in digital twin and smart manufacturing are presented in Table 2.

Table 2. Most productive institutions (≥ 7 papers), with citations and impact index in digital twin and smart manufacturing.

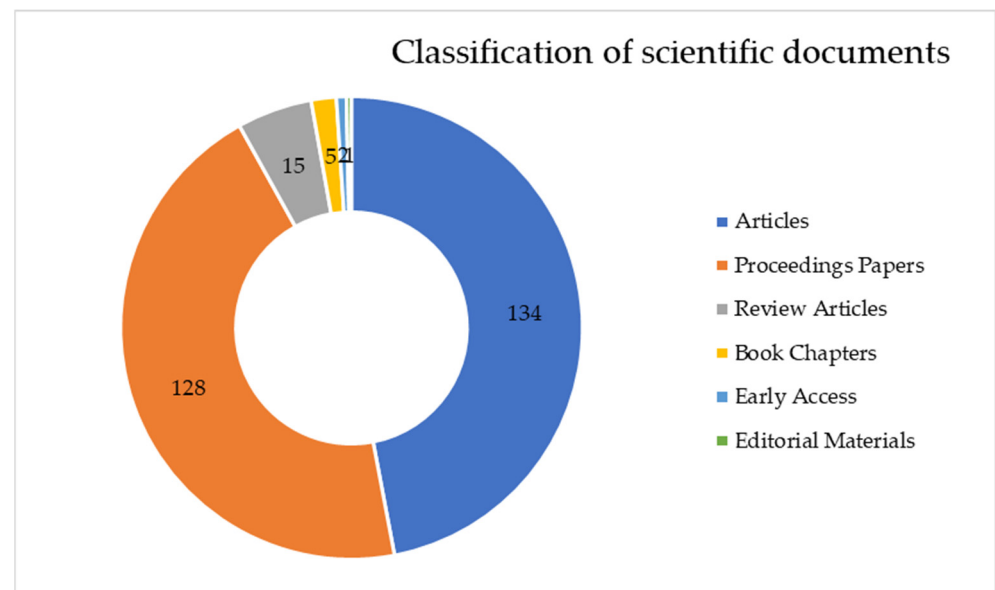
Affiliations	No. Doc	%	Citations	Impact Index
Beihang University	13	0.047	1648	126.77
Chalmers University of Technology	12	0.043	267	22.25
Guangdong University of Technology	10	0.036	455	45.5
Sungkyunkwan University SKKU	7	0.025	106	15.14
University of Cambridge	7	0.025	104	14.85
7 institutions	6	-	-	-
6 institutions	5	-	-	-
4 institutions	4	-	-	-
21 institutions	3	-	-	-
59 institutions	2	-	-	-
291 institutions	1	-	-	-

The next step, as presented in Table 3, was the journals analysis. A total of 35 journals were found to have published materials from researchers on this subject. The publisher with the highest number of articles published on this topic was Elsevier (89 documents), which also had the highest number of citations. The publisher with the next highest number of articles was IEEE with 59 documents, however, the impact factor of "Proceedings of IEEE" was 10,961 and the "Article Influence Score" was 4.298, unlike Elsevier where some journals did not have an impact factor and the journals mainly about medicine had the highest impact factor. Table 3 presents the journal publishers that published the most articles, with the number of citations and the impact index.

Table 3. Publishers with the highest number of publications (≥ 3 papers) with citations and impact index in digital twin and smart manufacturing.

Publisher	No. Doc	%	Citations	Impact Index	H-Index
Elsevier	89	32.24	2451	27.54	25
IEEE	59	21.37	1348	22.85	13
Springer Nature	46	16.66	1273	27.67	14
Taylor & Francis	19	6.88	390	20.53	9
MDPI	14	5.07	270	19.29	8
American Society of Mechanical Engineers	7	2.54	12	1.71	2
Iop Publishing Ltd.	4	1.45	12	3	1
American Society for Testing and Materials	3	1.09	6	2	2
Korean Society for Precision Engineering	3	1.09	13	4.33	2
Sage	3	1.09	14	4.67	2
4 journals	2	-	-	-	-
21 journals	1	-	-	-	-

Figure 3 shows the distribution of the different types of scientific publications. The great majority of publications were scientific articles closely followed by proceedings papers.

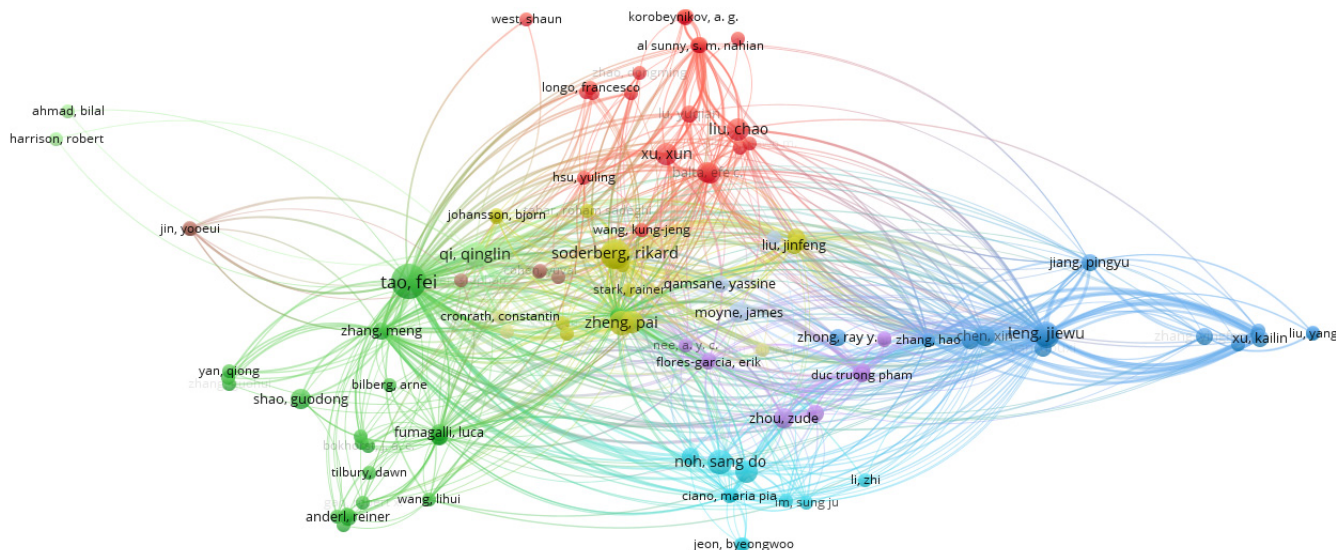
**Figure 3.** Classification of scientific documents on digital twin and smart manufacturing.

In order to see which part of the world was most preoccupied with the subject, an analysis of countries in relation to the numbers of publications was undertaken. Table 4 shows the countries with the highest number of publications (≥ 3 papers). It can be seen that the countries with the highest number of authors who had published at least one material in digital twin and smart manufacturing were China (66), followed by USA (43), and then Italy (31). In countries where one or two articles have been published, we can observe that the subject is becoming a subject of interest, and that development on this topic will increase.

Table 4. Countries with the highest number of publications (≥ 3 papers) with citations and impact index in digital twin and smart manufacturing.

Country	No. Doc	%	Citations	Impact Index	H-Index
China	66	23.913	3147	47.68	26
USA	43	15.580	541	12.58	11
Italy	31	11.232	534	17.23	12
Germany	24	8.696	388	16.17	9
South Korea	22	7.971	158	7.18	7
Sweden	21	7.609	382	18.19	8
England	20	7.246	306	15.3	9
Singapore	15	5.435	598	39.87	8
Russia	8	2.899	20	2.5	2
Austria	7	2.536	39	5.57	2
5 countries	6	-	-	-	-
3 countries	5	-	-	-	-
5 countries	4	-	-	-	-
5 countries	3	-	-	-	-
6 countries	2	-	-	-	-
15 countries	1	-	-	-	-

Regarding the networks that can be created, we analyzed the network of citation based on the authors (as a unit of analysis). VOSviewer was used to visualize the networks. As can be seen in Figure 3, there were 11 clusters and 1438 links, and the total link strength was 2186. Only authors with a minimum of two documents were analyzed, and of the total number of authors, only 141 met the threshold. Based on all the authors, the largest set of connected items consisted of 120 items (Figure 4).

**Figure 4.** Network of citation analysis using the authors as a unit (general analysis).

By conducting an analysis of the resulting clusters, we found that, for example, the largest cluster had 25 items, followed by a cluster of 23 items, and two clusters of 15 items. The main contributors in the first cluster were: Al Sunny, Balta Efe, Barton Kira, Choi Sangsu, Hsu Yuling, Hu Liwen, Korobeynikov, Leu Ming, Liu Chao, Longo Francesco, Lu Yuquian, Ngoc-tu Nguyen, Nicoletti Letizia, Padovano Antonio, Shahriar Rakib, Shukalov, Tilbury Dawn, Wang Kung-Jeng, Wang Wei, West Shaun, Xu Xun, Zakoldaev, Zhao Dongming, Zharinov I., and Zuo Ying. An analysis of the ideas published in the biggest cluster mainly showed a digital twin framework for smart manufacturing, performance monitoring and anomaly detection, service-oriented application

for a 4.0 knowledge navigation in the smart factory, virtual factory of the Industry 4.0, and automation, etc., [48–53].

The second largest cluster presented digital twin as a comprehensive digital representation of an individual product in which a digitalized product life cycle will play an integral role. Additionally, the authors presented the challenges and constraints that companies face when trying to implement these systems. The communication aspect of digital twin with a number of other applications was shown as a major factor in achieving a complete virtual representation of an asset, process or product. Another element identified as a part of the analysis conducted in this cluster was also the analysis of the symmetry between real and virtual space that enables the analysis of systems under real world conditions. All this could be possible if multiphysics models, sensors and bidirectional data connections between the digital and the physical twin are used [15,17,54–60].

Figure 5 exemplifies the importance and influence of Tao F. on the subject, which coincides with the previous analysis.

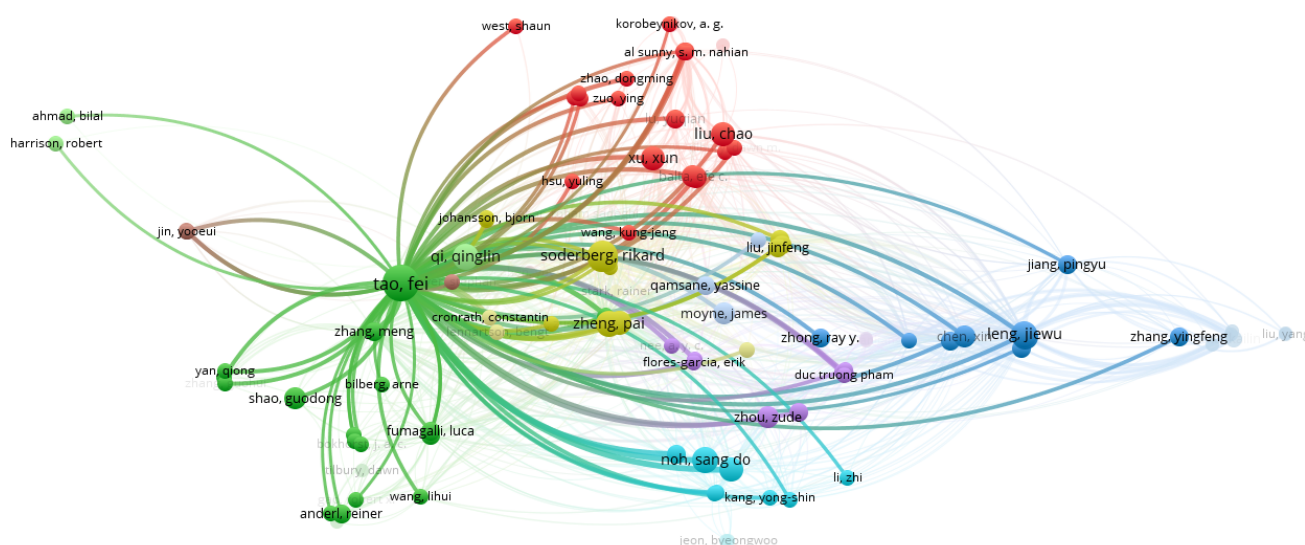


Figure 5. Network of Tao F. citation analysis using the authors as a unit (general analysis).

3.2. Specific Search: Digital Twin and Smart Manufacturing and Industry 4.0

For the specific analysis, a total of 121 articles were found, published and written by 395 authors, from 205 institutions, and 43 countries. Similar to the general search and analysis, the basic bibliometric indicators such as year of publication, most productive authors, journal, institutions and countries, in addition to the connection between descriptors, is presented.

Figure 6 shows how the literature has been distributed since the initial presentation of the topic in a material in 2016, until 2020. It can be observed that, similar to the general search, the latter two years, 2019 and 2020, represented 76.7% of the total scientific production. Although the increase between 2019 and 2020 was not that high as 2018 to 2019, we can still say that there was an increase in publication of the subject among researchers.

A total of 395 authors contributed to publishing at least one article on digital twin and smart manufacturing, and Industry 4.0. Under this criteria, the top researcher, namely, the one with the highest productivity, was Soderberg R. with seven materials. In the general search, he was the second highest author to have published an important number of publications. Lindkvist L., Liu C. and Xu X. were authors with more than six publications who were not present in the first search. Regarding citations, Tao F. was also in first place with an impact index of 221, compared with the next author, of just 86.75, as it can be seen in Table 5.



Figure 6. Diachronic productivity of digital twin and smart manufacturing and Industry 4.0 materials published in Web of Science since 2016.

Table 5. Most productive authors (≥ 4 papers), with affiliations, citations and impact index in digital twin and smart manufacturing and Industry 4.0.

Author	No. Doc	%	Citations in WoS Core	Impact Index	Affiliations
Soderberg R.	7	5.785	194	27.71	Chalmers University of Technology
Warmefjord K.	7	5.785	194	27.71	Chalmers University of Technology
Lindkvist L.	4	3.306	166	41.50	Chalmers University of Technology
Liu C.	4	3.306	231	57.75	Cardiff University
Tao F.	4	3.306	884	221.00	Beihang University
Xu X.	4	3.306	347	86.75	University Auckland
5 researchers	3				
30 researchers	2				
354 researchers	1				
745 researchers	1	-	-	-	-

Table 6 shows the affiliations of the authors. Only a few of the 205 institutions stood out with more than four publications on the subject. The institution with the most numerous scientific production was Chalmers University of Technology with eight publications, followed by Beihang University and Polytechnic University of Milan, each with five publications. The institutions with the highest number of publications in digital twin and smart manufacturing, and Industry 4.0, are presented in Table 2. There were 174 institutions with just one material.

Table 6. Most productive institutions (≥ 3 papers), with citations and impact index in digital twin and smart manufacturing, and Industry 4.0.

Affiliations	No. Doc	%	Citations	Impact Index
Chalmers University of Technology	8	6.612	198	24.75
Beihang University	5	4.132	889	177.8
Polytechnic University of Milan	5	4.132	310	62
Guangdong University of Technology	4	3.306	176	44
University of Auckland	4	3.306	347	86.75
Aalborg University	3	2.479	51	17
Nanyang Technological University	3	2.479	190	63.33
National Institute of Education Singapore	3	2.479	190	63.33
RWTH Aachen University	3	2.479	3	1
22 institutions	2			
174 institutions	1	-	-	-

Similar to the general search and analysis, the next step, as presented in Table 7, refers to the publishers. Again, Elsevier was the publisher with the highest number of publications (40), followed by IEEE with 27 publications. The difference between this and the earlier analysis is that MDPI is now in fourth place, and Taylor & Francis is in fifth, while previously for the general analysis it was the other way around. Although Springer Nature was in third place, MDPI had a higher impact index and, respectively, H-index. Table 7 presents the publishers that published the most articles, with the number of citations and the impact index.

Table 7. Publishers with the highest number of publications (≥ 2 papers) with citations and impact index in digital twin and smart manufacturing and Industry 4.0.

Publisher	No. Doc	%	Citations	Impact Index	H-Index
Elsevier	40	33.058	1636	40.9	18
IEEE	27	22.314	1069	39.59	9
Springer Nature	17	14.050	198	11.65	5
MDPI	10	8.264	151	15.1	7
Taylor & Francis	5	4.132	47	9.4	3
American Society of Mechanical Engineers	4	3.306	0	0	0
Asme	2	1.653	3	1.5	1
Iop Publishing Ltd.	2	1.653	0	0	0
Sage	2	1.653	12	6	2
12 journals	1	-	-	-	-

Scientific documents were also classified for the specific analysis (Figure 6). Proceedings papers and articles represented 89.25% of the scientific papers published by researchers. Figure 7 presents the classification based on the number of publications.

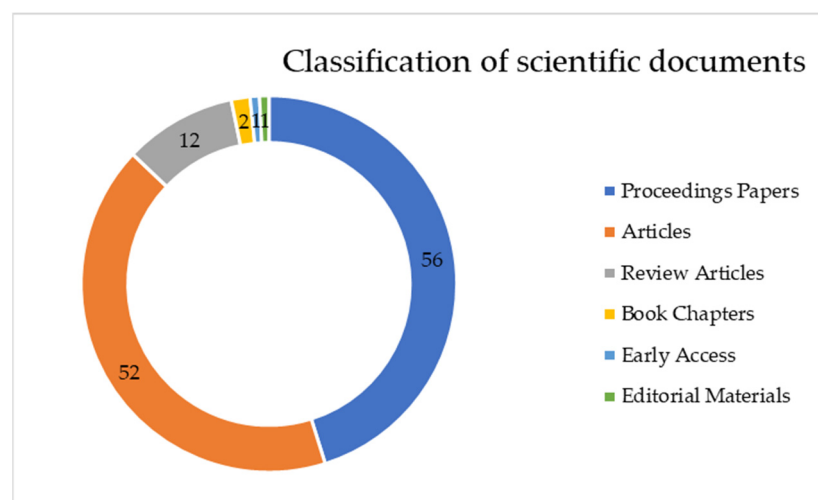


Figure 7. Classification of scientific documents on digital twin and smart manufacturing, and Industry 4.0.

Table 8 presents the countries with the highest number of publications (≥ 4 papers) in relation to the number of publications. The countries with the highest number of authors that published at least one material in digital twin and smart manufacturing and Industry 4.0 were from Italy (18) and China (18), followed by an identical number of documents from authors in Germany, Sweden and USA (12, respectively).

Table 8. Countries with the highest number of publications (≥ 4 papers) with citations and impact index in digital twin and smart manufacturing, and Industry 4.0.

Country	No. Doc	%	Citations	Impact Index	H-Index
China	18	14.876	1302	72.33	13
Italy	18	14.876	430	23.89	9
Germany	12	9.917	259	21.58	6
Sweden	12	9.917	338	28.17	6
USA	12	9.917	67	5.58	5
Singapore	9	7.438	532	59.11	5
Hungary	5	4.132	22	4.4	3
New Zealand	5	4.132	347	69.4	4
Russia	5	4.132	14	2.8	1
South Korea	5	4.132	36	7.2	3
Brazil	4	3.306	57	14.25	3
Denmark	4	3.306	60	15	3
6 countries	3	-	-	-	
10 countries	2	-	-	-	
15 countries	1	-	-	-	

The network of citations based on the authors (as a unit of analysis) was also analyzed for the specific analysis. VOSviewer was used to visualize the networks. As shown in Figure 8, there were 60 clusters and 71 links, and the total link strength was 90. Again, only authors with a minimum of two documents were analyzed, and from the total number of authors only 72 met this threshold. From this analysis, the largest set of connected items is presented in Figure 9.

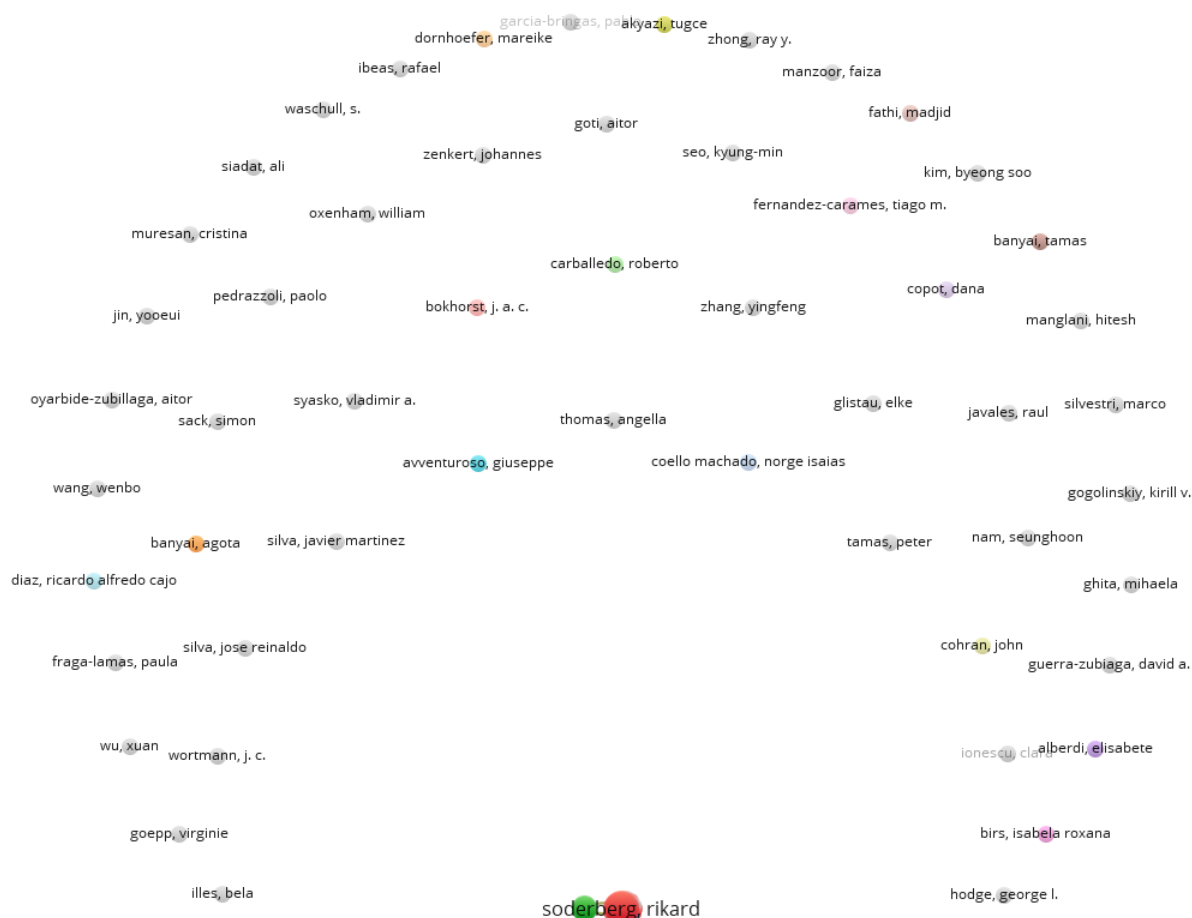


Figure 8. Network of citation analysis using the authors as a unit (specific analysis).

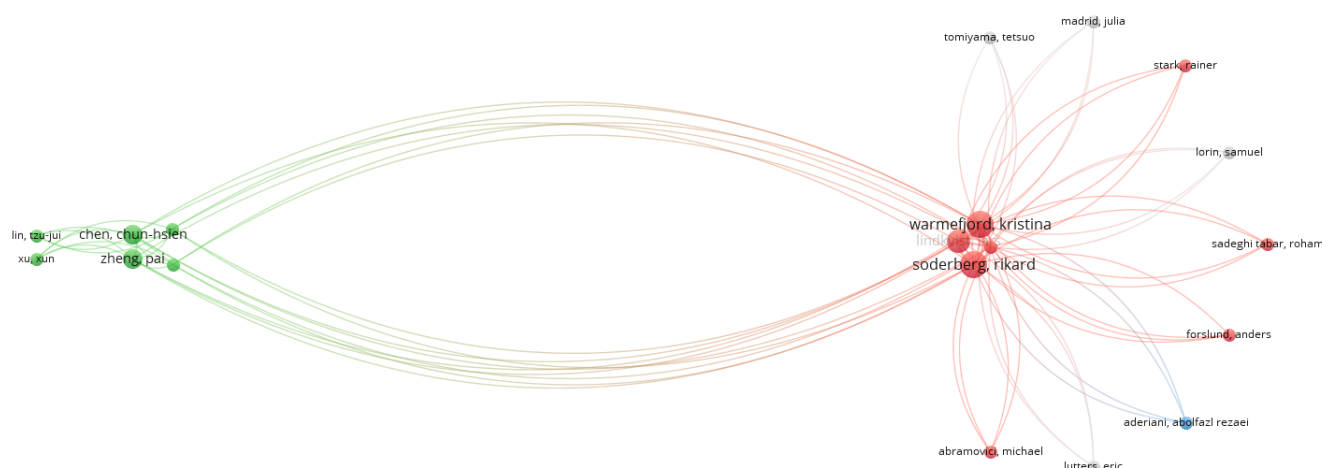


Figure 9. Network of citation analysis using the authors as a unit, showing the main cluster (specific analysis).

As observed from this cluster, the most influential connection was between the authors Kristina Warmefjord and Rikard Soderberg. Additionally, their knowledge extends to Zheng Pai and Chen Chun-Hsien. The research in the field also presents a collaboration between Kristina Warmefjord and Rikard Soderberg, in which they study digital twin-driven production mainly regarding assembly lines [61], try to find an effective method for spot welding sequence optimization [62], or try to identify industrial challenges in areas such as management, system-level, education, working process and simulation [63]. The findings in the cluster are in accordance with the analysis in Table 5 where Soderberg R., Warmefjord K. and Lindkvist L. were the authors that had the highest number of publications in digital twin, smart manufacturing and Industry 4.0.

4. Discussion

This research facilitates the evolution of scientific production in digital twin, smart manufacturing, and Industry 4.0. These subjects were the most discussed topic of 2021, therefore, the selection was based on technological evolution and where we are heading to. Although the first publication in this field was in 2016, the evolution of publication is on an ascending trend. In general, research shows the strong connection between digital twin, smart manufacturing, and Industry 4.0. The growth in literature on this subject is essentially due to technological development in all areas [64,65]. Conducting this analysis, we can observe how studies were carried out during this time in terms of evolution. Therefore, the research questions stated in the beginning can now be discussed.

Q1. How did the publications on digital twin and smart manufacturing evolve? How did they evolve for digital twin and smart manufacturing and Industry 4.0?

Regarding the evolution of the publications, the subject only started to emerge in scientific literature five years ago. Since its first appearance, many researchers have presented and shown the way the subject has evolved in various fields and different industries. A rapid growth was seen in 2019 and 2020, with these years accounting for more than 90% of the materials published over the five years [66,67]. The same pattern can be seen for the specific search, where 2019 and 2020 also hold the record for the years with the highest number of publications. Additionally, this research question highlights the evolution of the subject in the digital world by demonstrating that interest is continually growing among researchers and scientists worldwide. An increase in the number of publications, as demonstrated by the number of publications that were eliminated for the year 2021, show that digital twin, smart manufacturing and Industry 4.0 are the motors of change, because they provide a link between the physical and digital world that is comprehensive and real. Applications of the lifecycle of industrial products can be performed through research, due to engineering software and digitalized equipment [30]. Additionally, it could

be observed that the evolution of the subject brought with it research papers that focused on the connection between real and virtual systems, and the opportunities, benefits, and challenges that this technology brings. This is consistent with the findings of [68,69].

Q2. Which authors have published the highest number of publications on the subject, and which authors have the highest number of citations?

In relation to the most important authors within the field of study proposed, Tao F. was the author with the highest number of publications (12) and citations (1645) in the field of digital twin and smart manufacturing, while the author with the highest number of publications (7) and just 194 citations in the field of digital twin and smart manufacturing and Industry 4.0 was Soderberg R. He was also the author with the second highest number of publications for the general search. Although Tao F. was not the highest author in the specific search, he still had the highest number of citations (884). However, based on the three keywords used, the most influential author was Tao F. from Beihang University. This analysis was strongly connected with China, which had the greatest number of publications on this topic. Considering the evolution in the field, the author analysis represents the interest of scientists in the field, that the identified authors will be highly cited and also will continue to lead the scientific community in the area of digital twin, smart manufacturing and Industry 4.0. Therefore, whether we are talking about digital twin from the point of view of real vs. virtual systems, manufacturing processes or automation in manufacturing, it can be seen that Tao F. was one of the main contributors. This is also in agreement with [68,69] which mentioned some important contributions of Tao F. such as Digital twin-driven product design, manufacturing and service with big data, Digital Twin Shop-Floor: A New Shop-Floor Paradigm Towards Smart Manufacturing, Digital Twin and Big Data Towards Smart Manufacturing and Industry 4.0: 360 Degree Comparison, etc., [15,17,70].

Q3. Which institutions, publishers and countries focused most of their attention on digital twin, smart manufacturing, and Industry 4.0?

Chalmers University of Technology and Beihang University stood out in both the general and specific searches as institutions having the most productive authors in this area. Thus, we can say that they were the most influential institutions on the subject. The cumulated percentage covered by these institutions was over 9% for both searches. Analysis of the top institutions showed that the research conducted by scientists was performed in institutions that placed a great importance in providing research infrastructure. Thus, this analysis shows that investment in technology within institutions will represent an important part in the evolution of digital twin, smart manufacturing and Industry 4.0.

Analysis of the publishers that stood out in terms of publishing the largest number of articles showed Elsevier in first place, and IEEE in second place, with a cumulated percentage of over 79% of the total number of publications. For both searches and analyses, Elsevier, IEEE and Spring Nature were the top three journals that had the highest number of documents published. A change was observed for the fourth and fifth place, that reversed between the general and specific searches (in the general search, Taylor & Francis were fourth and MDPI fifth, while in the specific search, MDPI was fourth and Taylor & Francis fifth). Considering that only ISI Web of Knowledge was analyzed, it is possible that other publishers may have achieved first place if we had introduced a larger number of scientific platforms. The analysis of publishers was selected as being important, as authors tend to choose publishers with high recognition among the scientific community.

The countries with the greatest number of publications were China (first place), USA (second place) and Italy (third place) in the general search, while for the specific search, China and Italy equally occupied first place, followed by Germany and USA equally being in second place. If correlated with the citations analysis, China remained in first place. The most productive institution was from China, which is in accordance with [71].

Q4. What type of documents are most frequently published?

The two most frequently used types of material observed from the analysis were "articles" and "proceeding papers", comprising over 78% of materials for both searches,

and therefore, a substantial majority of the total number of publications. Since these types cover most of the field, other types of document categories do not have sufficient representation to warrant mentioning their important role for the subject in the scientific literature. This parameter was important in the analysis because for long time the “proceeding paper” had a different understanding, and was assigned within the WoS database to journal articles that initially were conference papers. They were later assigned two labels, articles and proceedings papers, since analysis revealed differences between the number of pages and citations, thus giving us the chance to also differentiate them in this paper. It was seen that these types are the preferred manner in which scientists/researchers choose to present their findings to the scientific world [72].

Q5. What citation nodes are the most influential in the network map?

After conducting the analysis using VOSviewer, it was observed that the network revolved around Tao F. for the general search, with other authors just starting to collaborate with the created clusters. This demonstrated that Tao F. is currently the author with the highest influence on this subject. Additionally, the specific search revealed that Sodenberg R. is the author with the strongest connection of the three keywords used in this paper. The analysis of citation nodes was performed because the frequency of citations constitutes an academic value and impact mark. Thus, in our networks, we could see the most influential authors and their importance in the field based on the number of citations and links created.

Further analysis of the documents from the selected articles showed that there were some elements that are closely connected to the concept of digital twin, such as physical entity, virtual entity, real and virtual environment, connection between real to virtual, twinning, advantages, disadvantages, challenges, DT and product life-cycle, data, implementation, and virtual entities integration, etc., [15,26,70,73–83]. All mentioned references, and many others, describe these elements as themes, with some points being addressed and presented. For example, one important element discussed the parameters from the real environment that need to be addressed in the virtual environment in order to have a solid connection between them [84–87]. These parameters are also in accordance with [69] because they found similar themes that they approached, along with future research directions.

With the exception of answering the questions, increasing productivity and employee efficiency can be achieved using devices utilized in the smart industry. Digital twin has the ability to provide an edge-to-cloud architecture that will contribute to the optimization of operational costs. Until 2019, digital twin concepts and smart manufacturing were mainly applied in industries from aerospace to naval [71].

The progress in technology, along with the COVID-19 pandemic, caused companies to rethink their future plans due to unpredictable times, leading to businesses starting to build intelligent twins, creating mirrored environment [72]

Scientists have also analyzed the terminology and framework of digital twin, smart manufacturing and Industry 4.0, showing, therefore, that the standards are only now just being established. For example, the International Organization for Standardization (ISO) is currently developing:

- The concept and terminology (IEC AWI 30173);
- The manufacturing framework (ISO/FDIS 23247-1);
- The framework for health and well-being in smart cities (IEEE 11073) [88,89].

Future research is needed in novel sensors, which has not been sufficiently explored and will bring benefits related to 5G communication [90].

Another possible area for research within the field of digital twin and smart manufacturing, where the vision of application is not just for the next period but for the next decade or more, is healthcare. Although some technology exists (digital twin in cardiology), collaboration between the healthcare industry and scientific knowledge will contribute to the exploration of other healthcare problems, leading to personalized medicine in the future [91–93].

Also, digital twin technology is still at its beginning in agriculture and construction [94]. Regarding agriculture, digital twin technology can assist/improve storing and collecting data, categorize different activities related to workflow, analyze data, apply/learn/measure the content and capacity of the soil, conduct a simulation regarding crops and their outcomes, prediction weather for future productivity, and analyze invasive factors, etc., [95].

Considering the findings, synchronization is the main element that contributes to the development of DT technologies. The aspect that is intensively studied in many areas is that of being able to synchronize the reality with the virtual space, to gather all the data and properly use them [96]. Linking not just real to virtual, but in addition, linking elements/entities inside the virtual space is also a challenge due to the fact that proper interactions need to be established for the digital twin platform to work.

There are studies that focused on the technical challenges that come along with digital twin technology development, but unfortunately there are still areas where research is needed, such as the user's point of view when discussing the attitude, experience or even acceptance of digital twin technology. There are elements, such as users' personality, that need to be considered when using digital twin technology, because this can have an influence on the product design, production planning, and the decision-making process, etc., [97–100].

A challenge for the development of digital twin is the creation of a platform that integrates and connects different systems that already exist. A framework that incorporates all dates without resulting in inconsistencies would help build an integrated digital twin platform necessary for the economic environment, regardless of its size (SMEs or large companies) [101,102].

Smart manufacturing is not possible without proper integration of the elements mentioned, and a common understanding (about the domain, process, production, application, and requirements) is the basis for future development [103].

Manufacturing industries such as aerospace, automotive and power generation are still investing in research to construct a digital twin that has all the capabilities required in physical space, in the virtual space, using digital twin technologies [18,104].

A very important aspect that needs to be considered regarding the challenges is that uncertainty and the ever-changing environment are factors that are common to manufacturing industries due to the differences in the customer demands, technology evolution and product design. Thus, digital twin technology used in smart manufacturing needs to keep in mind that we are dealing with a very complex system, so the ability to be flexible is highly important [105].

Additionally, digital twin should be able to evolve in linking engineering, economic, technological data and any other challenges that the manufacturing industries face. The real challenge is to allow enough time and money for the development and implementation of digital twin technology for smart manufacturing [106].

Study Limitations

For a high quality bibliometric analysis, it is necessary to mention its limitations.

First, the analysis was performed only using WoS, therefore further studies should also address other databases.

Second, this study had a quantitative point of view, presenting the productivity and the impact of the material published. Future bibliometric analysis can be performed with a focus on the qualitative point of view, by selecting important identified themes to explore and discuss, selecting an industry, and analyzing from both points of view the evolution of an industry in correlation to a theme and the innovation on the subject, etc.

Therefore, we present a strong connection in technology between digital twin, smart manufacturing, and Industry 4.0. Additionally, the bibliometric maps/networks can be extended beyond the current study, to show networks of co-authors, co-words, etc.

5. Conclusions

The bibliometric analysis used in this paper represents a tool for researchers to observe the current state on a selected topic.

The aim of this study was to show the ever-changing technology and its rapid evolution by exemplifying the topics most currently discussed in industry: digital twin, smart manufacturing and Industry 4.0. A considerable evolution of this subject was observed to have occurred since 2019, which demonstrates that research and innovation on the subject have just started to increase.

Digital twin is an important part of future technology development that will influence the world's industries as we know them today. Thus, it is necessary to understand the connection between digital twin, smart manufacturing and Industry 4.0, to be able to further innovate and improve the working process in all industries.

This article was inspired by the existing facts of the subject, in order to present the ongoing evolution of this topic based on scientific literature.

Considering that all three fields of study are currently in full development, more studies are needed to contribute to scientific literature on this topic. Additionally, topics such as agriculture, healthcare, 5G communication and construction need more research in order to apply a technology that can answer realistic problems and can move these domains to the next level of evolvement. To have a worldwide view on the subject, researchers from different countries should engage in highly productive collaborations.

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Article

Climate Change-Greenhouse Gas Emissions Analysis and Forecast in Romania

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Abstract: Greenhouse gases (GHG), such as carbon dioxide, methane, nitrous oxide, and other gases, are considered to be the main cause of global climate change, and this problem has received significant global attention. Carbon dioxide has been considered the most significant gas contributing to global climate change. Our paper presents an analysis of the greenhouse gas emissions in Romania along with a forecast for the years to come. For the study, data from the National Institute of Statistics and Eurostat were gathered and used for the analysis in order to present the results. To obtain the results, the data gathered were analyzed using forecasting methods that can be of help in solving some uncertainties that surround the future. The greenhouse gas (GHG) emissions trends in Romania were analyzed both for linear and exponential function methods. The obtained results showed that the linear function analysis of total GHG emissions in Romania had a forecast accuracy higher than the exponential function method. From the analytical methods used we can draw the conclusion that the emissions are on a descending scale and choosing a proper method is important in analyzing data.



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Keywords: climate change; greenhouse gas emissions; environment; carbon dioxide; EU GHG emissions; forecast analysis; chronological series analysis; analytical method analysis

1. Introduction

The biggest threat to the environment and also to a country's economic situation comes from the climate changes that occur. An analysis over the past 150 years revealed an increase in median temperature by one degree Celsius [1]. The highest temperatures ever recorded since 1850 until now happened after 1995. It is estimated that the annual median temperature by 2100 will increase by 4 to 5 degrees Celsius [2,3]. The Fourth Assessment Report by Working Group I of the Intergovernmental Panel on Climate Change (IPCC) estimated that global climate change is forecasted to result from six scenarios of GHG aerosol emissions, taken from a larger set of scenarios from the IPCC Special Report on Emissions Scenarios. Working Group I assessed climate change under these scenarios, including ocean-atmosphere general circulation models (GCMs) and simple climate models (SCMs), with some models that include carbon-cycle feedback for the climate-change projections. These scenarios are identified as A1FI, A1B, A1T, A2, B1, and B2, with the lowest cumulative emissions being projected by the B1 scenario and the highest by A1FI. They estimated that the A1FI emissions scenario would lead to a warming of 4 °C in the 2070s relative to pre-Industrial temperatures [4].

According to Liu and Raftery [5], based on a fully statistical probabilistic model for forecasting future fossil fuel and industry carbon emissions, the probability of staying below a warming of 2 °C is only 5%.

The impact of climate change can be seen mostly through extreme climate events like tornados, heatwave, floods, etc., all happening more and more often both in Europe as well as in other parts of the world [6]. Natural ecosystems, water reserves, and human

health are highly affected in each part of the globe. For example, in Europe, rains have increased in the north/northwest side. The economic sector, once developed in accordance with the region and the climate, now will be affected and produce suffering for the natural ecosystem, with devastating consequences, some implying the loss of biodiversity.

Sustainable climate change systems in the context of decreasing environmental impact is a key subject included in the broader topic of environmental protection in Europe. The Sustainable Development Report 2019 mentions the need to take urgent action to combat climate change and its impact [7]. In this respect, the European Commission created the legal framework and policies for climate and energy from 2020 to 2030—COM (2014), which set one important target, reducing greenhouse emissions by 2050 to under 80–85%, which is actually a level below the level recorded in 1990 [8]. In addition, the new targets for Europe set by the EU mentions the point of reaching a climate-neutral continent by 2050, a goal set in the European Green Deal. The related legislation is binding and involves a commitment to climate neutrality [9].

The climatic sensitivity of global wildfire activity was analyzed by researchers [10]. Using satellite-derived wildlife products and processes, they were able to present the climate factors that influence wildfires. Process-oriented fire models helped to simulate past and future wildfires. Thus, their results present the spatiotemporal dynamics of burned areas along with their possible response to climatic factors [10].

Different areas around the world were analyzed in order to highlight the features of regional climate change. King et al. [11] chose to analyze the glaciers draining from the Geladandong ice caps since the 1960s. Fu et al. [12] presented the results related to climate change in the Tibetan Plateau using global climate change model simulation.

Surface air temperature and precipitation are the climatic factors that are usually analyzed [13]. Global temperature trend analysis was the main topic in several scientific articles [14–16]. Mudelsee M. [16] used a system to generate a time series of global surface temperature.

The earth system is influenced highly by living organisms because they impact the formation of clouds and atmospheric dust and alter the concentration of GHG in the atmosphere [17–19]. The World Meteorological Organization specified that the period between the years 2011 and 2020 was the warmest decade on record [20]. According to scientists and environmental experts, to be able to stop this level of change, to stop biodiversity change, it is necessary to reduce GHG emissions along with applying at a worldwide level a proper legal framework and directive that contains strategies and actions for the future. The difference between being able to fulfil the legal framework set in place and moving ahead as the situation is now will be determined by the financial capacity of each country.

Regarding the studies conducted that analyzed GHG emissions, many concluded that the main responsible factor for climate change disaster is GHGs of anthropogenic origin [21–24].

According to the Kyoto Protocol, GHGs include six gases, namely, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6) [25]. The most common GHG emitted by human activities is carbon dioxide. Anthropogenic GHGs include carbon dioxide from burning fossil fuels, deforestation, land clearing for agriculture, degradation of soils, methane from agricultural activities, waste management, energy use and biomass burning, nitrous oxide from agricultural fertilizers, and fluorinated gases from industrial processes and refrigeration [26,27].

In State of the Global Climate 2020 report it is mentioned that globally averaged mole fractions of carbon dioxide (CO_2) have already exceeded 410 parts per million (ppm), and if the CO_2 concentration follows the same pattern as in previous years, it could reach or exceed 414 ppm in 2021 [20].

Alhindawi et al. [28] investigated the GHG emissions from the transportation sector and developed a multivariate linear regression and double exponential smoothing model for the projection of GHG emissions from this sector.

Andrejiova et al. [29] presented in their research the current situation regarding GHG emissions in the air in 27 European Union (EU-27) member states. The authors compared the European Union member states on the basis of 15 examined parameters (population, area, the number of commercial airports with more than 15,000 passengers per year, the total GHG emissions, the amount of aviation GHGs, the amounts of individual aviation GHG emissions (CO_2 , N_2O , CH_4 , HFC), the total amount of PM2.5 particulate matter in the air, etc.) by applying the principal component analysis method and a cluster analysis. They reported that in the years 2012 to 2018 in almost all EU-27 member states, there was an increase in aviation GHG emissions.

In another study, Saleh et al. [30] investigated CO_2 emissions using a prediction support vector machine (SVM) model, which considered variable energy consumption that has an impact on the emergence of CO_2 emissions. The authors considered electrical energy and burning coal as energy consumption that directly affects increasing CO_2 emissions. The trial-and-error approach was applied in order to obtain a better prediction model with lower error.

Li et al. [31] proposed a new forecasting model for carbon emissions related to energy consumption in the Beijing–Tianjin–Hebei region from 2017 to 2030 based on the extreme learning machine (ELM) algorithm optimized by grey prediction theory and a support vector machine (SVM). They proved that the SVM-ELM model has higher prediction accuracy than the SVM model and ELM model through the analysis of empirical research. In the same way, Zhou et al. [32] proposed a combined forecasting model based on the rough set and grey prediction models as well as the support vector machine (SVM) model to forecast carbon emissions from 2012 to 2017. They used the data on Chinese carbon emissions from 1992 to 2011.

Another study that used the support vector machine method for the prediction of CO_2 was conducted by Sun et al. [33]. The authors presented a method based on principal component analysis (PCA) and an improved least squares support vector machine (LSSVM) prediction.

Lee et al. [34] analyzed the uncertainty of GHG emissions using the parametric Monte Carlo simulation method and the non-parametric bootstrap method, whereas Akyol and Ucar estimated the greenhouse gas emissions of Turkey in the year 2030 using a time series forecasting algorithm in the WEKA (Waikato Environment for Knowledge Analysis) data mining software [35].

Kijewska and Bluszcz [36] analyzed the level of differentiation of European Union member states in terms of the emissions of four greenhouse gases and identified groups of similar countries based on these criteria. The authors used a taxonomic method-cluster analysis, namely, the agglomerative algorithm, which enables the extraction of objects that are similar to each other from the data and then merges them into groups. Their conclusion was that among the largest emitters of greenhouse gases are Germany, the United Kingdom, France, Turkey, Poland, Italy, and Spain.

In their research, Ding et al. [37] explored the dynamic relationship between business growth and carbon emissions performance by constructing and using a time series model to predict the trend of carbon emissions. They used the time series method (ADF unit root test, cointegration test, and VAR model) to investigate 805 companies listed on the Taiwan Stock Exchange from 2012 to 2017. Their results showed a long-term dynamic relationship between business growth and carbon emissions performance. Tubiello et al. [38] assessed the GHG emissions from drained organic soils. To better highlight the emissions, they were able to organize the data in two important domains—land use and agriculture—and then just the N_2O and CO_2 emissions per unit area were used for the analysis. Their conclusion showed a significant presence of CO_2 in the emissions from drained organic soils.

GHG emissions were also analyzed from a positive point of view by seeing whether there is a connection between agricultural GHG emissions and productivity growth [39]. The analysis continued and analyzed GHG emissions in correlation to renewable energy [40] and non-renewable energy. It was observed that the CO₂ emissions decreased in the case of renewable energy.

To summarize, the EU efforts and thus, Romanian efforts, focus on reducing GHG emissions, keeping in mind along the way that this process should not interfere with a country's economic state.

The present manuscript's objective was to conduct an analysis on GHG emissions in Romania in the EU context starting with the legislative framework in both the EU and Romania, as well as aspects of GHG emissions in the EU and Romania, and then conduct a forecast analysis of GHGs using data from Eurostat and the Romanian National Statistic Institute.

According to the 4th Biennial Report of Romania, the general trend of GHG emissions in Romania shows a strong decrease compared to the base year. Thus, between 1989 and 2018, total GHG emissions (excluding Land Use, Land-Use Change, and Forestry-LULUCF) decreased by 62.10% and net GHG emissions (including LULUCF) decreased by 68.32%. CO₂ had the largest share of total GHG emissions, followed by CH₄ and N₂O. The emissions trends by sector in 2018 was as follows: Total GHG emissions from the energy sector accounted for the largest share (66.32%), followed by those from the agriculture sector, with a share of 17.1%, and those from industrial processes and the product-use sector, with a share of 11.58% [41].

2. Materials and Methods

In order to reach the research objective, we used data from the official statistics platforms Eurostat and INS (Romanian National Statistic Institute, Bucharest, Romania), focusing on the total GHGs emissions in Romania and the EU, GHG emissions by sector (energy, industrial process and product usage, waste and agriculture), GHG emissions per capita, and GHG emissions intensity of energy consumption. Our intention was to deepen the correlation between the two databases. The forecast analysis was done using MSOffice Excel statistics using the forecasting tools available. Forecasting theory was chosen based on the fact that the databases had past information that was of help for future prediction. Before applying the forecasting tool, the data were pre-processed because we observed missing data from some states in the EU.

Since we had a set timeline, year by year, a forecast analysis using chronological series was used. The chronological time series (SCr) is a set of values that a certain value can take (quantitative and qualitative) at different moment or during successive timeframes. In our case, the timeframes were successive and had the same length, so we used SCr of moments with equal timeframes between moments. Knowing this, the median indicators of the chronological time series were calculated.

- Median level for SCr intervals

This can be calculated as a simple arithmetic average by the ratio between the sum of the series terms and the number of terms:

$$\bar{y} = \frac{\sum_{t=1}^n y_t}{n} \quad (1)$$

where we have the following terms:

n —number of terms;

y_t —the series terms;

- SCr moments with equal intervals between moments—the median level is calculated as a chronological simple average, a particular case of the chronological weighted average where $h_1 = h_2 = \dots = h_n - 1 = h_n = h$ and h represents the interval length (in time units).

Then we have:

$$\overline{y_{cr}} = \frac{\sum_{i=1}^{n-1} A_i}{\sum_{i=1}^{n-1} h_i} = \frac{\frac{(y_1+y_2)h}{2} + \frac{(y_2+y_3)h}{2} + \dots + \frac{(y_{n-1}+y_n)h}{2}}{(n-1)h} = \frac{y_1 \frac{h}{2} + y_2 h + \dots + y_{n-1} h + y_n \frac{h}{2}}{(n-1)h} = \frac{\frac{y_1}{2} + y_2 + \dots + y_{n-1} + \frac{y_n}{2}}{n-1} \quad (2)$$

where:

- h_i represents the length of the intervals between moments t_i and t_{i+1} , $i = 1, \dots, n-1$, expressed in time units.
- A_i represents the simple moving chronological average (for example: $A_1 = ((y_1 + y_2) \times h)/2$).
- Absolute average change (absolute average gain)

This indicator can be determined as a simple average based on absolute modifications (changes) with a mobile base using the equation:

$$\overline{\Delta} = \frac{\Delta_{n/1}}{n-1} = \frac{y_n - y_1}{n-1} \quad (3)$$

y_n —the last term of the SCr;

y_1 —the first term of the SCr;

n —number of terms.

This indicator/parameter shows with how many concrete unit measures the level of process is modified, on average, during the timeframe analyzed.

- Dynamic average parameter (increase or decrease)

This parameter can be determined as a geometrical average of the mobile base coefficients (parameters) using the following equation:

$$\overline{I} = \sqrt[n-1]{\frac{y_n}{y_1}} \quad (4)$$

This parameter shows how many times, on average, the level of the analyzed process has been modified considering the timeframe considered for calculating.

- Dynamic rhythm (relative average change or relative median gain or median increase/decrease ratio)

$$\overline{R} = \overline{I} - 100 = (\overline{I} - 1)100 [\%] \quad (5)$$

This shows the percentage of increase/decrease, on average, of the process level from one period to another over the entire time horizon.

The analytical method—linear trend analysis and exponential trend analysis were used because they offer a more exact adjustment of the chronological series because they consider all the SCr terms.

The equation that describes the linear trend analysis is:

$$\hat{y}_t = a + b \quad (6)$$

Based on this, the parameters a and b of the function were calculated as follows:

$$a = \frac{\sum y_t}{n} = \bar{y} \quad (7)$$

$$b = \frac{\sum t \times y_t}{\sum t^2} \quad (8)$$

Regarding the exponential trend, the equation that best describes the analysis is:

$$\hat{y}_t = a \times b^t \quad (9)$$

For the exponential trend after the logarithm of the relationship and applying the least squares method, we can determine parameters a and b as follows:

$$\log a = \frac{\sum \log y_t}{n} \quad (10)$$

$$\log b = \frac{\sum t \times \log y_t}{\sum t^2} \quad (11)$$

3. Results and Discussion

3.1. Brief Overview of GHG Emissions in the European Union

In order to achieve a sustainable future for the next generations, the EU is constantly developing methods and tools to monitor the progress of European countries in reducing the impact of GHG emissions. A reduction in the negative impact of GHG emissions can be achieved through an increase in public and industry awareness. The strategic EU documents that are considered to have an impact on GHG emissions are included in Table 1.

Table 1. Strategic EU documents impacting GHG emissions and the main actions mentioned.

Strategic Document	Main Actions	Source
European Green Deal	"The European Commission proposed in September 2020 to raise the 2030 GHG emission reduction target, including emissions and removals, to at least 55% compared to 1990."	https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en , accessed on 21 August 2021
Regulation on the Governance of the Energy Union and Climate Action	"EU has adopted integrated rules to ensure planning, monitoring and reporting of progress towards its 2030 climate and energy targets and its international commitments under the Paris Agreement."	
EU Emissions Trading System Effort Sharing Regulation with Member States	"All sectors will contribute to the achievement of the 40% target by both reducing emissions and increasing removals."	https://ec.europa.eu/clima/policies/ets_en https://ec.europa.eu/clima/policies/effort_en , accessed on 21 August 2021
European Climate Law	"The European Commission proposed on 4 March 2020 the first European Climate Law to enshrine the 2050 climate-neutrality target into law."	https://ec.europa.eu/clima/policies/eu-climate-action/law_en , accessed on 21 August 2021
Long-term low GHG emission development strategy of the EU and its member states	"The endorsement of the climate neutrality objective was reached following an inclusive institutional and societal debate based on the strategic long-term vision proposed by the European Commission which includes a detailed analysis of solutions that could be pursued for the transition to a net zero GHG emissions economy and insights regarding the corresponding strategic priorities and an enabling framework that would allow reaching climate neutrality by 2050."	https://unfccc.int/documents/210328 , accessed on 14 October 2021
A Clean Planet for All—A European strategic long-term vision for a prosperous, modern, competitive, and climate-neutral economy	"Research, development and demonstration will significantly reduce costs of breakthrough technologies. This will lead to genuinely new products replacing today's industrial products, such as carbon fibre or stronger cements reducing the volume of production while increasing product value. A net-zero GHG emissions economy will see new business concepts develop with re-use and additional services at its core."	https://eur-lex.europa.eu/legal-content/EN/TXT/?uri= , accessed on 21 August 2021

According to Eurostat and the scientific community, the GHG emissions resulting from human activity are the main cause of environmental decline, mainly Earth's average

temperature increase over the last 250 years. The GHG emissions generated in 2019 in the EU were 8.4%, which was less than the GHG emissions in 2000, according to Eurostat. There was a period when the emissions slightly increased from 2002 to 2008, when the trend started to descend. The GHG emissions recorded by Eurostat presented the highest value for Luxemburg, with 30.8 metric tons per capita, in 2005, which in 2019 decreased to 20.3, whereas the smallest value recorded was in Latvia.

Romania is part of the new GHG emissions system that needs to be properly implemented in all of Europe. Efforts and significant investments have been made to align the local policies and practices to the European Community regulations. The situation is evolving and changes are made constantly.

In Figure 1, the total national emissions of the so-called “Kyoto basket” of GHGs are presented for the EU states. This includes carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), and the so-called F-gases (hydrofluorocarbons, perfluorocarbons, nitrogen trifluoride (NF₃), and sulfur hexafluoride (SF₆)). The EU member states report the emissions annually according to the United Nations Framework Convention on Climate Change (UNFCCC). As can be seen in Figure 1, there are still some differences among EU states. In Figure 1, the cumulative data are presented for each country, whereas for the European Union–27 countries, only the cumulative average is presented.

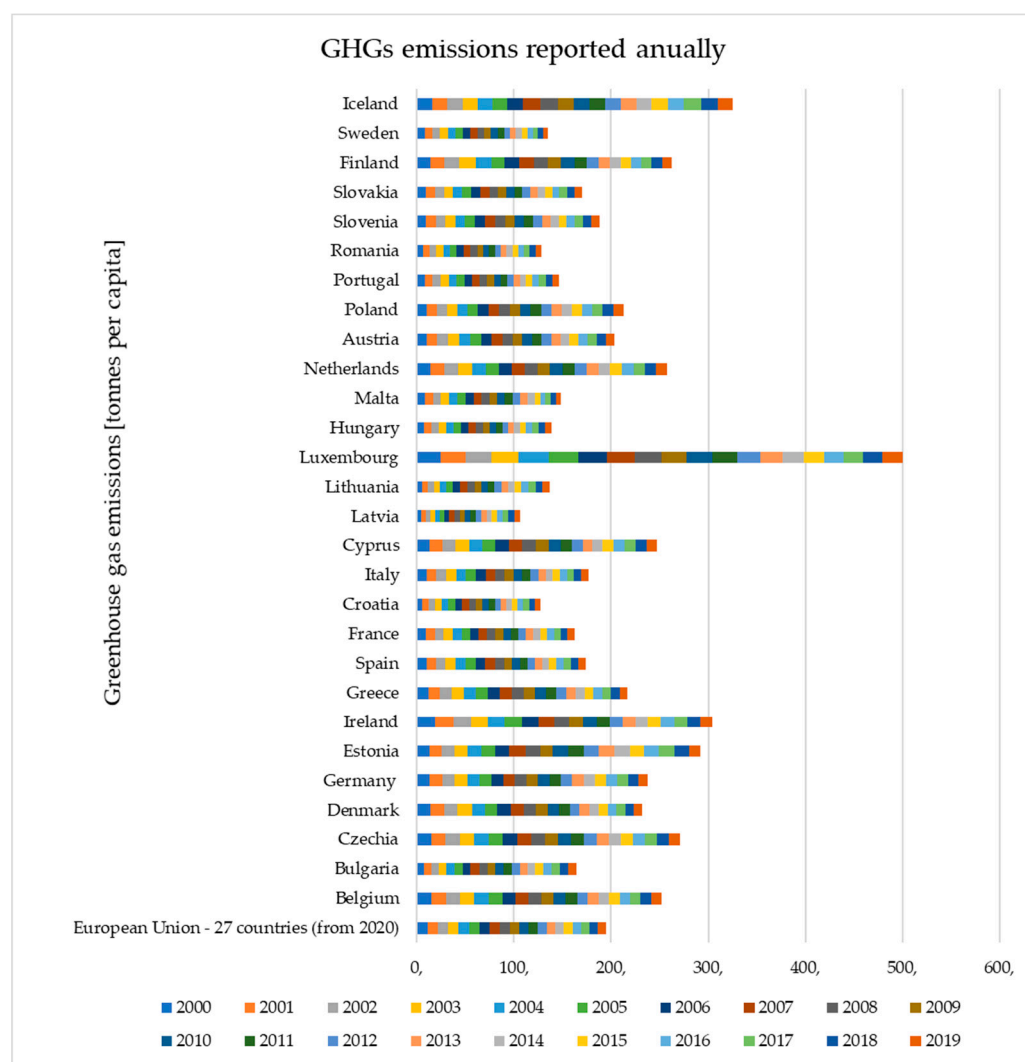


Figure 1. GHG emissions per capita (source: own elaboration based on Eurostat 2019).

Based on data reported by the member states, the EU climate action and the European Green Deal set a plan to cut emissions by 2030 by at least 55%. The ultimate goal is for Europe to become by 2050 the world's first climate-neutral continent. The initiatives and the measures put in place can have an impact if the GHG emissions are cut as the package of measures states and also by investing in research and innovation. In addition, if we compare the EU with other countries/continents, we can say that in 2020 the US withdrawal from the Paris Agreement and the projections were different from the EU. At the same time, China has adopted renewable energy much faster, thus leading to a decrease in GHG emissions [42].

GHG emissions from all operators covered by the European Union Emissions Trading Scheme (ETS) declined by 13.3% in 2020 compared to 2019. Additionally, in the energy sector the emissions decreased by 14.9% due to reduced electricity consumption along with using renewable energy that replaced the energy produced using coal. The industrial emissions also decreased by 7%. Considering the fact that in 2020 the COVID-19 pandemic started, the European Commission is not sure whether the emissions decrease can be attributed just to the regulation's efficiency.

Using the data available on Eurostat and applying Excel forecast tools, Figures 2 and 3 were created.

There is a significant decrease in GHG emissions by 2050, as can be seen in Figure 2. If the current plan for the European Union is implemented, then the emissions will decrease by 35% in 2030 and by 61% in 2050 compared to 2000. Additionally, if the analysis is done by taking into consideration 1990, the base year for many researchers, we could see a decrease of 60.25% by 2050, so just a 0.75% difference between the years 1990 and 2000. A great difference can be seen in Luxembourg, with less than 37% GHG emissions in 2030 and 76% in 2050 compared to 2000.

As can be seen from Figure 3, the countries that will change the most are Spain and Portugal from dark blue (values that are very high), and the country that actually will not move forward if the legislation, regulations, and implementation of GHG emissions reduction strategies do not change is Turkey [43]. We chose to add Turkey due to the fact that it demonstrates one of the worst scenarios, where regulations and the implementation of GHG reduction are not properly addressed.

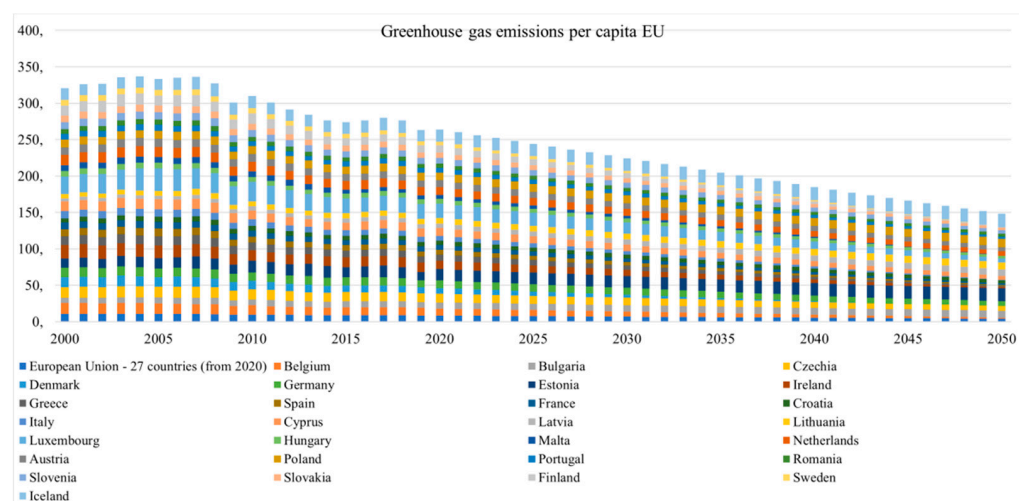
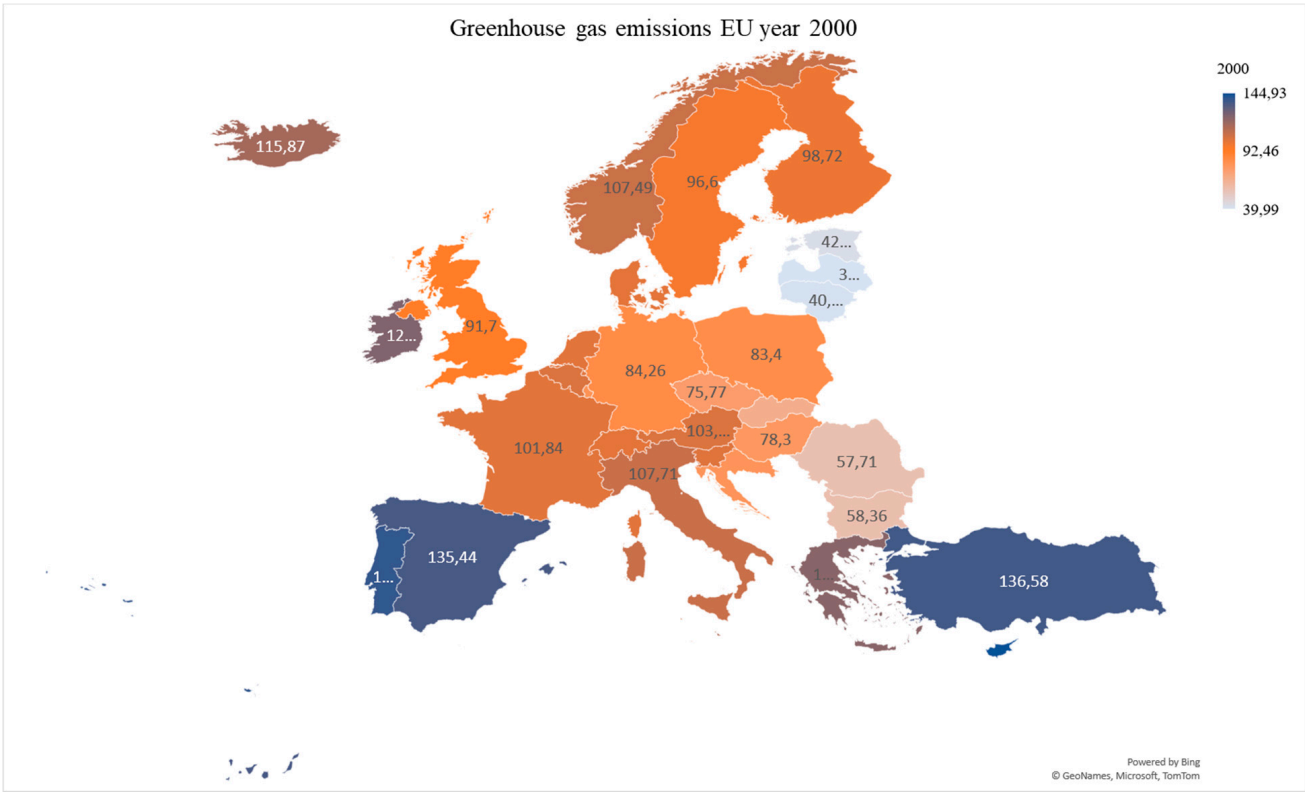
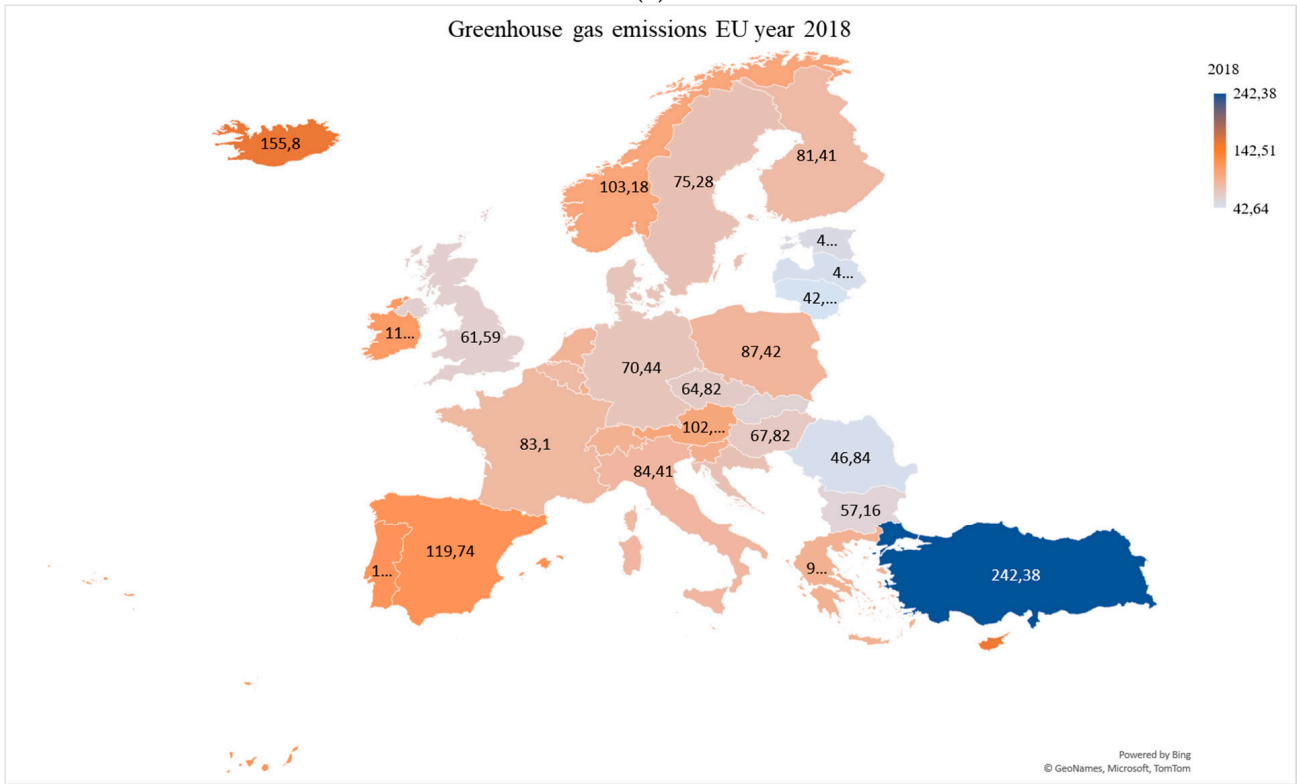


Figure 2. GHG emissions forecast for 2050 per capita (source: own elaboration based on Eurostat 2019).

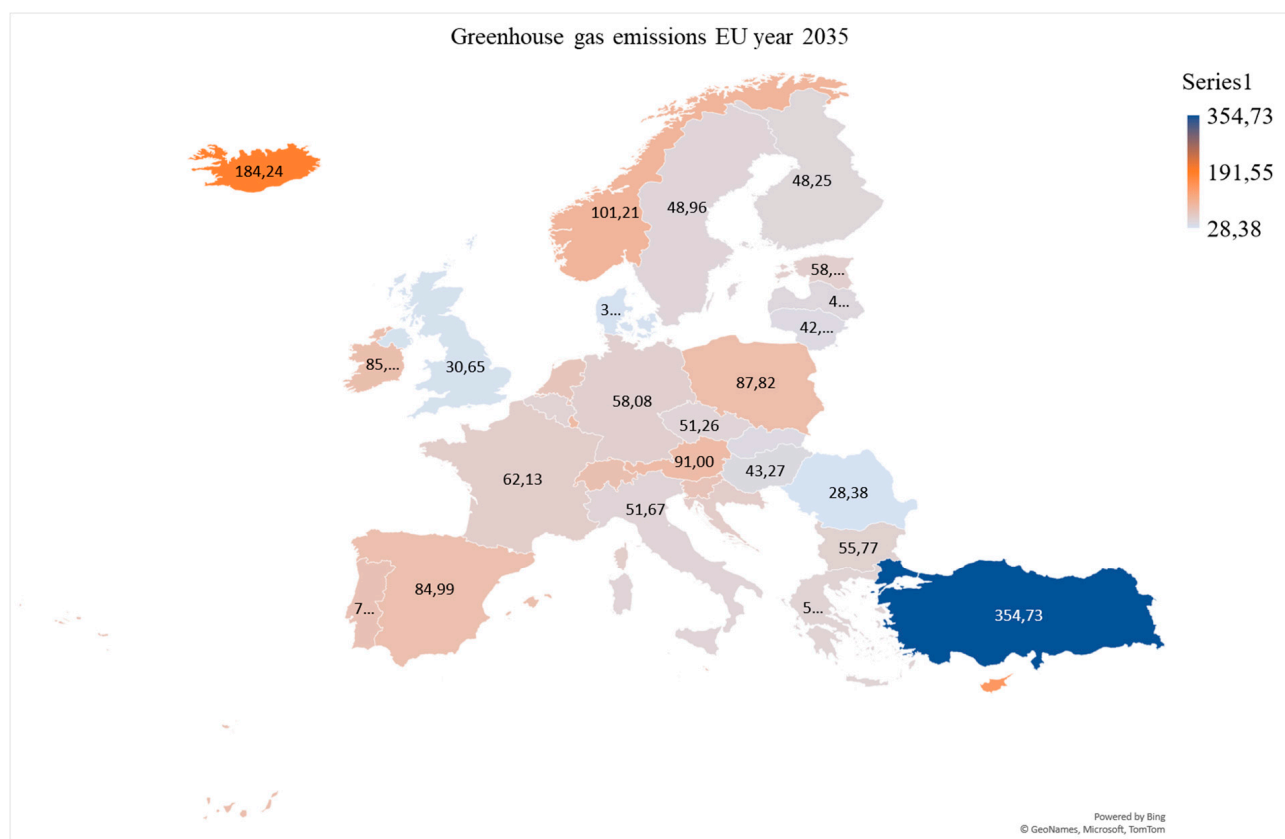


(a)

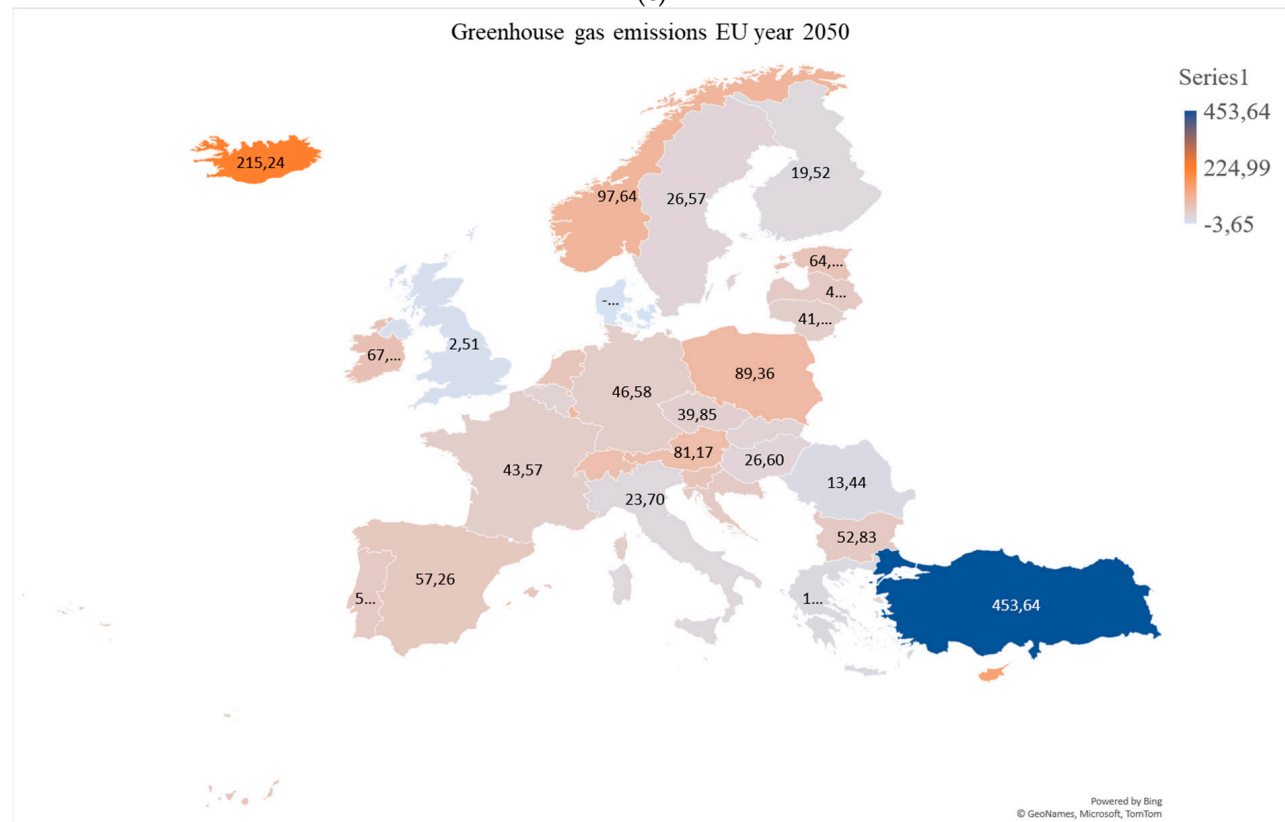


(b)

Figure 3. Cont.



(c)



(d)

Figure 3. Map of European GHG emissions per capita (source: own elaboration based on Eurostat 2019 and applying forecasting tools): (a) year 2000, (b) year 2018, (c) year 2035, (d) year 2050.

It is necessary to keep in mind that we are now in the fourth phase of EU ETS, which applies to 2021–2030 period, in correlation with the Commission Implementing Regulation (EU) 2018/2066 of 19 December 2018, aimed at monitoring and reporting GHG emissions. In addition, during the fourth phase the principles of Stage 3 of the EU ETS remain the same. The main potential value of the EU ETS is to make the price of GHG emissions visible throughout the production and consumption chain, thus paving the way for an efficient low-carbon economy. Only full bidding for emissions can determine their real price, as it is the necessary economic incentive to contribute to this transition. Since 2013, companies must bid in order to obtain an emissions share, shares that are fewer each year than the previous year. For example, in 2020 there were 70.9 million certified emissions reductions (carbon credits) for developing countries and those that are conducting clean development mechanism activities. There was a high number of requests for these credits.

In the same context, Dritsaki and Dritsaki [44] investigated the optimum model to forecast CO₂ emissions in the EU-28 based on annual data (from 1960 until 2014). The authors forecasted CO₂ emissions for six years (2015–2020) and used an autoregressive integrated moving average (ARIMA) (1,1,1)-autoregressive conditional heteroscedasticity (ARCH) (1) model combined with the linear ARIMA model and the conditional variance of the ARCH model. Their findings support the fact that the year 2020 presented a considerable decrease in CO₂ emissions, reaching 33.8% less than in the year 1990 (Kyoto Protocol) [44].

3.2. GHG Emissions Analysis and Forecasting in Romania

A total of 28 states submitted to the EU in 2020 their strategies for lowering GHG emissions in the long term. The ambitious goals for climate change were set while working with a global coalition of countries and international institutions. Despite all this, it seems that the EU needs better knowledge of the GHG emissions reduction plan and regulations.

Romania carries out an annual inventory of GHGs in order to comply with its European obligations and international regulations. Both the annual reporting obligations to the UNFCCC and the EU annual reporting requirements applied to all member states must be met. Specialized GHG services are being developed in Romania as a result for adoption of the Kyoto Protocol [45]. The aspects that are most often considered and can be used by industries of all size operations are:

- Conformity verification, which is done under the international standard ISO 14065. This gives credit for a series of local, regional, and global emissions schemes. The companies that are developing in order to provide this kind of service usually have experience in EU ETS.
- GHG emissions inventory and product verification against internationally accepted standards.
- Carbon footprint—the first step for any business, which means making a verifiable carbon footprint for the organization or product and identifying opportunities to reduce costs by developing low-carbon business strategies and a roadmap for reducing GHG emissions.

Considering the data available on Eurostat, in Figure 4 we have the Romanian GHG emissions that present a descending slope from the first available data in 2000. It can be seen that since 2007, when the emissions had a value of 131,532.46 metric tons, the highest value reported by Romania, the GHG emissions decreased to 91,656.49 metric tons in 2008, which represents an improvement of 30%.

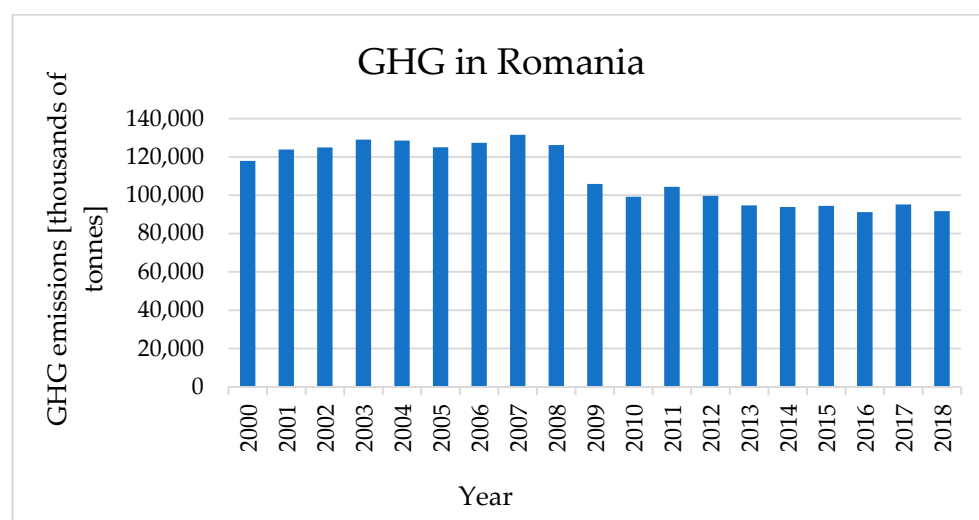


Figure 4. GHG emissions in Romania.

Using the data available on Eurostat and applying Excel forecast tools, Figures 5 and 6 were developed. Since forecast accuracy is a key indicator, it is necessary to mention that at the end of the analysis scientists usually use relative approximation error, root mean squared error, mean absolute percentage error, or mean absolute deviation.

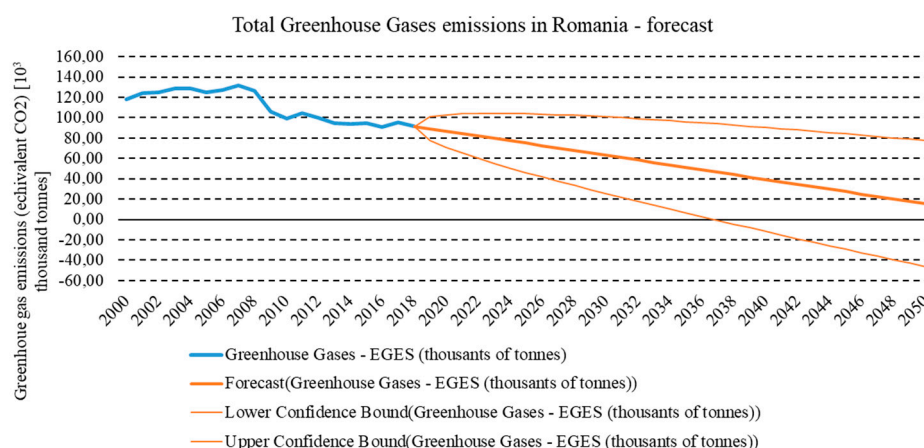


Figure 5. Total GHG emissions in Romania (source: own creation based on Eurostat).

Figure 5 shows the forecast and the boundary values for the confidence interval. To apply this method, a 95% confidence interval was selected in order to see the future values within this range (calculated as a normal distribution). The smoothing factor α in our forecast was 0.9, which indicates that the amount of smoothing was reduced, thus more weight could be placed on the more recent observations.

The same forecast tool was also used for the analysis of the emissions intensity of the energy consumption, as shown in Figure 6. The symbol used was I_{GES} and the data were measured in a thousand-metric-tons CO_2 equivalent. As can be seen, the highest value recorded happened in 2007, with a 90,370.00 metric ton CO_2 equivalent, whereas the lowest value of 66,259.00 metric ton CO_2 equivalent was registered in 2016. A 36% improvement can be seen in 2018 compared to 2007, but a 1% decrease compared to 2016. Although from 2000 to 2018 the values slightly decreased, the improvement in GHG emissions registered was 18%. From 2000 to 2007, when the European Commission issued the 2007/589/EC: C Commission Decision of 18 July 2007 establishing guidelines for the monitoring and reporting of GHG emissions, the emissions were increasing year by year, but this regulation

and others that were issued since then contributed to decreasing GHG emissions due to their implementation among member states.

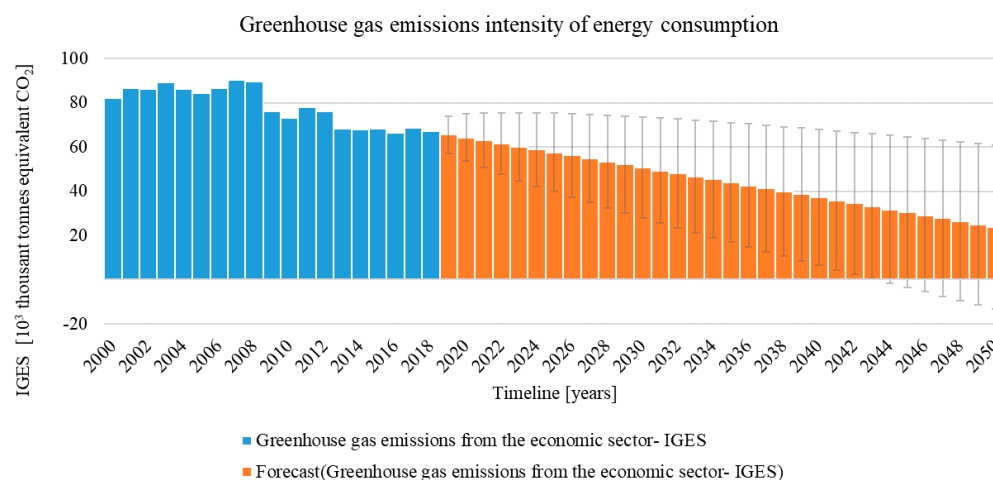


Figure 6. GHG emissions intensity of energy consumption (source: own creation based on Eurostat).

Figure 7 presents just four sectors because these are the largest source sectors of emissions.

The data reported to Eurostat from 2000 to 2018 present that the energy sector was the highest pollutant of GHGs. Their reported value never decreased under a 76,404 thousand metric ton CO₂ equivalent, the highest value being recorded in 2003. The emissions quantity decreases were visible mainly between 2007 and 2018, an improvement of 26%. The difference between the sectors is significant. The next sectors that were close in the reporting numbers (the CO₂ equivalent) were industrial processes and product usage and agriculture.

As can be seen in Figure 7, their reported values were in the range of an approximately 19,000 metric ton CO₂ equivalent. The highest value recorded in industrial processes and product usage was 22,457.98 in the year 2004, whereas the lowest value was 11,769 in the year 2013. Unfortunately, the decreasing trend was not consistently linear, with the correlation coefficient in this case being $R^2 = 0.64$. In 2018, the values reported were 14% higher than in 2013 and 30% lower than in 2000. In agriculture, 2018 recorded higher emissions than 2010, when the lowest emissions were recorded. The increase was by 13% compared to 2010, still 7% higher than 2000 but a 4% decrease when compared to 2007. Since 2010, the values of GHG emissions continuously increased year by year and if we do not change the regulations in this sector the emissions registered now will not be much different in 2035 or 2050.

If we analyze the last sector in Figure 7, the waste sector, we can see that although the values reported were lower than in previous sector, the trend was actually increasing. The values registered in 2018 were 5809 metric tons of CO₂ equivalent and in 2000, 5303 metric tons of CO₂ equivalent. As can be seen, a 9.5% increase in GHG emissions was recorded. The highest value reported during this time was in 2017, whereas the lowest was in 2011. The GHG emissions from waste in the EU fell by 42% since 1995, but as can be seen from Romania's data, it is necessary to apply better waste management and regulations. By focusing on recycling and reducing disposal of waste as landfill, many EU member states were able to register lower values for emissions from waste. If Romania changes its waste treatment policies or applies the European regulations as it should, thus creating a more circular economy, then emissions will be reduced and climate change will present a lower impact. The waste sector accounts for about 3% of total GHG emissions [46].

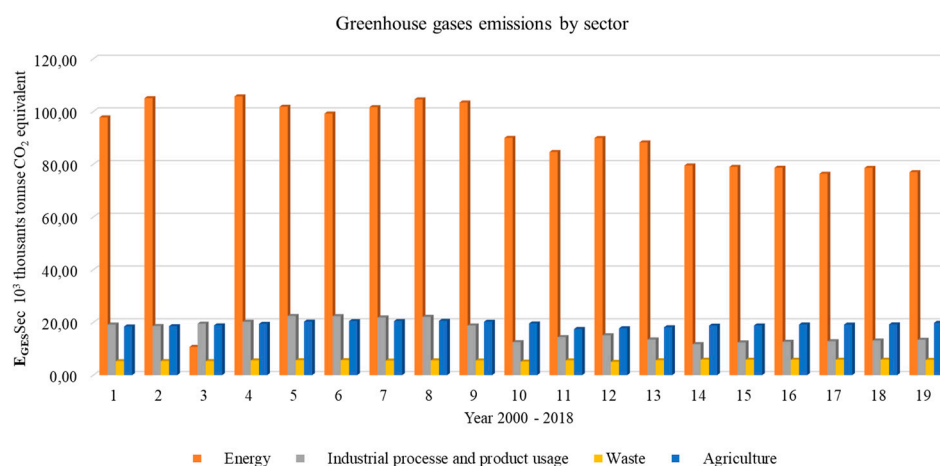


Figure 7. GHG emissions by sector (source: own creation based on Eurostat).

3.3. GHG Emissions Statistical Analysis in Romania

3.3.1. Chronological Series Analysis

As previously mentioned, the first analysis that was conducted was done by using time series techniques, specifically chronological series (SCr) analysis. The time series techniques were used to look back on patterns of the history of GHG emissions reporting; thus, if we can identify and project the pattern then we have our forecast. Chronological series component analysis can explain the past and present evolution of processes and phenomena but also offers the possibility to predict their behavior in the near or distant future through future projection of evolution models and past behavior. This implies a fundamental supposition that past models and trends that happened in the past will also be valid in the future. This assumption is closer to the truth for the immediate period, whereas for a longer period of time some factors might intervene that can modify the preestablished behavior. Despite the apparently random nature of variable manifestation within a timeframe, usually there is a basic pattern, either theoretical or fundamental, that can be identified, and that contains different elements and reflects the influence of some factors in such a manner that the original series can be reproduced as accurately as possible.

As said, the timeframes are successive and have the same length, so we used SCr of moments with equal timeframes between moments. Knowing this, the median indicators of the chronological time series were calculated.

Medium level for SCr intervals:

$$\bar{y} = \frac{\sum_{t=1}^n y_t}{n} = 110,746.87 \text{ thousand tonnes CO}_2 \text{ equivalent} \quad (12)$$

Then the equation for SCr moments with equal intervals between moments is:

$$\overline{y_{cr}} = \frac{\sum_{i=1}^{n-1} A_i}{\sum_{i=1}^{n-1} h} = \frac{\frac{y_1}{2} + y_2 + \dots + y_{n-1} + \frac{y_n}{2}}{n-1} = 111,079.16 \text{ thousand tonnes CO}_2 \text{ equivalent} \quad (13)$$

The interval length is 1 year.

The absolute average change (absolute average gain) result was:

$$\bar{\Delta} = \frac{\Delta_{n/1}}{n-1} = \frac{y_n - y_1}{n-1} = -1456.18 \text{ thousand tonnes CO}_2 \text{ equivalent}. \quad (14)$$

Regarding the dynamic average parameter (increase or decrease), the result was:

$$\bar{I} = \sqrt[n-1]{\frac{y_n}{y_1}} = 0.986 \quad (15)$$

The last indicator of the chronologic series was the dynamic rhythm (relative average change or relative median gain or median increase/decrease ratio):

$$\bar{R} = (0.986 - 1) \times 100 = -1.4 [\%] \quad (16)$$

Thus, based on the data used we can say that the average GHG emissions is the equivalent of 111,079.16 metric tons of CO₂. The emissions decreased in the analyzed period by an equivalent of 1456.18 metric tons CO₂ on average in a year, which means 0.986 times. The dynamic rhythm result shows us that the GHG emissions only decreased by 1.4%. It is necessary to further analyze this dynamic rhythm in a few more years to see whether things have started to change for the better, by not just 1.4% but, if possible, by a higher percentage.

3.3.2. GHG Emissions Analytical Method Analysis

Analytical methods offer a more exact adjustment of the chronological series because they consider all the chronological series terms. These methods assume using the appropriate mathematical/analytical functions to determine the trend values. The fundamental problem is choosing the right type of function, also called the trend adjustment function. Most used functions are linear, polynomial, hyperbolic, exponential, logistics, and parabolic. Choosing one function can be done by graphic representation. The data gathered from Eurostat is a chronological series formed from an odd number of terms, so in this case the central point of the series was $t = 0$ and the rest of the terms were symmetrical to that one.

Using graphical representation, in Figures 8 and 9 we can see the GHG emissions trend in Romania both for linear and exponential analysis. As can be observed from the correlation coefficient, the linear trend analysis was a better fit because $R^2 = 0.7557$, unlike $R^2 = 0.7376$ for the exponential trendline analysis. The difference between the correlation coefficients was not significant, which is why this both methods are acceptable but still will need further analysis in the future.

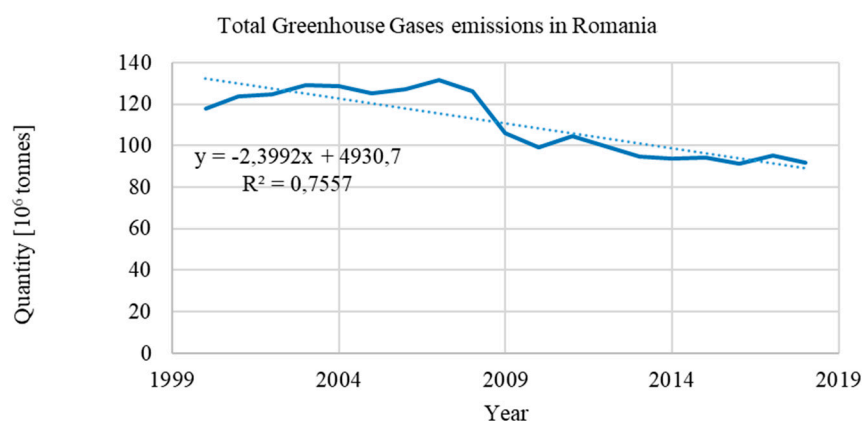


Figure 8. Total greenhouse emissions in Romania—linear trend analysis.

For the linear analysis the parameters a and b are:

$$a = \frac{\sum y_t}{n} = \bar{y} = \frac{2,104,190.6}{19} = 110,746.87 \quad (17)$$

$$b = \frac{\sum t \times y_t}{\sum t^2} = \frac{-1,367,537.61}{570} = -2399.19 \quad (18)$$

Thus, the equation that describes the linear trend analysis is:

$$\hat{y}_t = a + bt = 110,746.87 - 2399.19t \quad (19)$$

The values were calculated and are presented in Table 2.

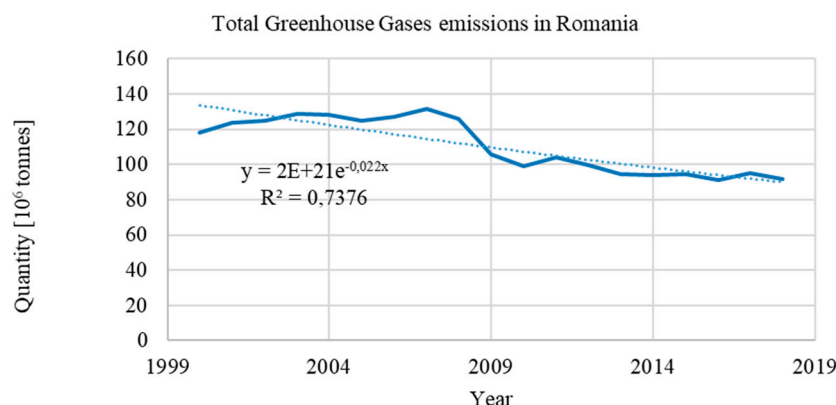


Figure 9. Total greenhouse emissions in Romania—exponential trend analysis.

Table 2. Linear trend analysis of total GHG emissions in Romania.

Years	y_t	t	t^2	T^*y_t	\hat{y}_t	$y_t - \hat{y}_t$	$(y_t - \hat{y}_t)^2$
2000	117,874.98	−9	81	−1,060,874.81	132,339.57	−14,464.59	209,224,480.20
2001	123,818.21	−8	64	−990,545.67	129,940.38	−6122.18	37,481,036.11
2002	124,891.01	−7	49	−874,237.07	127,541.20	−2650.19	7,023,481.72
2003	129,051.47	−6	36	−774,308.82	125,142.01	3909.46	15,283,899.33
2004	128,491.31	−5	25	−642,456.55	122,742.82	5748.49	33,045,155.10
2005	125,006.10	−4	16	−500,024.41	120,343.63	4662.47	21,738,667.06
2006	127,334.60	−3	9	−382,003.79	117,944.44	9390.16	88,175,056.12
2007	131,532.46	−2	4	−263,064.92	115,545.25	15,987.21	255,590,918.54
2008	126,179.68	−1	1	−126,179.68	113,146.06	13,033.62	169,875,172.92
2009	105,847.91	0	0	0.00	110,746.87	−4898.96	23,999,799.10
2010	99,170.01	1	1	99,170.01	108,347.68	−9177.67	84,229,655.73
2011	104,377.84	2	4	208,755.68	105,948.50	−1570.66	2,466,960.03
2012	99,615.38	3	9	298,846.15	103,549.31	−3933.92	15,475,752.92
2013	94,638.20	4	16	378,552.80	101,150.12	−6511.92	42,405,083.14
2014	93,878.21	5	25	469,391.05	98,750.93	−4872.72	23,743,397.79
2015	94,448.55	6	36	566,691.30	96,351.74	−1903.19	3,622,135.83
2016	91,182.74	7	49	638,279.18	93,952.55	−2769.81	7,671,859.43
2017	95,195.44	8	64	761,563.52	91,553.36	3642.08	13,264,722.16
2018	91,656.49	9	81	824,908.41	89,154.17	2502.32	6,261,582.46
TOTAL	2,104,190.60	0.00	570	−1,367,537.61	2,104,190.60	0.00	1,060,578,815.71

As can be seen, the resulting equation was the linear trend equation for which the correlation coefficient is equal to 1. It can be observed that the analysis was correct because the sum of the GHG emissions reported and the sum of the GHG emissions adjusted are equal. After calculating the relative approximation error for the linear trend analysis, we can say that the forecast accuracy is high because it is below 10%.

$$\varepsilon = 5.44\% \quad (20)$$

For the exponential method we used the equation above to determine the parameters, so they were:

$$\log a = \frac{\sum \log y_t}{n} = \frac{95.76}{19} = 5.04 \quad (21)$$

$$\log b = \frac{\sum t \times \log y_t}{\sum t^2} = \frac{-5.46}{570} = -0.00957 \quad (22)$$

Thus,

$$a = 109,711.5 \quad (23)$$

$$b = 0.978 \quad (24)$$

In this case the exponential equation will be:

$$\hat{y}_t = a \times b^t = 109,711.5 \times 0.978^t \quad (25)$$

The values were calculated based on Table 3.

Table 3. Exponential trend analysis of total GHG emissions in Romania.

Years	y_t	t	t^2	T^*y_t	\hat{y}_t	$y_t - \hat{y}_t$	$(y_t - \hat{y}_t)^2$
2000	117,874.98	−9	81	−1,060,874.81	132,339.57	−14,464.59	209,224,480.20
2001	123,818.21	−8	64	−990,545.67	129,940.38	−6122.18	37,481,036.11
2002	124,891.01	−7	49	−874,237.07	127,541.20	−2650.19	7,023,481.72
2003	129,051.47	−6	36	−774,308.82	125,142.01	3909.46	15,283,899.33
2004	128,491.31	−5	25	−642,456.55	122,742.82	5748.49	33,045,155.10
2005	125,006.10	−4	16	−500,024.41	120,343.63	4662.47	21,738,667.06
2006	127,334.60	−3	9	−382,003.79	117,944.44	9390.16	88,175,056.12
2007	131,532.46	−2	4	−263,064.92	115,545.25	15,987.21	255,590,918.54
2008	126,179.68	−1	1	−126,179.68	113,146.06	13,033.62	169,875,172.92
2009	105,847.91	0	0	0.00	110,746.87	−4898.96	23,999,799.10
2010	99,170.01	1	1	99,170.01	108,347.68	−9177.67	84,229,655.73
2011	104,377.84	2	4	208,755.68	105,948.50	−1570.66	2,466,960.03
2012	99,615.38	3	9	298,846.15	103,549.31	−3933.92	15,475,752.92
2013	94,638.20	4	16	378,552.80	101,150.12	−6511.92	42,405,083.14
2014	93,878.21	5	25	469,391.05	98,750.93	−4872.72	23,743,397.79
2015	94,448.55	6	36	566,691.30	96,351.74	−1903.19	3,622,135.83
2016	91,182.74	7	49	638,279.18	93,952.55	−2769.81	7,671,859.43
2017	95,195.44	8	64	761,563.52	91,553.36	3642.08	13,264,722.16
2018	91,656.49	9	81	824,908.41	89,154.17	2502.32	6,261,582.46
TOTAL	2,104,190.60	0.00	570	−1,367,537.61	2,104,190.60	0.00	1,060,578,815.71

In addition, for the exponential trend analysis the relative approximation error was calculated, but the result was above 10%, which shows that this method is not accurate.

Considering the results, we can make a choice regarding the optimum method using the following criteria:

- We select the graphic representation of the adjusted chronological series that best fits the real values;
- We select the chronological series trend function for which the sum of the adjusted values is closest to the real values;
- We select the adjusted function for which the sum of the squares of the differences between the adjusted and real values is minimum;
- We select the function that has the minimum mean square deviation.

Considering all the criteria between the two analytical methods used for analyzing the total GHG emissions, we can say that the most exact method is the linear trend method.

The Adjusted Method	$\sum (y_t - \hat{y}_t)^2$
Linear function method	1,060,578,815.71
Exponential function method	7,231,706,537.04

The criteria selection is also sustained by the relative approximation error that was calculated.

$$\varepsilon_{linear} < \varepsilon_{exponential} \quad (26)$$

$$5.44\% < 12.32\% \quad (27)$$

Although the results were achieved using the basics tools for a statistic analysis, they revealed that if we do not apply the proper method for analysis then we will not be able to predict the emissions as close to what actually happens as we would like. For example, as seen from the relative approximation error, the exponential forecast leads to different

results. The methods used in the paper were selected to be expressed in a simple way in order to be easily understood by scientists and interested people in the changes in GHG emissions.

3.4. Study Limitations

For a great quality analysis it is necessary to mention the limitations.

Although the forecasting method used in the article is conventional and expressed good results, future research should consider combining both conventional and newly developed methods of forecast analysis. The recommendation to combine them comes from the fact that each method has its own advantages and limitations and only together can they present accurate results.

Significant results can be obtained using conventional forecast methods that use statistical modeling/analysis based on mathematical models that provide statistical diagnostic significance tests and using machine learning models that can accelerate data processing, automate forecasts, and increase adaptability to changes.

Due to the fact that the data collected had a clear period of time, the chronological analysis was a good fit, but to sustain the results, more combined methods should be considered because every analysis has its own limitations, including this method.

In this respect, in our future analysis we intend to analyze future data related to GHGs using IT tools, but for the start of our research we limited the analysis to the basics (forecasting tool from Excel).

4. Conclusions

Due to technological development in the past 30 years, the environment suffered changes that have had an impact on the environment in the long term, thus affecting the life of future generations. Because people's needs increased in this time, the GHG emissions that resulted from these processes also increased.

Thus, this paper highlights the GHG emissions and the importance of good emissions management. Based on the results of our research, it can be seen that statistics are a tool that can be used in predicting GHG emissions for the conditions that the current factors do not change. The regulations and policies that are adapted year by year influence any analysis. Environmental management and analysis tools are needed and should constitute an important part of the sustainable development plan. Assessing the situation based on known data will help stakeholders make better and more informed decisions.

A better system that can be used for calculating and monitoring GHG emissions is at the moment a requirement not just for Romania but for other countries as well. This conclusion can be drawn from the dynamic rhythm calculated that showed only a 1.4% improvement in the reduction of GHG emissions.

In addition, from the analytical methods used we can draw the conclusion that emissions are on a descending scale and choosing a proper method is important in analyzing data.

Regarding the results presented in the paper, it must be mentioned that one weakness that the forecast method should have addressed is using more analysis methods. Using more methods could have ensured a larger comparison between the results, thus resulting in a more accurate forecast. At the same time, the use of chronological series and the analytical methods analysis both showed a decrease in GHG emissions.

The forecasting tool from Excel showed that in the time analyzed, some improvements were made, and if we move forward in the future using the current regulations and policies, it is possible to achieve the Green Deal goal. Of course, the stakeholders' attitude towards changing and adapting to the EU directives will highly influence the future outcome.

Although in Europe there are states that are making considerable progress, there are still other countries like Romania that need support to implement the proper tools. Therefore, in order to see improvement in the numbers reported to the EU, in Romania it is necessary to:

- Ensure transparency in the emissions quantity for each stakeholder, disregarding the sector;
- Include better rights and obligations for stakeholders;
- Provide the tools/means to change the current processes to sustainable, zero emissions ones;
- Offer state grants for companies adapting to green energy and zero emissions;
- Implement proper legislation for selecting, managing, and monitoring waste, using green energy for recycling;
- Maintain a decrease of at least 1.4% in GHG emissions, as shown in our analysis;
- Maintain a descending trend in the values GHG emissions generated and gathered, which are then reported to the EU;
- Use the proper statistical methods to analyze the trends in GHGs emissions (from our research, linear trend analysis is one option);
- Implement, on a national scale, carbon recovery machines or high-carbon-using trees in every part of the country.

In addition, the improvements mentioned before can be achieved only by conducting future scientific research on GHG emissions. One important indicator that should be analyzed is the carbon footprint, which is easy to understand since there is global interest in it and it is measured in quantitative units, but still, it is necessary to keep in mind that one weakness is the insufficient accuracy of the data. Future research should analyze each industry by itself and its GHG emissions, and from the results develop the proper tools for successful GHG emissions reduction.

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ROMANIAN BIOMASS PELLET MARKET – TECHNO-ECONOMIC ANALYSIS / PIAȚA ROMÂNEASCĂ A PELETELOR DIN BIOMASĂ - ANALIZĂ TEHNICO- ECONOMICĂ

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ABSTRACT

Biomass is currently the most widespread form of renewable energy, and its exploitation is constantly increasing due to concerns about the major impact of fossil fuel consumption, in terms of climate change, global warming and their negative impact on the human factor. Biomass can be transformed using modern technologies into solid, liquid, and gaseous fuels. One of the most widely used biomass biofuels is wood pellets. Pellets obtained from woody biomass represent a very successful renewable energy source, due to their characteristics that include high density, high calorific value, low moisture content, but also ease of storage and transport. Romania's biomass pellet industry has recorded significant growth due to the increasing demand for green energy. Investment in modern technology improves production efficiency and enhances competitiveness in international markets. However, fluctuations in raw material prices such as biomass transportation costs and moisture content often affect profit margins. Improving infrastructure and continued investment in research and development are crucial to strengthening Romania's position in the global renewable energy market. In this context, the purpose of the article is to present an analysis for Romanian pellet market industry.

REZUMAT

Biomasa este în prezent cea mai răspândită formă de energie regenerabilă, iar exploatarea acesteia este în continuă creștere datorită preocupărilor legate de impactul major al consumului de combustibili fosili, în ceea ce privește schimbările climatice, încălzirea globală și impactul negativ al acestora asupra factorului uman. Biomasa poate fi transformată cu ajutorul tehnologiilor moderne în combustibili sub formă solidă, lichidă și gazoasă. Printre cei mai utilizați biocombustibili din biomasă sunt peletele din lemn. Peletele obținute din biomasă lemnoasă reprezintă o sursă de energie regenerabilă de mare succes, datorită caracteristicilor acestora care includ densitate ridicată, putere calorică mare, conținut de umiditate scăzut dar și ușurință în depozitare și transport. Industria peletelor din biomasă din România a înregistrat o creștere semnificativă datorită cererii tot mai mari de energie verde. Investițiile în tehnologii moderne îmbunătățesc eficiența producției și sporesc competitivitatea pe piețele internaționale. Cu toate acestea, fluctuațiile prețurilor materiilor prime, cum ar fi costurile de transport al biomasei și conținutul de umiditate, afectează adesea marjele de profit. Îmbunătățirea infrastructurii și investițiile continue în cercetare și dezvoltare sunt esențiale pentru consolidarea poziției României pe piața globală a energiei regenerabile. În acest context, scopul articolului este de a prezenta o analiză pentru industria românească a pieței peletelor.

INTRODUCTION

In the context of climate changes and their effect on the environment and the human factor, biomass has been promoted as an important resource for reducing greenhouse gas emissions through its conversion into biofuels (Ilham, 2022). The European Environment Agency has stated that to meet the global goal of reducing the carbon footprint by 50% by 2050, increasing the use of renewable energy is one of the most significant greenhouse gas reduction policies implemented by various countries of the EU (Bui-Duy et al., 2023).

Bioenergy, or energy derived from bio-based sources, represents a type of renewable energy that is environmentally friendly and economically viable. Thus, in the last decade, bioenergy production in the form of solid, liquid, or gaseous fuels has begun to play an important role in the global energy mix (*World Bioenergy Association, 2019; Jelonek et al., 2020*).

Biomass fuel pellets represent one of the most important energy sources that can be a promising substitute for fossil fuels (*Sarker et al., 2023*). At present, pellets are the most cost-effective technique to convert biomass into fuel and are a rapidly growing component of the energy sector (*Jelonek et al., 2020*). According to Statista report and as it can be seen in Figure 1, the European demand for wood pellets is expected to grow to more than 38 million metric tons by 2025, thus Europe is expected to remain the most important target market for wood pellets through 2025. In 2020, the European Union led the world pellet production with 13 MMT (million metric tons), followed by North America with 11 MMT, China with 10 MMT, South America with 4.4 MMT and Oceania with 0.8 MMT (<https://www.statista.com/statistics/243910/global-wood-pellet-consumption-outlook/>).

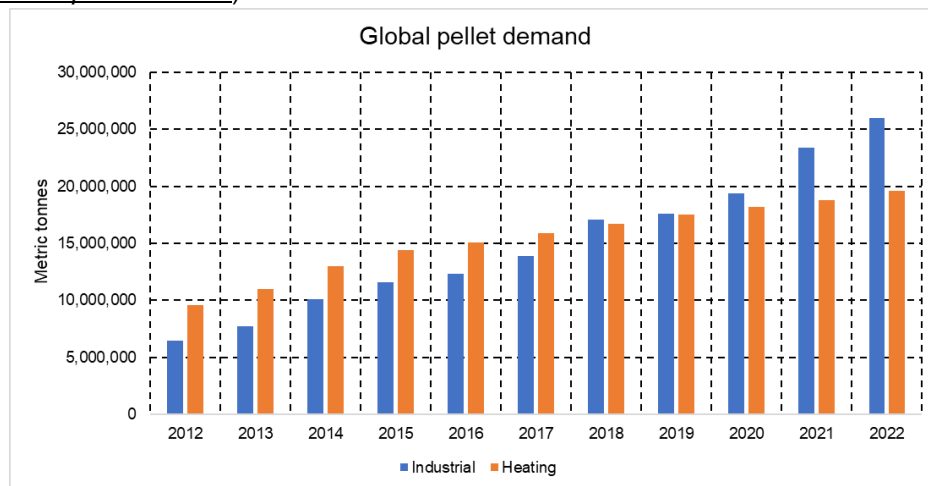


Fig. 1 – Global pellet demand for a 10-year timeframe (TCPEL, 2022)

The ENplus certification scheme defines three pellet quality classes, namely: ENplus A1, ENplus A2 and ENplus B (*European Pellet Council, 2015; Paraschiv et al., 2017*).

A1 quality class pellets (premium quality) are the most commonly used; pellets are obtained only from untreated wood residues, they are mainly used in the residential sector for burning in individual stoves and boilers, they produce the lowest amount of ash and have the highest calorific value.

A2 quality class pellets are obtained from raw materials with a high content of tree bark, they are used for combustion in larger installations and produce a larger amount of ash.

B quality class pellets (industrial class) are obtained from a wide range of raw materials, including chemically treated wood by-products, produce the highest amount of ash and have a significantly lower calorific value than that of class A2.

The most common biomass feedstocks used for pellets production are wood processing industry waste, agricultural and forest residues, and energy crops. The pellets produced from these biomass feedstocks have a high density and an extremely low moisture content (<10%), and a high energy conversion efficiency (about 75%) (*Paraschiv et al., 2017; Pradhan et al., 2018*).

Many works can be found in the literature focused on techno-economic analysis used to estimate the production cost of wood pellets. In their research, Ebadian et al. (*Ebadian et al., 2021*) have modelled an inter-continental agricultural pellet supply chain and estimated the production cost and price of agricultural pellets. In a recent study, Visser and co-workers (*Visser et al., 2020*) reviewed existing literature on pellet costs and performed a techno-economic analysis of the impact of different design variables on cost components (feedstock type, production location and pellet plant size). Schipfer et al. (*Schipfer et al., 2020*) carried out another study where the main objective was to establish a framework to test the European residential wood pellet market for competitive spatial equilibrium using modern trade theory.

Sarker et al., (2023) realised a techno-economic analysis of torrefied fuel pellet production from agricultural residue via integrated torrefaction and pelletisation process. The authors tested and compared two scenarios: scenario 1 - pelletisation of torrefied biomass with additives and scenario 2 - pelletisation of torrefied biomass without any external additives and they reported that the economic analysis suggests that both

scenarios are profitable. In their results highlighted that the lowest selling price of generated torrefied pellets was found to be \$103.4 at the plant gate for scenario 1 and \$105.1 per tonne for scenario 2. Furthermore, sensitivity analysis indicates that, in producing pellets for both scenarios, among all variable costs, labour cost has a greatest impact on net present value and minimum selling price. A similar study was carried out by *Manouchehrinejad et al.*, (2021), which investigated the techno-economic analysis of two integrated torrefaction and pelletisation systems: torrefaction before pelletisation and torrefaction after pelletisation configurations to produce torrefied wood pellets. The authors reported that the minimum selling price for torrefaction before pelletisation is \$207 Mg⁻¹ at the plant gate and \$197 Mg⁻¹ for the torrefaction after pelletisation configurations.

In the context of the current global focus on environmental protection and carbon dioxide emission reduction, the biomass pellet market has become an important part of the energy infrastructure of many European countries, including Romania. As the demand for renewable energy increases significantly, the pellet industry becomes even more important in providing clean and sustainable energy.

Europe has been a major player in the growth of the biomass pellet industry, having been at the forefront of the establishment of laws and policies that encourage the effective use of renewable energy sources. The pellet industry has changed dramatically during the 1990s as concerns over climate change and the high expense of fossil fuels have grown. Thanks to persistent efforts to establish favourable legal frameworks and to invest in cutting-edge technologies for the manufacture and use of pellets, several European nations, including Germany, Sweden, and Austria, have emerged as leaders in the production and consumption of biomass pellets. In figure 2, the top 5 countries that had the highest production in 2021 are presented.

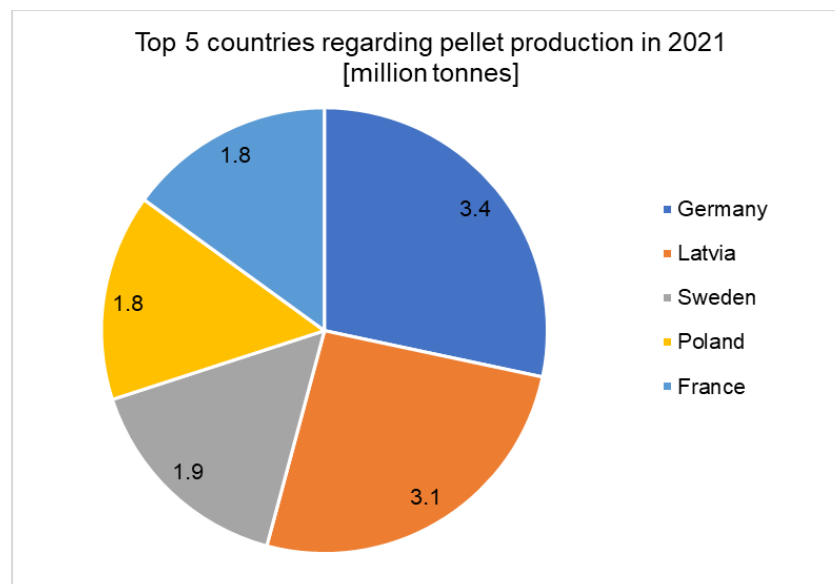


Fig. 2 – Top 5 countries in 2021 that had the highest pellet production
(adapted after *Bioenergy Europe Statistical Report*, 2021)

The Romanian market has evolved in a way that closely resembles European patterns over the past few decades, exhibiting gradual development. The Romanian government has encouraged the growth of the meat industry through a number of legislative and policy efforts, which has increased the quantity of biomass resources used and broadened the country's energy mix. Romania has the potential to dramatically improve its position on the biomass market by putting into practice efficient growth plans and investing in state-of-the-art technologies, even though it is currently in a relatively early stage of development in comparison to other European nations. The literature on the techno-economic analysis of Romanian pellet production is scarce. In this context, the main aim of this article is to present an analysis for Romanian pellet market industry.

MATERIALS AND METHODS

The economic assessment involves the computation of the net present value (NPV) and profitability index (PI) for the investment. The methodology for the economic analysis followed the model of the authors *Pantaleo et al.*, which was used to analyse the market for pellets in Italy. Applying the prices currently used in Romania and the data available from different suppliers, the techno-economic analysis was possible.

Net Present Value (NVP) is defined as the total present value for the projected return on an investment that is offset by its initial outlay. NVP is used to determine initiatives or projects that will produce the greatest return in relevant time frames. In addition, NVP is used to verify that a business choice will last for a defined period of time by meeting its objective benchmark and demonstrating more viability in competition with alternatives. To determine NPV, the company's cumulative profits over a certain number of years are discounted using a marginal rate of return (Alizadeh et al., 2023).

The NPV can be calculated based on Equation (1):

$$NVP = -\beta + \sum_{j=1}^T \frac{\phi_j}{(1+R)^j} \quad (1)$$

where β is the initial investment;

T is the project lifetime, [in years];

ϕ_j is the cash flow in each year (j).

The discount rate or cost of capital is shown by R in the above equation.

Profitability index (PI) is used to assess how much profit may come from a particular investment. The PI is calculated according to Equation (2) (Pantaleo et al., 2020):

$$PI = \frac{NVP}{C_{Investment}} \quad (2)$$

where the cost of investment ($C_{Investment}$) is calculated according to Equation (3) (Pantaleo et al., 2020):

$$C_{Investment} = C_{pell} + C_{dry} + C_{chip} + C_{store} + C_{inst} + C_{eng} \quad (3)$$

where:

C_{pell} - the cost of pelletizing the plant;

C_{dry} - the cost of drying the plant;

C_{chip} - the cost of pre-treatment processes;

C_{store} - the cost of storage;

C_{inst} - the cost of plant installation;

C_{eng} - the plant engineering cost.

Payback Time (PBT) is the time (in years) required for the capital invested in an asset to be repaid by the net cash flow it produces. A shorter PBT is preferable because it gives the investor a clear idea of how long the initial outlay will be at risk. PBT is the period of time in years that a project needs to pay back its initial investment (δ) through earnings after interest and taxes (μ) (Alizadeh et al., 2023).

The equation for estimating PBT is presented in Equation (4):

$$PBT = \frac{\delta}{\mu} \quad (4)$$

Before starting to analyse the cost, a modelling process of the pelletization process was realized using the program for business process modelling ADONIS Communities. In Figure 3 the process is presented considering that the trigger is represented by the demand for pellets on the market.

Adonis Software offers a methodical approach to comprehend, record, and enhance the way that operations are carried out. For increasing productivity, effectiveness, and flexibility, modelling processes is an essential activity. It promotes a better knowledge and administration of company processes by providing a comprehensive perspective on how work is done.

The pelletizing process is adapted according to the raw material used, but usually includes the following stages: reception of the raw material, drying, grinding, pelletizing, cooling, packaging, as can also be seen in figure 3.

The size reduction of lignocellulosic biomass is an important step in the pelletization process. This influences a number of factors, such as compaction, the contact area between the particles, the friction forces between the pressed material and the die wall, but also the material flow. Biomass shredding is done with the help of hammer mills, which are chosen according to the feedstock type, the degree of humidity and the production capacity (Whittaker and Shield, 2017).

Water is a key parameter in the pelletization process, biomass moisture being one of the most important parameters that determine the durability of the pellets. The optimum moisture content differs depending on the type of biomass used, such as: for pine it is between 6–13%, straw 8–15% and Miscanthus 20–25%. Biomass drying is carried out with fully automated continuous flow dryers (Whittaker and Shield, 2017). In the pelletizing process, the optimum moisture content is considered to be between 10-15% (Pradhan et al., 2018).

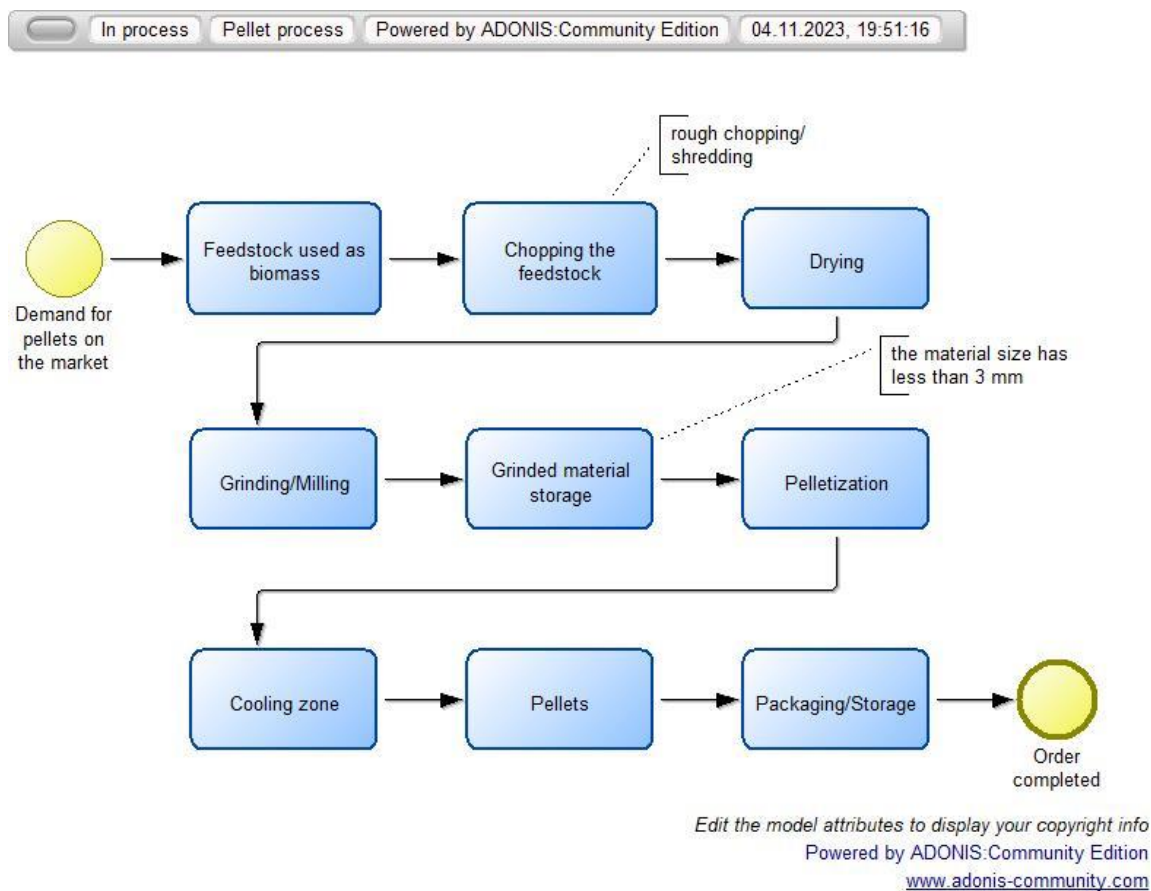


Fig. 3 – Modelling of the pelletization process

Pelletizing process represents the operation of transforming the biomass feedstock into fuel. The producing pellets process involves placing biomass under high pressure and forcing it through the cylindrical holes of a die. This process is known as extrusion (Paraschiv et al., 2017; Ciolkosz, 2023).

Cooling is the mandatory operation to be performed after pelletizing, due to the high temperature of the finished product when exiting the extrusion die. The outlet temperature can reach 90 - 100°C, there being a risk of damage to the finished product if it is further stored or packaged at this temperature (Ciolkosz, 2023).

Semi-automatic or fully automated machines are used to pack the pellets in plastic bags or special material bags. Pellets can be used for domestic use (ovens or home heating) or industrial use (gasification, pyrolysis and co-generation (Paraschiv et al., 2017; Pradhan et al., 2018).

RESULTS

Since European Union proposed a raise in renewable energy consumption by 2030, countries started analysing the current situation regarding the global demand for renewable energy and the investments necessary for achieving the proposed goal (Council of the European Union, 2018).

In paper (Pantaleo et al., 2020), the authors made inquiries and presented the pellet production industry. One of the main conclusions stated the necessity of an accurate techno – economic assessment (Thek and Obernberger, 2012). Also, the studies demonstrated the influence of physico-chemical and mechanical characteristics of the biomass on the production process of pellets which implies an influence on the pellet market evaluation from the point of view of investments, operational and maintenance costs necessary for developing a pellet factory (Junginger and Sikkema, 2008; Castellano et al., 2015).

Regarding the analysis conducted in the present article it is necessary to mention the fact that the pellet production line is experimental being a part of the Testing Department from The National Institute of Research – Development for Machines and Installations Designed for Agriculture and Food Industry – INMA Bucharest. Also, some of the parameters mentioned were determined through previous research and adapted for the economic evaluation proposed.

The economic viability assessment was done considering the economic model proposed by Pantaleo et al., (2020), the calculations being done using the equations proposed by the authors.

Thus, in the following table (Table 1) the data held constant are presented. Regarding the Cost of transport $C_{\text{transport}}$ the value in the table was selected by analysing the existing transportation market for raw materials, considering a distance of 100 km and a load of 20 t.

Also, the drying coefficient was obtained considering a biomass moisture content of 30% that after drying process will have 10% moisture content. The electricity needed per t of pellet was experimentally determined by researchers from the institute while the maintenance coefficient was selected based on literature research (Nolan et al., 2010). Regarding the determination of the electricity needed, for experiments, the determination of power consumption, electricity consumption, and specific electricity consumption of equipment in the flow was determined for every equipment that is a part of the process. Thus, the means for the working capacity, power consumption and specific power consumption was considered. The mean of the parameters resulted after subjecting the equipment to 3 tests (Chitoiu, 2011).

Table 1

Technical and economic parameters remaining constant		
Parameters	Unit	Value
Maximum production capacity Q_{max}	t/hour	0.15
Production load factor i_u	%	75
Hourly production capacity Q	t/hour	0.113
Number of daily shifts n_{shifts}	-	1
Number of annual production hours H	hours/year	2016
Annual pellet production Q_{pellet}	t/year	226.8
Pellet moisture content m_{pellet}	%	10
Cost of transport $C_{\text{transport}}$ (1)	lei/t/km	2
Drying coefficient k_{drying} (2)	-	0.015
Price of electricity $P_{\text{electricity}}$	lei/MWh	500
Electricity needed per t of pellet E_{pellet} (3)	MWh/t	0.03
Annual cost of personnel C_{unit}	lei/year/person	36000
Maintenance coefficient k_M (4)	%	10
Lifetime of the plant n	years	6
Real discount rate r	%	3
Pellet market value P_{pellet}	lei/t	1100

In table 2 the technical and economic parameters that can vary for obtaining different scenarios are presented. The biomass amount and biomass price considered for the analysis were obtained by conducting a market analysis regarding the present pellet industry. Also, the average distance was selected according to the most common distance used for transportation of raw materials and considering that the surroundings are mainly fields that can represent potential biomass suppliers. Electricity needed for chipping was experimentally determined by researchers from the institute and also by one of the authors in his dissertation paper.

Table 2

Technical and economic parameters that can be varied for obtaining different scenarios

Parameters	Unit	Value
Biomass amount	t/year	2100
Biomass price	lei/t	50
Moisture content	%	12
Average transportation distance	km	50
Electricity needed for chipping	MWh/t	0,01
Personnel units per shift	units	2

Knowing the technical and economical parameters presented in the tables above the costs of investments, operation and maintenance could be calculated and are presented in table 3.

Table 3

Investments, operation and maintenance costs			
Investments costs	Value (lei)	Operation and maintenance costs	Value (lei)
C _{pell}	49700	C _{Biomass}	105000
C _{dry}		C _{Transport}	28232
C _{chip}		C _{Drying}	3150
C _{store}	20000	C _{Electricity}	13905.15
C _{inst}	6000	C _{Personnel}	72000
C _{eng}	4500	C _{Maintenance}	4920
TOTAL	79700	TOTAL	227207.15

Regarding the cost of plant installation and the cost of plant engineering cost were calculated based on the authors elaboration considering two technicians employed for 15 days and a cost of 200 lei/day and a net installation cost established on by the pellet market industry.

Based on values established, the financial analysis results could be calculated to see if the investment would be viable and how long it would take to recover the cost of an investment. The net present value (NPV), profitability index (PI) and payback time (PBT) are presented in the table below (Table 4).

Table 4

Results of the financial analysis.		
PBT—payback time; NPV—net present value; PI—profitability index		
Economic parameters	Unit	Value
Revenue	lei	249480
Cash Flow	lei	27192.85
PBT	year	2.93
NPV	lei	53299.17
PI	-	0.66

As it can be observed the investment would be recovered in 2.93 years which is comparable with other studies done by researchers (*Pantaleo et al., 2020; Uchezuba et al., 2019*).

CONCLUSIONS

For the Romanian market, it is important to identify and use low-cost raw materials with low moisture content in order to obtain pellets with high financial profitability, the analysis said. In addition, further analysis and optimization of the biomass supply chain, biomass processing, and final energy conversion should be conducted to better meet end-user needs. As it could be seen from the conducted analysis, the pellet industry market has potential, but further analysis is needed to assess which recipe would be the most profitable and competitive on the market. The biomass market in Romania is varied which allows companies an optimal development in the pellet industry. However, a thorough analysis of all the factors involved in the production of this type of renewable energy is necessary. Potential market segments in the industrial, residential, commercial and rural sectors should also be evaluated to determine the most suitable application, given the differences in pellet quality and cost. Therefore, in the Romanian pellet industry, supply chain optimization strategies and identification of potential market segments are crucial to ensure long-term financial viability.

Also, as it could be observed from the analysis conducted the investment in a pellet plant would be viable and could bring a plus to the fuel market in Romania. The technical and economic parameters in the paper, present the potential for Romanian use of agricultural and forestry solid biomass to produce clean energy and reduce greenhouse gas emissions. Although investments are still needed further investigation for both technical and economic aspects would require a close attention to the application of artificial intelligence in the manufacturing process for further optimization.

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CFD ANALYSIS OF THE SETTLING PROCESS IN A RADIAL CLARIFIER

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ANALIZA CFD A PROCESULUI DE DECANTARE ÎNTR-UN DECANTOR RADIAL

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Keywords: Computational Fluid Dynamics, fluid velocity, radial clarifier, Reynolds number

ABSTRACT

The objective of the present study was to make a theoretical study based on a CFD analysis for a conventional radial clarifier. The parameters of the Computational Fluid Dynamics analysis were set in the Ansys software, and after running the simulation, the values for fluid velocity, turbulence intensity and Reynolds number were obtained. Thus, it was obtained a fluid velocity of 0.103 m/s, a turbulence intensity of $3.82 \cdot 10^{-2}$ % and a Reynolds number of 14.7. This work can help researchers in the field, mainly, but also radial clarifier manufacturers to optimise the process.

REZUMAT

Obiectivul prezentului studiu a fost de a realiza un studiu teoretic bazat pe o analiză CFD pentru un clarificator radial convențional. Parametrii analizei dinamicii fluidelor computaționale au fost setați în software-ul Ansys, iar după rularea simulării, au fost obținute valorile pentru viteza fluidului, intensitatea turbulenței și numărul Reynolds. Astfel, s-a obținut o viteză a fluidului de 0,103 m/s, o intensitate a turbulenței de $3,82 \cdot 10^{-2}$ % și un număr Reynolds de 14,7. Această lucrare poate ajuta cercetătorii din domeniu, în principal, dar și constructorii de clarificatoare radiale în sensul optimizării procesului.

INTRODUCTION

Our planet has witnessed an escalating rate of industrialization, urbanization, and population increase over the past 50 years, which has had a negative influence on the quality of the world's water, air, and soil as well as on environmental degradation. Since it promotes sustainable water reuse while decreasing or eliminating pollution of natural water sources, wastewater treatment has become one of society's most important environmental problems (Alsina, 2008).

Current wastewater management techniques result in inefficient nutrient recovery and reuse, which can have negative effects on the ecosystem, including eutrophication, the climate, and world food security (Hoffmann et al., 2020; Öberg et al., 2020). Water issues are given a lot of attention in a circular economy, which entails more sustainably managing waste and raw materials (including water) (including wastewater) (Smol, 2022; Smol and Koneczna, 2021).

In recent decades, water and wastewater treatment plants have attracted the government's attention, especially through the dangers of wastewater pollution from urban areas (Chero et al., 2019). Most municipal wastewater treatment facilities are required by law to provide some type of treatment for all flows that enter their facilities, regardless of volume or duration (Clarifier Design, 2005).

In Romania, there is the problem of rainwater collection and reuse without being collected in wastewater treatment stations.

Solids removal is probably the most widely used method of water purification from primary mechanical treatment in wastewater treatment plants. A crucial phase in this process refers to the separation of sludge and suspended solid particles using gravity, a process called sedimentation, the equipment in which the process is carried out is called a clarifier. In these tanks, the wastewater is admitted to the tank at one end and the clarified water is discharged at the other end of the clarifier. For the correct deposition of particles, water should pour into the reservoir for enough time (Hasim et al., 2020).

To eliminate suspended solids from influent raw wastewater, primary clarifiers are frequently used in wastewater treatment facilities (Gernaey and Vanrolleghem, 2005).

Primary clarifiers, as the first stage of treatment, have an impact on the following biological and sludge treatment units as well as the production of biogas and electric energy in systems with anaerobic digestion and cogeneration.

As a result, primary clarifiers have a significant impact on the efficiency of the wastewater treatment facility as a whole (Patziger *et al.*, 2016; Griborio *et al.*, 2021).

In the general case, several distinct zones can be identified in a clarifier: the inlet zone, the sedimentation zone, the sediment accumulation zone (sludge zone) and the sediment discharge zone (Rus, 2001). The clarifier, as a major installation in wastewater treatment plants, can limit or define the performance of the treatment plant (Das *et al.*, 2016). In general, up to 50% of the total pollutant load in wastewater is removed by sedimentation (Manuals of British Practice in Water Pollution Control, 1980).

Many different things can have an impact on how well a clarifier is performing to illustrate this, the Reynolds number, the viscosity of the water, the type of movement of the water flow, and also the size and construction of the clarifier are the most important factors in the sedimentation unit (Chero *et al.*, 2019; Campbell and Empie, 2006).

Conventional clarifier models make up about one-third of the total cost of capital water treatment facilities because of the cost of land and construction. Numerous techniques have been developed to increase the effectiveness of tailing ponds, increase their hydraulic capacity, and reduce construction or operational costs (Saady, 2012). Recently, Computational Fluid Dynamics (CFD) analyses have become fast and easy to use. These new generation analyses offer a cheap means of testing and optimizing the hydraulic operation of both existing and design constructions (Al-Jeebory *et al.*, 2010). CFD is a quick, low-cost method for assessing engineering systems that are difficult to replicate in a lab or real-world situations. This gives it several benefits over traditional modelling techniques. Construction of more efficient and compact sedimentation tanks for conventional water treatment facilities can relate to a famous example of how CFD can build a "virtual prototype". Using CFD, it is possible to visualize the three-dimensional liquid flow inside a tank, which can increase solids separation and decrease turbulence.

The objective of the present study is to make a theoretical study based on a CFD analysis for a conventional radial clarifier. The parameters of the Computational Fluid Dynamics analysis were set in the Ansys software, and after running the simulation, the values for fluid velocity, turbulence intensity and Reynolds number were obtained.

MATERIALS AND METHODS

This study builds on earlier research that was done to optimize the sedimentation process (Zăbavă *et al.*, 2021). The research started with the simulation of the flow of a liquid-solid mixture in a radial clarifier, with a central supply area, made in ANSYS CFX. It is important to note that a 2D flow analysis inquiry was carried out, because the clarifier is radial, and a symmetry of the results appears. The preceding study's mathematical equations and simplifying hypotheses were applied to the modelling (Zăbavă *et al.*, 2021; Brennan, 2001; Kohnke, 1999; Parry, 2014; Sharifi *et al.*, 2019).

It should be noted that was run one simulation for a usual clarifier in which the supply pipe had diameter=1 m over, height=5.5 m (the usual case). A simplified 3D modelling of the radial clarifier was performed (Fig. 1), but also a section through the central area of the clarifier, a section that also passes through the middle area of the supply pipe (Fig. 2), using SolidWorks 2016 SP 0.0.

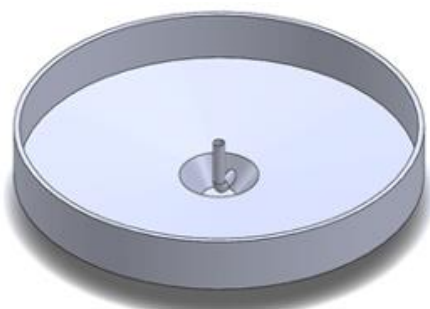


Fig. 1 - Isometric view of a radial clarifier, designed in SolidWorks: 1 m supply line
(Zăbavă *et al.*, 2021)

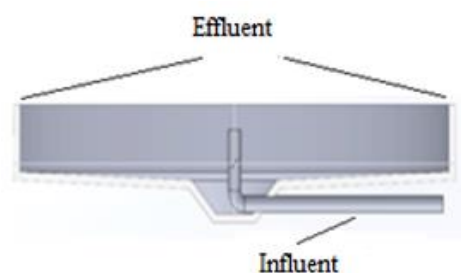


Fig. 2 - Section in the central area for the clarifier with 1 m supply line
(Zăbavă *et al.*, 2021)

The model was drawn in the “Design Modeler” module and are presented in Figure 3.

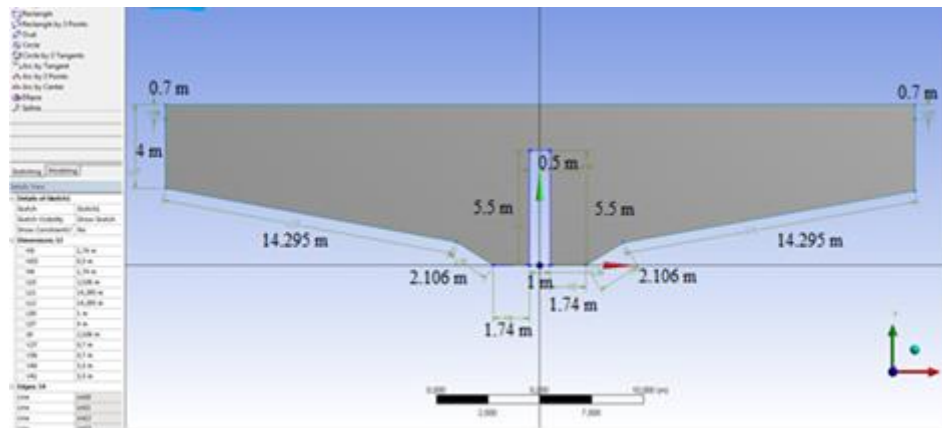


Fig. 3 - Geometric model drawn for the analysis of the clarifier with a feeding pipe with 1 m supply line (Zăbavă et al., 2021)

Therefore, 250 divisions have been set for Edge Sizing and for Edge Sizing 2 - 300, basically both groups define the geometry of the model. In these areas, a reasonable level of numerical prediction accuracy was effectively ensured by imposing a considerable number of finite volume divisions, considered delicate for the 1 m feed pipe clarifier. The surface area of the geometric models was then divided into finite volumes using the triangulation method, Quadratic option. Finally, the grid was given a smoothness of grade 3. After grid generation (which took about 60 minutes), a grid with 372395 elements and 729904 nodes was obtained for the clarifier with 1 m feed pipe (Figure 4).

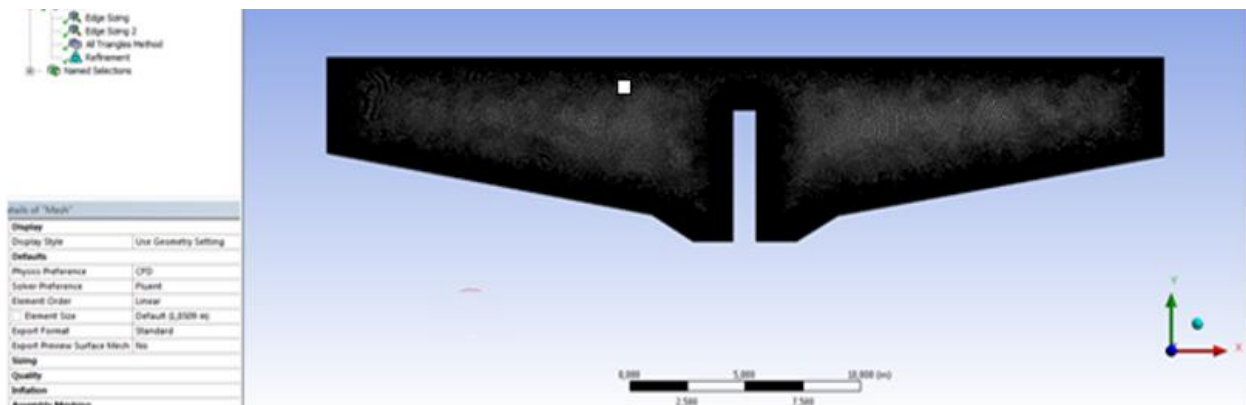


Fig. 4 - Finished volume mesh obtained for the geometric model with 1 m supply line (Zăbavă et al., 2021)

Following discretization, the water feed zone and the water outlet zone were configured as independent zones (Figure 5).

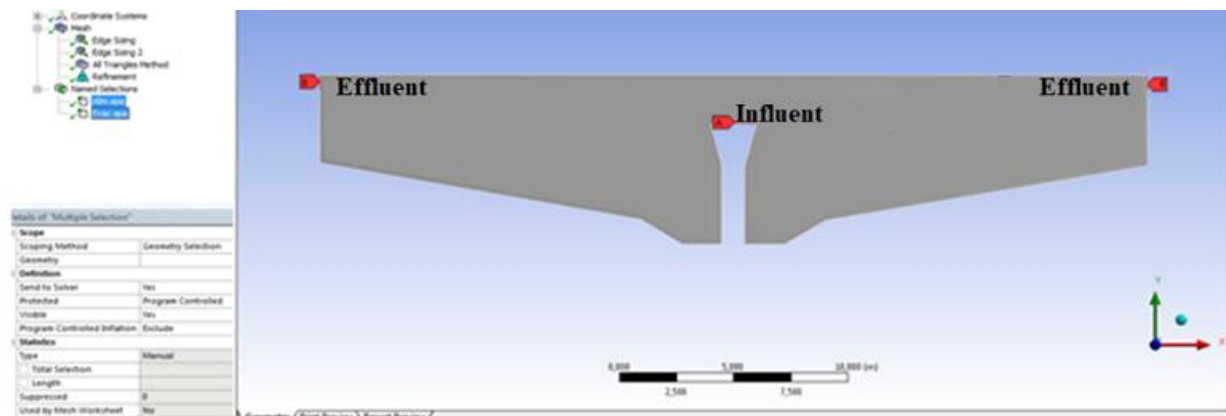


Fig. 5 - Water supply and discharge areas for the clarifier (Zăbavă et al., 2021)

With the CFD option as the physical reference, the discretized network cells were automatically assigned to be fluids. Knowing all the values involved in the relation of the Reynolds number, its calculation was performed for the two geometric models, using the calculation formula:

$$Re = \frac{v \cdot \rho \cdot d}{\vartheta} \quad (1)$$

It has a value of 40449.44 for this clarifier, which frames the flow regime as a turbulent one. In order to support the study, the mathematical model k- (2 equations) was used. The RNG (Re-Normalization Group) option was chosen as the k-model to improve study accuracy. This approach to renormalizing the Navier-Stokes equations to account for the effects of motion at lower scales was initially put forth in the publication (Yakhot, 1992).

The calcium carbonate to be injected in the water supply area, the injection position, the particle diameter (0.001 m), the flow rate (0.1 kg/s), the time to inject (from 0 to 180 s simulation time), the collision behaviour, and the simulation boundary conditions were all set before the discrete phase was activated. With the velocity-inlet option and a primary fluid feed rate of 0.036 m/s, the water supply area has been configured as the supply region, and the water discharge area has been configured as the outflow. At this point, the operating conditions (pressure and gravitational acceleration) were also established. The analysis approach was then chosen (Figure 6).

The second order equations for pressure, impulse, turbulent kinetic energy, and dissipation rate were selected to achieve the highest calculation accuracy.

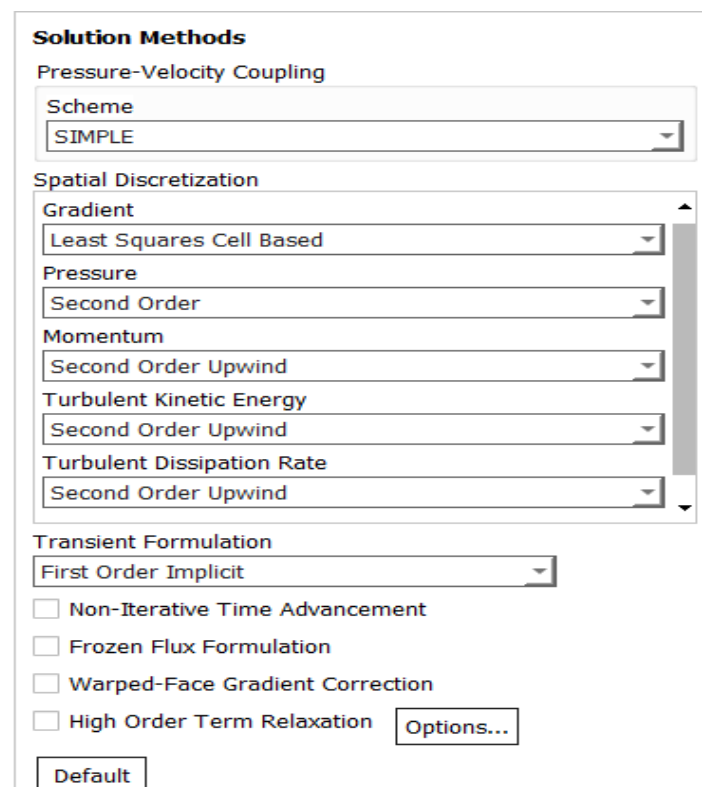


Fig. 6 - Choosing the analysis method in the Ansys program

The following settings were used to finish the calculation: Step size for the calculation was 0.005 seconds, there were 36,000 steps total, and there were 20 iterations for each time step. By dividing the total number of steps (36,000) by the calculation step size (0.005 s), the overall simulation duration (180 s) was determined. The calculation was started by clicking the "Calculate" button. While executing the calculation, the software simultaneously plots the residual value variation curves (Figure 7).

According to ANALYSIS TOOLS, (2008; Stat Trek), this analysis's residual values attained a value of 10^{-4} for this type of clarifier.

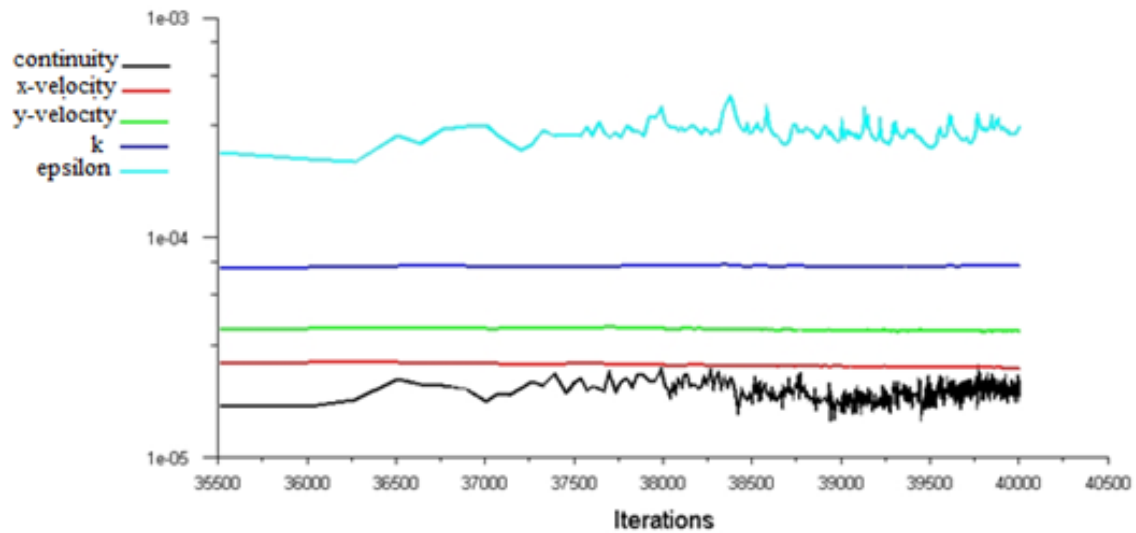


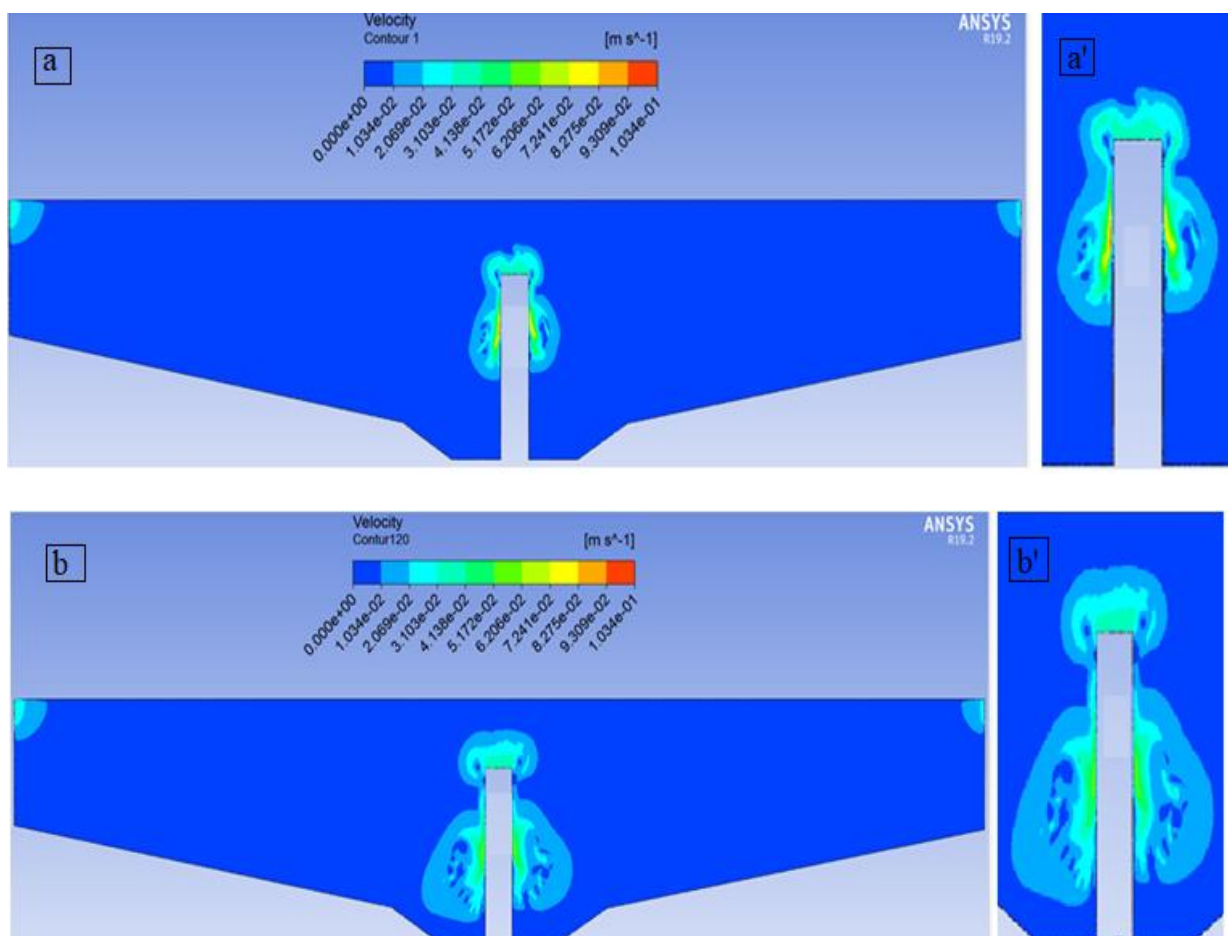
Fig. 7 - Residual values variation curves

RESULTS

The data for velocity, the Reynolds number in each cell, and the intensity of the turbulence at 60 s, 120 s, and 180 s (the simulation time) are reported in this section. It should be noted that a study on a few of the results reported below was conducted by one of the authors of this paper and published in the Ph.D. thesis.

Fluid velocity analysis

Figure 8 displays the velocity distribution for the clarifier with a feeding pipe of 1 m to 60 s, 120 s, and 180 s, as well as specifics of the feeding in those same timeframes.



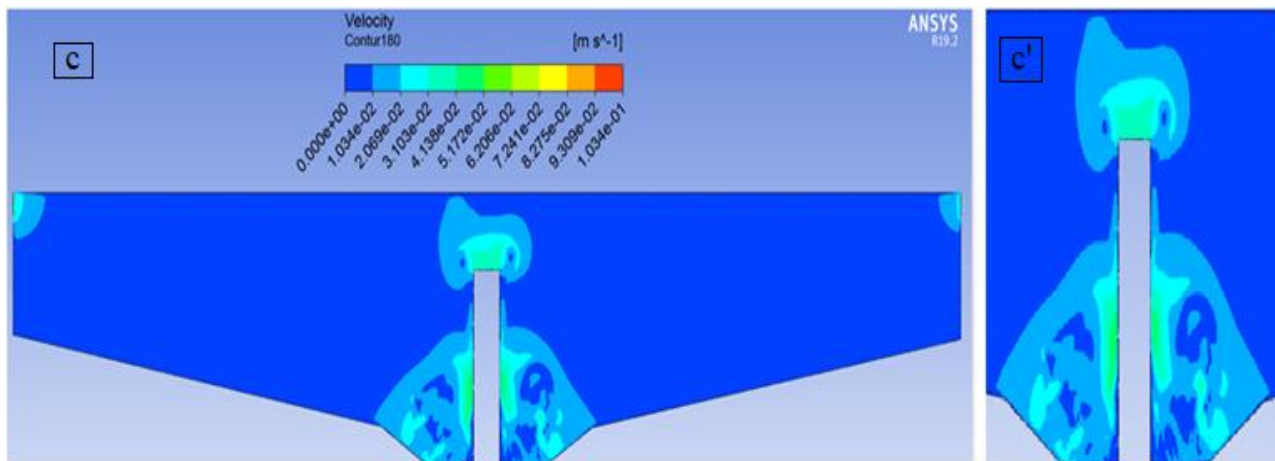


Fig. 8 - Clarifier velocity distribution at 60 s (a), 120 s (b) and 180 s (c), respectively details in the feeding area, in the same time intervals (a'-c')

Figure 9 shows the vector projection of the velocity at $t=180$ s for the clarifier with the supply pipe of 1m.

The vortex area can be easily observed, and further fluid propagation can be expected. Also, the tendency to move can be expected, at least for another period, in the bottom area of the decanter. This disadvantages the sedimentation process because the sediments are already on the bottom of the sedimentation tank and can be taken up by the water flow and lifted into the fluid mass. This will increase the final sedimentation time.

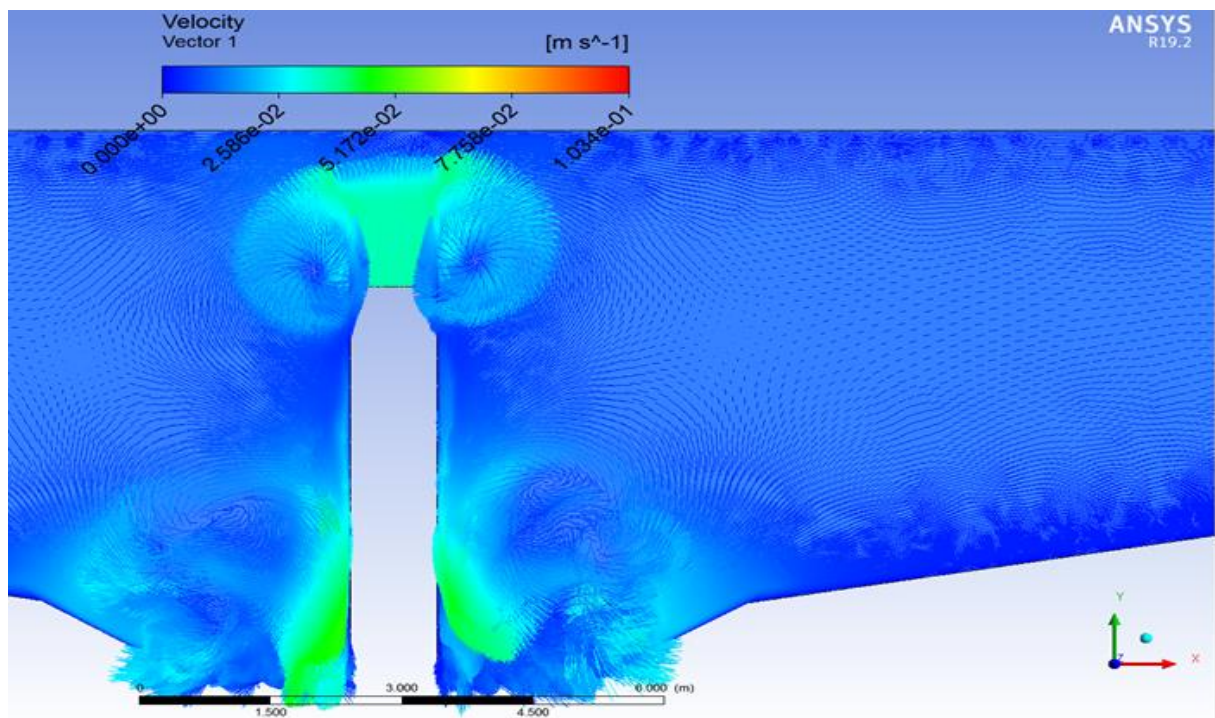


Fig. 9 - Vector projection of the velocity at $t=180$ s for the clarifier with 1m supply pipe

Reynolds number analysis

Figure 10 displays the Reynolds number's distribution along the diameter of the clarifier with the feeding pipe of 1 m, at 60 s, 120 s and 180 s. Also, details from the feeding zone, for the same time are presented here. Although for the supply area (inside the pipe) the calculated Reynolds number determined a turbulent regime, immediately after the entry of the fluid inside the clarifier, the regime becomes laminar, which favours the sedimentation process.

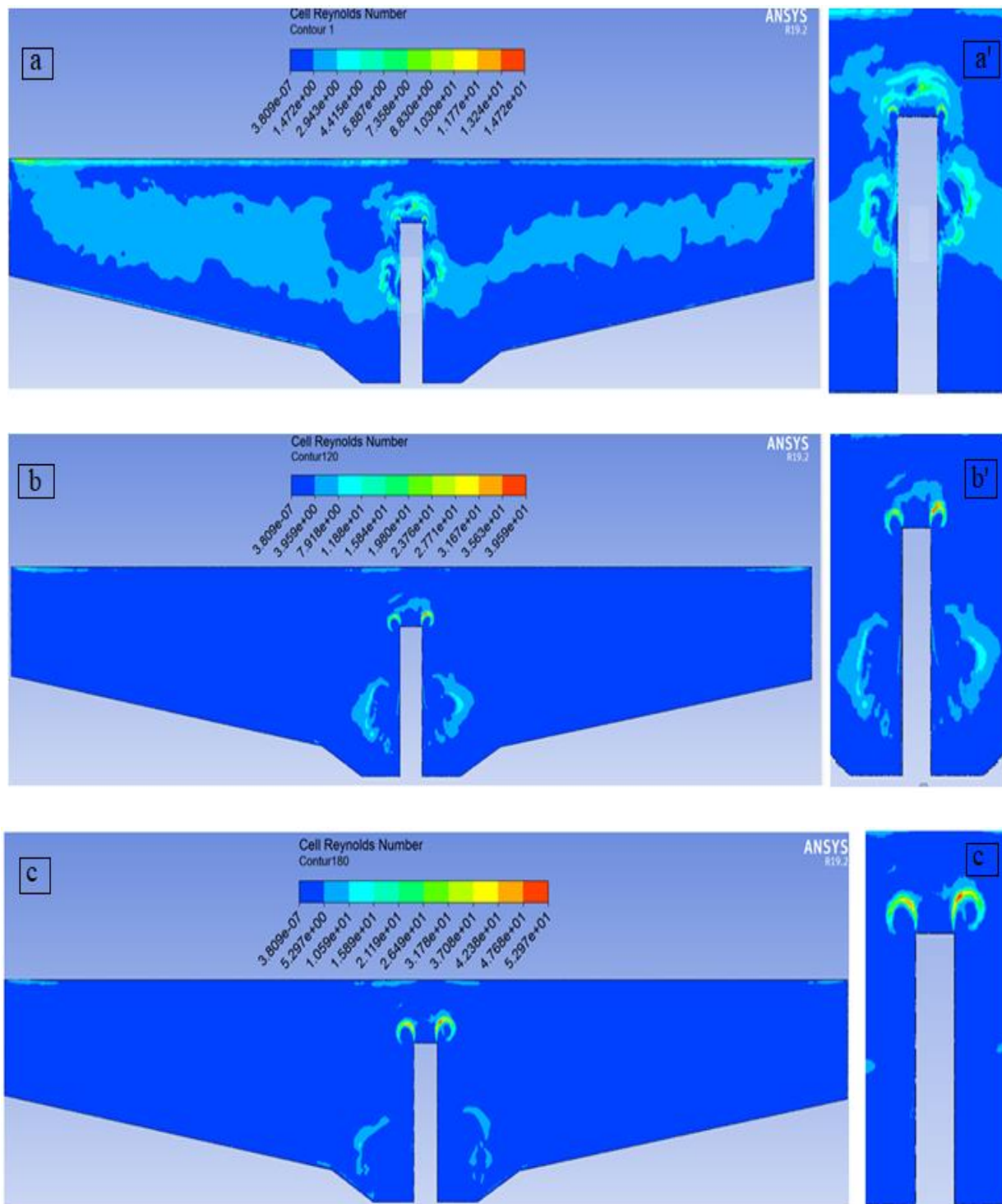


Fig. 10 - Reynolds number's distribution at 60 s (a), 120 s (b) and 180 s (c), respectively details of the feeding area, in the same time intervals (a'-c')

Turbulence intensity analysis

Figure 11 shows the distribution of turbulence intensity along the diameter of the clarifier with the feeding pipe of 1 m, at 60 s, 120 s and 180 s. The literature describes turbulence intensity as the ratio of standard deviation of fluctuating fluid velocity to the mean fluid speed, and it represents the intensity of fluid velocity fluctuation (Zhang, 2013; Mudde et al., 2005).

If the maximum turbulence intensity remains constant at $3.82 \cdot 10^{-2} \%$ over the entire length of the simulation time, it is interesting to analyse the evolution in time of the turbulence intensity over the length of the clarifier.

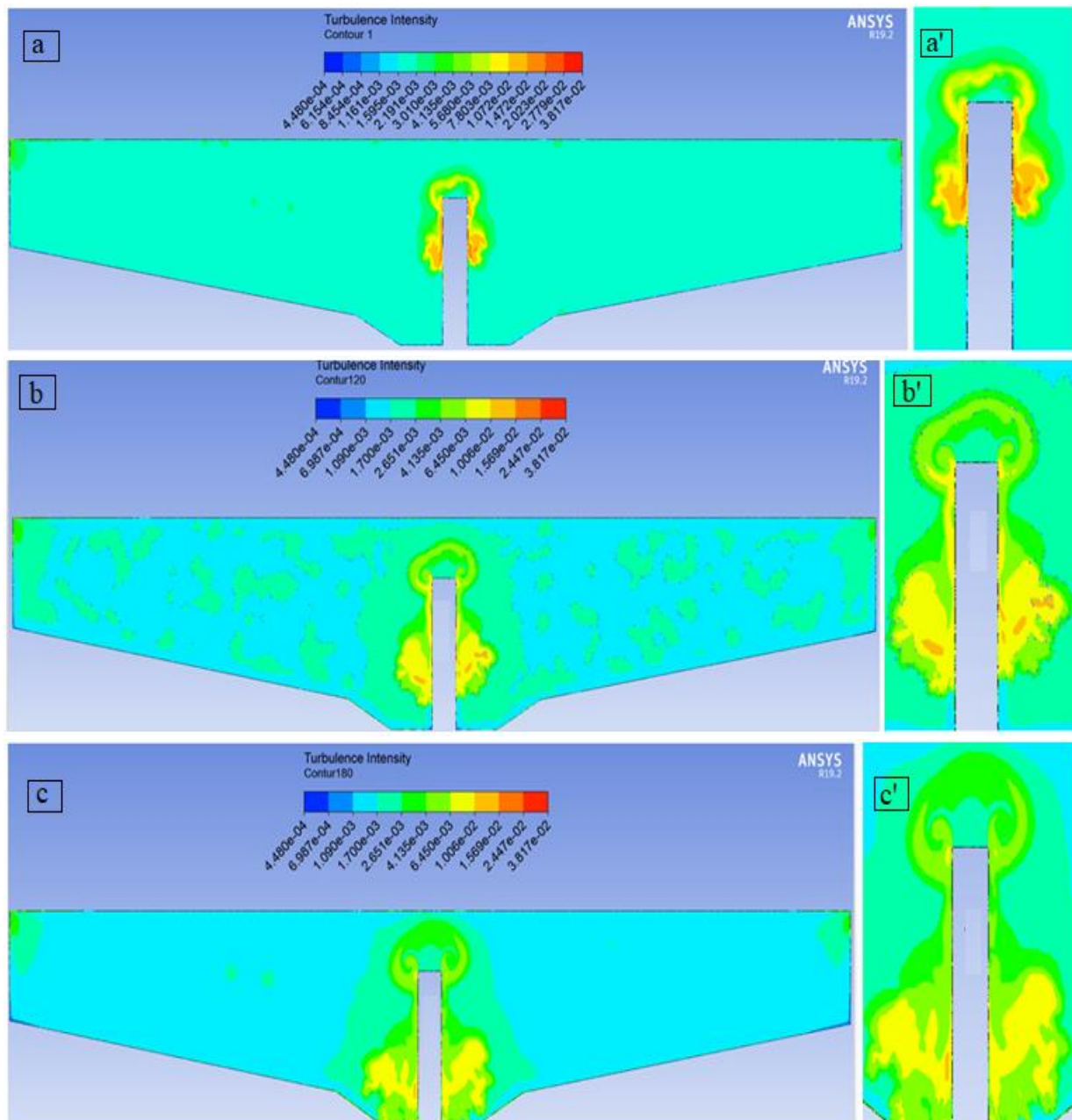


Fig. 11 - Clarifier turbulence distribution at 60 s (a), 120 s (b) and 180 s (c), respectively details of the feeding area, in the same time intervals (a'-c')

Analysing the results obtained for the clarifiers with 1 m supply pipe, regarding the fluid velocity analysis, despite the feeding area's velocity being set to 0.036 m/s, it is apparent from this number that there are locations in the clarifier where the velocity is 0.103 m/s. In the feeding area, velocity values are at their highest values. As presented in Figure 8, it is shown that the direction of travel is typically in the direction of the clarifier's bottom. This is caused by the vortices that form at the supply pipe's left and right corners at the end of the pipe. This results at the bottom of the clarifier in a considerable pressure difference in the fluid mass.

The Reynolds number study's highest values for the clarifier diameter were 14.7 for $t=60$ s, 39.6 for $t=120$ s, and 53 for $t=180$ s. Although, initially, the tendency to move is towards the water evacuation areas, due to the appearance of vortices in the limit areas of the supply pipe, the fluid velocity increases, and proportionally with it, the Reynolds number also increases. Additionally, it could be seen that the presence of eddies affects the shift in travel direction from "mainly to the outlet" to "largely to the bottom" of the clarifier. Looking at the evolution of the Reynolds over time, an increasing tendency can be seen, but it will not increase so much as to go out of the area of a laminar regime on the diameter of the clarifier.

Also, regarding the turbulence intensity analysis showed that at $t=60$ s, the average value of the turbulence intensity was $1.70 \cdot 10^{-3}$ % but, with the appearance of vortices, which cause part of the fluid to move to the bottom of the clarifier, the turbulence intensity decreases in the radial direction of the clarifier to $1.09 \cdot 10^{-3}$ % at $t=120$ s and $t=180$ s. In time, the zones of maximum for the turbulence intensity are getting closer and closer to the bottom of the clarifier.

It should be mentioned that the results obtained agree with the results obtained by other researchers (Chero *et al.*, 2019; Griborio *et al.*, 2021; Griborio *et al.*, 2014; Shahrokhi *et al.*, 2013; Czernek *et al.*, 2014; Sharifi *et al.*, 2019).

CONCLUSIONS

Analysing the results obtained for the clarifiers with 1m supply pipe, regarding the fluid velocity analysis, despite the feeding area's velocity being set to 0.036 m/s, it is apparent from this number that there are locations in the clarifier where the velocity is 0.103 m/s. In the feeding area, velocity values are at their highest values.

In terms of the results of the Reynolds number analysis, the values increased during the three time periods looked at, with the minimum value being 14.7 and the maximum being 53.

Also, regarding the turbulence intensity analysis showed that at $t=60$ s, the average value of the turbulence intensity was $1.70 \cdot 10^{-3}$ % but, with the appearance of vortices, which cause part of the fluid to move to the bottom of the clarifier, the turbulence intensity decreases in the radial direction of the clarifier to $1.09 \cdot 10^{-3}$ % at $t=120$ s and $t=180$ s. The results obtained agree with the results obtained by other researchers. This work may help researchers in the field, mainly, but also the builders of radial clarifiers.

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Article

Prediction of Leaf Break Resistance of Green and Dry Alfalfa Leaves by Machine Learning Methods

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Abstract: Alfalfa holds an extremely significant place in animal nutrition when it comes to providing essential nutrients. The leaves of alfalfa specifically boast the highest nutritional value, containing a remarkable 70% of crude protein and an impressive 90% of essential vitamins. Due to this incredible nutritional profile, it becomes exceedingly important to ensure that the harvesting and threshing processes are executed with utmost care to minimize any potential loss of these invaluable nutrients present in the leaves. To minimize losses, it is essential to accurately determine the resistance of the leaves in both their green and dried forms. This study aimed to estimate the breaking resistance of green and dried alfalfa plants using machine learning methods. During the modeling phase, five different popular machine learning methods, Extra Trees (ET), Random Forest (RF), Gradient Boost (GB), Extreme Gradient Boosting (XGB), and CatBoost (CB), were used. The correlation coefficient (R^2), root mean square error (RMSE), mean absolute error (MAE) and mean absolute percentage error (MAPE) metrics were used to evaluate the models. The obtained metric results and the graphs obtained from the prediction values of the models revealed that the machine learning methods made successful predictions. The best R^2 (0.9853), RMSE (0.0171), MAE (0.0099) and MAPE (0.0969) values for the dry alfalfa plant were obtained from the model established with the ET method, while the best RMSE (0.0616) and R^2 (0.96) values for the green alfalfa plant were obtained from the model established with the RF method and the best MAE (0.0340) value was obtained from the model established with the ET method. Additionally, the best MAPE (0.1447) value was obtained from the model established with the GB method.

Keywords: breaking stress; alfalfa; extra trees; CatBoost; machine learning



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1. Introduction

Alfalfa plants are necessary for animal feeding both in Turkey and worldwide, and they are used extensively. Green and dry can be consumed as grass, as well as silage can also be used. Alfalfa plants are rich in protein, mineral substances, trace elements, and vitamins, and they give high-quality grass [1]. There are losses in the nutritional value of alfalfa plants due to different reasons, from harvesting to utilization. These losses are generally losses due to plant respiration, nutrient loss, losses caused by rain damage, losses due to leaf breakage, and losses due to mechanization applications (mowing and conditioning, machine type, harrowing, baler) [2].

In animal nutrition, alfalfa is mostly used in dry form, but it undergoes significant nutrient losses during drying [3]. For alfalfa grass under natural drying conditions, the dry matter, crude protein and crude amount of cellulose losses increase even more. Although dry matter losses are realized between 15 and 25%, this rate is between 35 and 100% under rain damage depending on the weather conditions. Leaf losses increase due to the

decrease in product moisture. Alfalfa leaves contain 70% of the crude protein and 90% of the vitamins. Leaves are also 40% more digestible than stems [4]. For this reason, the leaf losses that may occur in the plant should be minimized. To minimize the loss rate, mowing, raking and baling operations should be completed early in the morning, which increases the drying time of the product, and therefore, higher quality and higher efficient feed can be obtained [5].

Various studies have been carried out on the physico-mechanical properties of forage crops until today, but studies on the breaking resistance of alfalfa leaves have not been found much in the literature. The determination of the leaf break resistance is very important to improve the design, optimization and efficiency of the necessary machinery, equipment and cutting tools for harvesting and threshing alfalfa plants with minimum leaf loss. King and Vincent (1996) [6] studied the determination of the static and dynamic properties of flax plants indigenous to New Zealand. Yilmaz and Gokduman (2014) [7] determined the leaf breaking resistance of sage plants according to different moisture contents. As a result of the experiments conducted at three different moisture contents, it was reported that the leaf breaking force varied between 4.3 and 6.5 N (Newton). Arevalo et al. (2013) [8] investigated the mechanical properties of rosemary stems. In their study, they found that the compression forces causing deformations were low, about 2 N, and the shear force required to break the bundle at the harvest point varied between 30 and 50 N on average. Shinnars et al. (1987) [9] found that longitudinal shearing of alfalfa stems required less than 1/10 of the energy required to shear alfalfa transversely. Öten et al. (2018) [10] carried out studies on the determination of both the green and dry leaf breaking resistance of some clover genotypes collected from the natural flora of Antalya province. It was reported that the highest leaf break force value was 1.0419 N and the lowest was 1.0022 N in the dry samples. Prince et al. (1969) [11] investigated the hardness modulus of green and dried alfalfa samples and found mean values of 0.225 GPa and 1.45 GPa, respectively. Türker (1992) [12] performed experimental measurements on 1700 alfalfa to determine the cutting resistance of alfalfa. The effects of factors such as the blade speed, blade opening, blade type, diameter of the alfalfa at the cutting point and cutting time on the cutting resistance of alfalfa were determined. Halyk and Hurlbut (1968) [13] reported that the stem of alfalfa has a tensile strength in the range 9–36 MPa and that this strength is dependent on the moisture content.

The literature shows that studies related to the evaluation of the mechanical qualities required to maintain the leaf quality of alfalfa or other forage crops, as well as the design and modernization of the equipment required for harvesting and threshing and the optimization of the operating parameters, are usually carried out under laboratory conditions and harsh field conditions. These techniques are exceedingly expensive, labor-intensive, and require a very drawn-out approach. Unconventional approaches can be employed in place of experimental procedures to precisely establish these required attributes in the current era where economy, energy, labor, and time are highly significant. The most popular non-conventional technique for figuring out the physical and mechanical characteristics of plant products is machine learning.

Machine learning, which is a sub-branch of artificial intelligence, can be defined as a method that makes predictions by using inferences from past experiences and data [14]. It focuses on teaching computers to learn from data and improve them through experience rather than being explicitly programmed to do so. In machine learning, algorithms are trained to find patterns and correlations in large data sets and make the best decisions and predictions based on this analysis [15]. Machine learning algorithms are one of the extremely popular methods applied to classification and regression problems in many fields, such as medicine [16,17], engineering [18,19], economy [20], education [21,22], business [23,24], natural sciences [25,26], sport sciences [27] and agriculture [28,29]. Alkali et al. (2014) [30] utilized an artificial neural network (ANN) to predict some mechanical properties of melon fruit. Kabas et al. (2023) [14] determined some engineering parameters of cherry tomatoes using machine learning algorithms. Cevher and Yıldırım (2022) [31] estimated the rupture

energy values of Deveci and Abate Fetel pear fruit using an artificial neural network (ANN). An artificial neural network can be used to better estimate the volume and surface area of a fruit according to Ziaratban et al. (2017) [32]. Kabas et al. (2023) [33] conducted an experiment on the determination of hazelnut's (*Corylus avellana* L.) terminal velocity and drag coefficient based on some fruit physical properties using machine learning algorithms. By using computerized mathematical and statistical processes on data, this technique models systems that make predictions. It belongs to the science of artificial intelligence. It includes several algorithms and method architectures. Numerous technical developments, such as speech and pattern recognition, data analysis, and prediction, have been made possible through machine learning. Using training data, machine learning, which learns and develops autonomously based on experience without outside assistance, may categorize and predict [34,35].

Knowing the leaf breaking resistance allows harvesting to be performed with a minimum leaf loss rate, thus minimizing leaf losses during harvesting and post-harvesting. This study aimed to provide an accurate prediction of the leaf break stress of alfalfa plants depending on some vegetative and mechanical parameters using machine learning. By using machine learning models, it was aimed to determine the most accurate model considering different inputs and network structures. The results obtained can be considered as an effective tool to deal with post-harvest losses of alfalfa leaves and to collect the necessary data for the optimization of existing processing systems and the design of the necessary machinery.

2. Materials and Methods

This research was carried out at Akdeniz University Vocational School of Technical Sciences, Antalya, Turkey, in 2023. Alfalfa (*Victoria cultivar*) obtained from local growers in Antalya province was used in the experiment. A total of 120 plant branches were taken as material, and 30 plant branches from each replicate were taken as the basis for this experiment in the trials carried out in 4 replicates in randomized blocks.

The measurements were carried out in the second year of cultivation and after the third mowing. The material to be measured for green breaking resistance was placed in containers filled with water to prevent moisture loss after mowing, with the cut ends in water and kept in this way until the measurement was performed.

2.1. Data Set

The petiole thickness of 120 alfalfa samples was measured with a digital caliper with a precision of 0.001 mm, and the petiole area was calculated with the formula $A = \pi \cdot d^2 / 4$ and the data were recorded.

A texture analyzer with a data sampling rate of 10 Hz and a 1000 N load cell with a sensitivity of 0.01 N was used to determine the breaking force of the leaves (Figure 1). A pulling speed of 8 mm min^{-1} was used to determine the leaf breaking resistance of alfalfa [36]. The device was calibrated following the calibration template before the analyses.

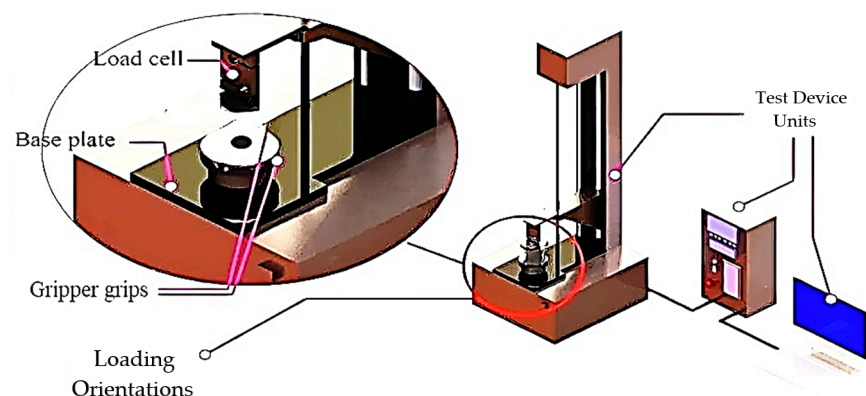


Figure 1. Biological material test instrument.

The leaves were fixed to the device with the help of a gripping jaw and the value read at the moment when the leaf broke away from the stem was determined as the breaking force of the leaf, and the obtained values were recorded on the computer with the help of a software. A force–deformation curve was created with the help of the obtained data (Figure 2). The rupture energy of the leaf was determined by calculating the area under the force–deformation curve. The breaking stress was calculated by the ratio of the determined leaf breaking forces to the petiole area.

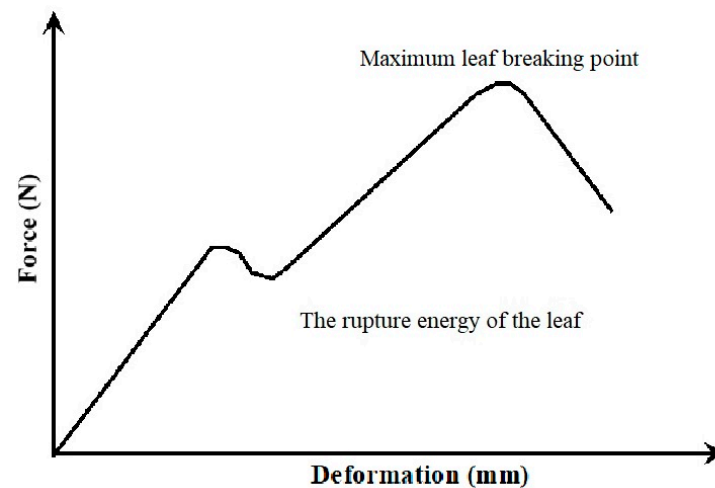


Figure 2. Force–deformation curve.

Trials were conducted when the main stems of the clover were green first, then dried at 105 °C for 24 h, and then the leaf breaking force measurement was realized. The input variables were the leaf stem diameter, leaf stem area, leaf breaking force, and leaf breaking energy, and the target variable was the leaf breaking stress. The whole variables used in the machine learning models are seen in Figure 3.

Input Variables	Target Variable
<ul style="list-style-type: none"> • Leaf steam diameter (mm) • Leaf petiole area (mm²) • Leaf breaking force (N) • Leaf breaking energy (J) 	<ul style="list-style-type: none"> • Leaf Breaking stress (Nmm⁻²)

Figure 3. Input and target values.

2.2. Machine Learning Methods

Machine learning, also known as predictive analytics or statistical learning, lies at the intersection of statistics, artificial intelligence, and computer science [37]. The goal of machine learning is to produce predictive or descriptive models using sample data or past experience so that the value of a continuous output or the class of a classificatory output can be predicted [38]. In this study, the leaf breaking stress of green and dried alfalfa plants was estimated using machine learning methods. During the modeling phase, five different machine learning methods, Extra Trees (ET), Random Forest (RF), Gradient Boost (GB), Extreme Gradient Boosting (XGB), and CatBoost (CB), were used. The models obtained using the five different methods were interpreted and the results were visualized. The data

set of the study was divided into training and testing data, and 80–20%, 75–25% and 70–30% ratios tried in the partitioning process (training, testing), respectively. The best results were obtained with the training 70% and test 30% partitioning, and these values were interpreted. The modeling and visualization stages were carried out using the Python programming language. The workflow of the machine learning process is shown in Figure 4.

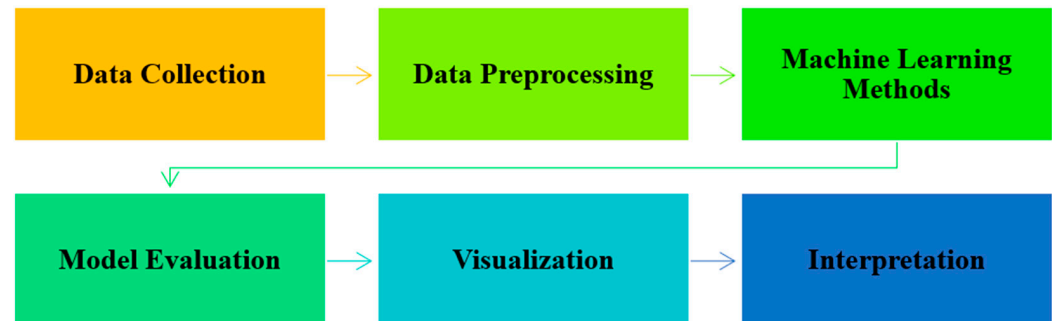


Figure 4. Workflow of the machine learning process.

The first stage of the machine learning process is to obtain the data to be used in the modeling. The second and one of the most important stages is data preprocessing. At this stage, if there are missing and/or noisy variables in the data set, these variables are removed from the data set or filled with an appropriate predicted value [39,40]. In the third stage, machine learning algorithms are applied. At this stage, the data set is divided into training and testing without applying the machine learning method. The model is trained on the training data set, and the success of the trained model is realized on the test data set. In the fourth stage, modeling results are obtained. In the fifth stage, graphs of the results are created and in the last stage, the models are interpreted.

2.3. Extra Trees

ET, an ensemble-based machine learning method, was developed as an extension of the RF method to avoid the overfitting problem and increase the classification accuracy [41]. In this algorithm, all the data sets are used to train all the trees in an ensemble rather than using the bagging method to generate the training subset for each tree. This randomization significantly reduces the variance compared to the ensemble ML models. Instead of utilizing the bagging approach to create the training subset for each tree, this algorithm uses all the data sets to train all trees in an ensemble. Comparing this randomization to the ensemble ML models, the variance is significantly reduced [42,43].

2.4. CatBoost

CatBoost is an ensemble-based machine learning method just like RF, ET, and XGB. Based on the GB method, CB is an advanced version of the GB method. CB successfully tackles categorical attributes and takes advantage of coping with them during training as opposed to pre-processing time. Another advantage of the CB algorithm is that it uses a new scheme to calculate the leaf values when choosing the tree structure. This helps reduce overfitting [44].

During the modeling phase, a series of decision trees are created. Each decision tree influences the next to improve the modeling performance. Thus, the next tree is created with less loss. In other words, each decision tree is influenced by and learns from the previous one. The goal here is to create a strong learner [45]. In GB, DTs are trained iteratively to minimize the loss function, as shown in Figure 5 [46]. The image shown below the trees shows the training error of the tree (red). The error rate is high in the first and second trees. The error rate is minimized in the Nth tree by reducing iteratively [47].

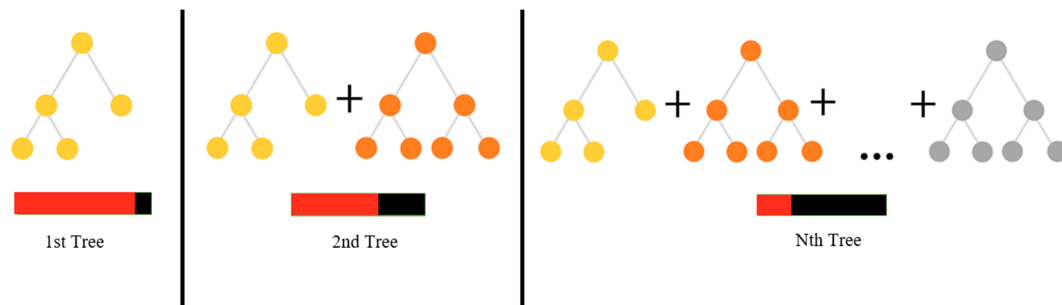


Figure 5. Iterative training of DTs in GB [47].

2.5. Gradient Boosting

The purpose of the GB algorithm is based on combining a set of weak models that together allow for creating a stronger model [48]. The basic idea behind this algorithm is to build new base learners in such a way that they are maximally associated with the negative gradient of the loss function associated with the entire ensemble [49].

The fact that the loss function can be selected by the practitioner makes the GB method flexible, and the implementation of boosting algorithms is relatively simple [50].

2.6. Extreme Gradient Boosting

XGB, a GB-based method, uses the gradient descent optimization algorithm [51]. A highly scalable, flexible and versatile tool, XGB is designed to exploit resources correctly and to cope with the limitations of the earlier gradient boosting [52]. The novelty of XGB lies in the fact that it includes an objective function [53].

The objective function consists of the combination of the regularization term, which is used to prevent overfitting of the model, and the loss function, which measures the difference between the predicted value and the real value [54].

2.7. Random Forest

RF, one of the most common ensemble learning methods, is frequently used in both regression and classification problems [55]. The purpose of ensemble learning is based on combining the results generated by solving the same problem using many classifiers [56]. This gives the model result a higher precision and generalization ability. The features chosen by each tree during the model's training process are just a small subset of the features chosen at random. The RF approach can achieve better generalization and anti-overfit abilities because of its strong randomness, which means that additional pruning is typically not required [57].

2.8. Models' Evaluation Criteria

Since the output variable that is tried to be predicted in this study is continuous, the mean absolute error (MAE), mean absolute percentage error (MAPE), the coefficient of determination (R^2), and root mean square error (RMSE) metrics were used to measure the prediction success of the established machine learning models [18,58,59]. The MAE, MAPE, R^2 , and RMSE metrics are defined in Equations (1)–(3), respectively.

$$RMSE = \sqrt{\frac{1}{m} \sum_{i=1}^m (X_i - Y_i)^2}, \quad (1)$$

$$MAE = \frac{1}{m} \sum_{i=1}^m |X_i - Y_i|, \quad (2)$$

$$MAPE = \frac{1}{m} \sum_{i=1}^m \left| \frac{Y_i - X_i}{Y_i} \right|, \quad (3)$$

$$R^2 = 1 - \frac{\sum_{i=1}^m (X_i - Y_i)^2}{\sum_{i=1}^m (\bar{Y} - Y_i)^2} \quad (4)$$

The coefficient of determination, proportion of explained variance, or R^2 for short, is known as a measure of the success of the independent variables in predicting the dependent variable [60]. R^2 can be defined as the proportion of the variance in the dependent variable that can be predicted from the independent variables [59]. In the R^2 metric, which takes a value between 0 and 1, it takes the value of 1 if the independent variables fully explain the dependent variable, while the value of 0 indicates the opposite situation. Accordingly, an R^2 value approaching 1 indicates that the success of the model is high [61]. Another performance metric for regression models, the MAPE is used for the interpretation of the relative error [62].

While the MAPE takes a value between 0 and ∞ , the mean absolute percentage error between the actual value and the prediction approaches 0, indicating that the success of the established model is high [59]. Prediction models with MAPE values between 10% and 20% are categorized as “correct/good”, whereas models with MAPE values below 10% are categorized as “high accuracy/very good” [63,64].

The RMSE is the square root of the mean of the squares of all the errors [65]. Like the MAPE, the RMSE measures, which take values between 0 and ∞ , are also used in the interpretation of regression problems. Values close to 0 indicate that the model is successful [66–68]. The MAE is another statistical measure that is used in the interpretation of regression problems. While it takes values between 0 and ∞ , values close to 0 indicate that the model is successful [18].

3. Results and Discussions

Modeling studies are very important in the evaluation of green and dry alfalfa leaf resistance. A statistical summary of some mechanical property data of dry and green alfalfa leaves used for the modeling study, including the means and standard deviations, is shown in Table 1. The differences between the mechanical properties of dry and green alfalfa are shown in Table 1. The leaf breaking force, leaf breaking resistance and leaf breaking tension of dry alfalfa are much lower than the values obtained in green alfalfa, which indicates that the leaf losses will be much higher in dry alfalfa. While the leaf breaking force of green alfalfa was 0.087 N, this value was found to be 0.031 N in dry alfalfa, and it is seen that there is a 64.36% decrease between these two values. This decrease was 61.65% in leaf breaking stress and 64.42% in leaf breaking energy. These values clearly show that the mechanical strength of alfalfa leaves decreases as they dry and so leaf losses will increase rapidly. Predicting the breaking resistance of alfalfa leaves in advance will make it possible to minimize the leaf losses that may occur during and after harvest.

Table 1. Experimentally measured values of green and dry alfalfa.

Plan Type	Variables	Mean \pm SD
Dried	Leaf stem diameter (mm)	0.561 \pm 0.157
	Leaf petiole area (mm ²)	0.261 \pm 0.152
	Leaf breaking force (N)	0.031 \pm 0.023
	Leaf breaking energy (J)	0.037 \pm 0.028
	Leaf breaking stress (N mm ^{−2})	0.158 \pm 0.204
Green	Leaf stem diameter (mm)	0.580 \pm 0.157
	Leaf petiole area (mm ²)	0.280 \pm 0.152
	Leaf breaking force (N)	0.087 \pm 0.055
	Leaf breaking energy (J)	0.104 \pm 0.066
	Leaf breaking stress (N mm ^{−2})	0.412 \pm 0.371

In this study, five different machine learning methods, Extra Trees, Random Forest, Gradient Boost, Extreme Gradient Boosting, and Cat Boost, were used. The performances

of the models were interpreted based on the evaluation metrics obtained as a result of the established modeling. The results of the models established to predict the breaking stress of the green alfalfa plant and dry alfalfa plant are shown in Table 2.

Table 2. Results of the machine learning models.

Plant Type	Model	Evaluation Criteria			
		RMSE	MAPE	MAE	R ²
Dried	Extra Trees	0.0171	0.0969	0.0099	0.9853
	CatBoost	0.0174	0.1068	0.0105	0.9838
	Gradient Boosting	0.0265	0.1936	0.0178	0.9624
	Random Forest	0.0306	0.2163	0.0191	0.9499
	Extreme Gradient Boosting	0.0223	0.1224	0.0124	0.9736
Green	Extra Trees	0.0707	0.1604	0.0340	0.9472
	CatBoost	0.0850	0.1806	0.0387	0.9239
	Gradient Boosting	0.1194	0.1447	0.0621	0.8497
	Random Forest	0.0616	0.2135	0.0363	0.9600
	Extreme Gradient Boosting	0.1026	0.1750	0.0542	0.8889

3.1. Interpretation of Modeling Results of Dried Alfalfa

According to the results in Table 2, for the dried alfalfa plant, the model established by the Extra Trees method is more successful in all the metrics. The best MAE value was obtained as 0.0099. The MAE value is close to 0, so it can be said that the model built is successful. The best MAPE value was obtained as 0.0969. Accordingly, the leaf breaking stress value of dried alfalfa plants can be estimated with an error of approximately 10%. This result shows that the model established with the Extra Tree method is successful. Similarly, the R² value was obtained as 0.9853. Accordingly, the independent variables explain approximately 98.5% of the variance of the dependent variable. Since the R² value obtained is close to 1, the established model is successful. The RMSE is a statistical metric that evaluates the error values of regression models built with machine learning methods. It is value close to zero, which indicates that the error obtained from the model is low, and this indicates that the established model is successful. The RMSE value was obtained as 0.0171. This result is close to 0 and shows the success of the established model. The worst RMSE, MAE, MAPE and R² values were obtained from the model established with the Random Forest method. The results for these metrics were 0.0306, 0.0191, 0.2163 and 0.9499, respectively. As a result, the most successful model in predicting the leaf breaking stress value of dried alfalfa was obtained with the ET method, while the worst model was obtained with the RF method.

There are no studies that have been found to predict the leaf breaking stress of any plant using machine learning methods. In the field literature, it is seen that regression and classification studies are carried out using artificial neural network, logistic regression, support vector machines, extra trees, light gradient boosting, random forest, and decision tree regression methods [14,33,69].

In their study, Kabas et al. [14] made predictions with the value of R²:0.97 with the artificial neural networks model, R²:0.91 with the logistic regression, and R²:0.81 with the decision tree regression model. In another study, Kabas et al. [33] predicted the value of R²:0.92 with the support vector regression model. Kocer et al. [58] made predictions with the value of R²:0.76 with the Extra Trees model, R²:0.73 with the Random Forest and R²:0.68 with the Light Gradient Boosting model. In this study, the best R² (0.9853), RMSE (0.0171), MAE (0.0099) and MAPE (0.0969) values for the dry alfalfa plant was obtained from the model established with the ET method.

In the machine learning models established to predict the breaking stress value of the dry alfalfa plant, the metric results were generally close to each other. The models were also more successful, with slightly better results in some metrics. Although the model established by the ET method was the most successful model in the MAE metric, all the

models obtained similar results. The differences between the models were negligible. Therefore, it can be said that all the models achieved successful results in the MAE metric. We can also make this comment for the RMSE and R^2 . In the RMSE and R^2 metrics, the model established with the ET method was more successful with small differences compared to the models established with other methods. Although the model established with the ET method was slightly more successful than the models established with other methods, the models established with the ET, CB, and XGB methods had similar values. It can be said that these models were more successful compared to the models established with the RF and GB methods in the MAPE metric.

3.2. Interpretation of Modeling Results of Green Alfalfa

Similarly, the machine learning model results established to predict the leaf breaking stress of green alfalfa plants are shown in Table 2. In terms of the R^2 and RMSE metrics, the model built with Random Forest is the most successful. The best R^2 value obtained is 0.96. Accordingly, the independent variables explain approximately 96% of the variance of the dependent variable. The established RF model is successful because the R^2 value is close to 1. The fact that the RMSE value is close to zero indicates that the error obtained from the model is low, which indicates that the established model is successful. The RMSE value is obtained as 0.0616, which is close to 0 and shows the success of the established RF model. In terms of the MAPE metric, the model built with Gradient Boosting is the most successful. The best MAPE value obtained is 0.1447. Accordingly, the leaf breaking stress value of green alfalfa plant can be estimated with an error of approximately 14.5%. This result shows that the model established using the GB method is successful. The worst RMSE, MAPE, and R^2 are 0.1194, 0.2163, and 0.8497, respectively.

Kuradusenge et al. [70] performed predictions with the value of R^2 :0.875 and RMSE: 129.9 with the RF model. In another study, Mostafaeipour et al. [71] produced predictions with the value of R^2 :0.953, MSE: 0.0102 and RMSE: 0.1010 with the Extreme Learning Machine model. Kabas et al. [72] produced predictions with the value of R^2 :0.9715, MAPE: 0.0146 and RMSE: 15.69 with the CatBoost model, and MAE: 10.63 with the RF model. In this study, while the best RMSE (0.0616) and R^2 (0.96) values for green alfalfa plant were obtained from the model established with the RF method, the best MAE (0.0340) value was obtained from the model established with the ET method. Finally, the best MAPE (0.1447) value was obtained from the model established with the GB method.

Figure 6 shows the scatterplots of the machine learning models. While the first graph was produced by the RF model, the second graph was produced by the ET model. Similarly, in the machine learning models established to predict the breaking stress value of the green alfalfa plant, the metric results are generally close to each other. When the predicted values and actual values are close to each other, the values will be on the $y = x$ line. However, as the predicted values deviate from the actual values, the values will not lie on this line. It is clearly seen in the scatterplot that the deviations in the model established with the RF method are greater than in the model established with the ET method. Accordingly, it can be said that the model established with the ET method makes more successful predictions. It is also possible to note that the figures support the metric results shown in Table 2. The models performed better on some metrics, with small differences. Although the model established using the ET method was the most successful model in the MAE metric, all the models obtained similar results. The differences between the models were negligible. Therefore, it can be said that all models achieved successful results in the MAE metric. We can also make this comment for the RMSE metric. In the RMSE metric, the model established with the RF method is more successful with small differences compared to the models established with other methods. The models established with RF, ET, and CB have similar values in the RMSE metric. On the other hand, the model established with the RF method is slightly more successful than the models established with the other methods. A similar situation is valid for the R^2 metric. Although the model established with the RF method is slightly more successful than the models established with other methods, the

models established with the ET and CB methods also have similar values. It can be said that the models established with RF, ET, and CB are more successful in the R^2 metric than the models established with the GB and XGB methods. Although the models established with GB, XGB and ET have similar values in the MAPE metric, the model established with the GB method is the most successful model in the MAPE metric.

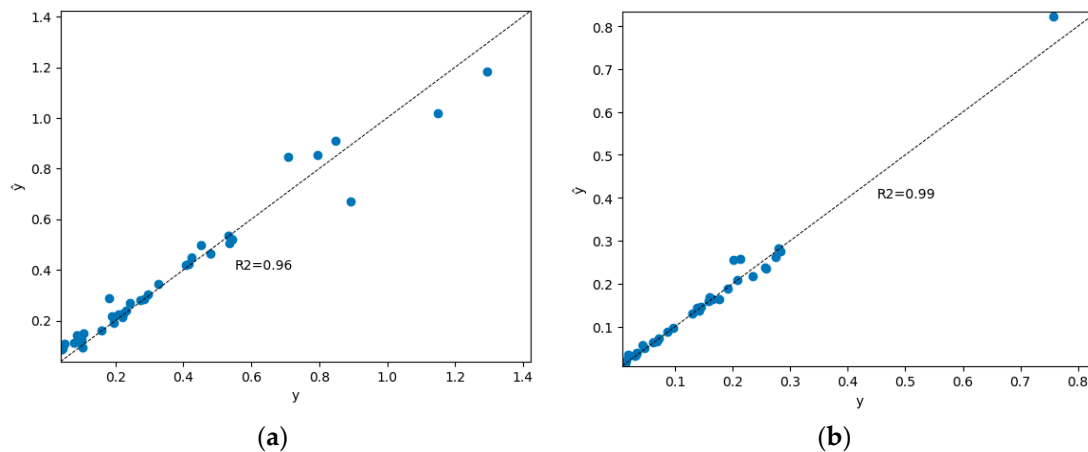


Figure 6. Scatterplots of machine learning models: (a) Random Forest and (b) Extra Trees.

Figure 7 shows the relationship between the actual and predicted breaking stress values. While the x-axis in the graphs shows the observations, the y-axis shows the stress value. Red lines show the actual values, dashed blue lines show the predicted values. The first graph was produced from the model in which we obtained the leaf breaking stress for the dried alfalfa plant using the RF method. The second graph was produced from the model obtained using the ET method. In both graphs, the actual and predicted values almost overlap. This shows that the established models are successful. The metric results shown in Table 2 and the line plots shown in Figure 7 support each other. The R^2 and MAPE values of the model established with the RF method are 0.9499 and 0.2163, respectively. On the other hand, the R^2 and MAPE values of the model established with the ET method are 0.9853 and 0.0969, respectively. These results show that although both models are extremely successful in predicting leaf breaking stress, it can be said that the model established with the ET method makes a more successful prediction. Accordingly, it can be said that the metric results and graphic results support each other.

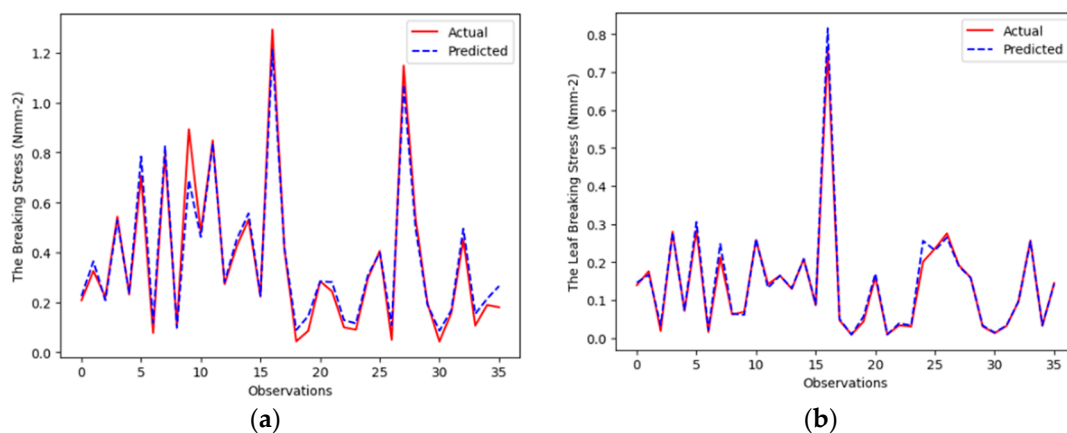


Figure 7. Line plots of the machine learning models: (a) Random Forest and (b) Extra Trees.

In this study, the leaf breaking stress of dried and green alfalfa plants was predicted using the Extra Trees, Random Forest, Gradient Boost, Extreme Gradient Boosting and Cat Boost methods. For the dried alfalfa plant, the best R^2 (0.985) value was obtained from

the model established using the Extra Trees method. Similarly, the best RMSE (0.0171) and MAPE (0.0969) values were obtained from the model established with the Extra Trees method. For the green alfalfa plant, the best MAPE (0.1447) value was obtained from the model established using the Gradient Boosting method. The best RMSE (0.0616) and R^2 (0.96) values were obtained from the model established with the Random Forest method.

4. Conclusions

Green and dried alfalfa leaf breaking stress characteristics are crucial factors in harvesting and threshing operations. The design and modification of machinery used in harvesting and threshing activities depend on these criteria. To compute these characteristics, a vast number of samples must be measured over an extended period of time. It takes a lot of time, money, and labor to measure a lot of samples. Various measuring mistakes also happen. Larger data sets, traits, and methods that can be utilized for future study may be developed together with more accurate and timely results for applications including discrimination, ranking, and prediction in the industrial sector.

In this study, the green and dried alfalfa leaf breaking stress value was successfully predicted using machine learning methods. The R^2 , MAE, MAPE, and RMSE metrics were calculated to evaluate the models. When the successful evaluations of the models for the dried alfalfa plant are made using the R^2 metric, the model established by the ET method is the most successful model. Independent variables explain approximately 98.5% of the variance of the dependent variable (Table 2). The proportion of variance of the dependent variable explained by the independent variables is 98.5%. When success evaluations are made using the RMSE, MAE and MAPE metrics, the model established with the ET method is the most successful model. The leaf breaking stress value of the dried alfalfa plant can be estimated with an error of approximately 10% (MAPE). The RMSE and MAE value are 0.0171 and 0.0099, respectively. Since the results are close to 0, it can be said that the established model is successful. In fact, all the model results have close values in the R^2 , MAE and RMSE metrics. However, the model established with the ET method has become the most successful model, obtaining better results with slight differences. The situation is slightly different for the MAPE metric. While the models established with the GB and RF methods produce worse results, the models established with the ET, CB and XGB methods are more successful with similar results. However, the model established with the ET method has become the most successful model, obtaining better results with slight differences.

When the success evaluations of the models for the green alfalfa plant are made using the MAPE metric, the model established using the GB method is the most successful model. The leaf breaking stress value of green alfalfa plant can be estimated with an error of approximately 14.5%. For the R^2 metric, the model established using the RF method is the most successful model. The proportion of variance of the dependent variable explained by the independent variables (Table 2) is 96%. For the RMSE metric, the model established with the RF method is the most successful model. The RMSE value is 0.0616. Since the result is close to 0, it can be said that the established model is successful. When success evaluations are made using the MAE metric, the model established with the ET method is the most successful model. The MAE value is 0.0099. Since the result is close to 0, it can be said that the established model is successful. In fact, all the model results have close values in the MAE and RMSE metrics. The situation is slightly different for the MAPE metric. While the models established with the RF and CB methods produce worse results, the models established with the GB, ET and XGB methods are more successful with similar results. The situation is slightly different for the R^2 metric such as the MAPE. While the models established with the GB and XGB methods produce worse results, the models established with the RF, CB and ET methods are more successful with similar results.

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Nomenclature

ANN	Artificial Neural Network
CB	CatBoost
DT	Decision Tree
ET	Extra Trees
GB	Gradient Boost
GPa	Giga Pascal
H	Hertz
J	Joule
MAE	Mean Absolute Error
MAPE	Mean Absolute Percentage Error
ML	Machine Learning
MPa	Mega Pascal
N	Newton
RF	Random Forest
R ²	Correlation Coefficient
RMSE	Root Mean Square Error
XGB	Extreme Gradient Boosting

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Article

Adaptive Multi-Robot Communication System and Collision Avoidance Algorithm for Precision Agriculture

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Abstract: In precision farming technology, the interest of the researchers has been focused on the applications of autonomous mobile robots for agricultural operations such as planting, inspection, spraying, and harvesting. However, each autonomous robot generally performs a single agricultural task. In this context, complete autonomy in precision farming can be achieved by using coordinated multi-robot systems that can easily and safely cooperate to accomplish agricultural tasks. The efficiency of the multi-robot system depends on the number of robots, the size of the robots, the distance between each robot, the instant location and heading angle of the robots, and the size of the farmland. This paper describes the development of wireless Robot to Robot (R2R) communication system architecture and the collision avoidance algorithm for multi-robot precision farming applications. The developed system uses the fusion of a digital compass and GPS receiver for wirelessly broadcasting the spatial and temporal data of the mobile robots through WiFi. In this study, WiFi broadcasting was chosen for reasons such as the advantages of long wireless signal range and strength, not being easily affected by weather and dust, low cost, and so on. The proposed system realizes the real-time wireless broadcasting of the mobile robot information for eliminating the collision of mobile robots and improving the level of safety management. The results show that the system has flexible, reliable, and adaptable solution, and thus can increase the efficiency of the multi-robot system in precision farming applications.

Keywords: robot-to-robot communication system; multi-robot system; WiFi; collision avoidance; precision farming



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1. Introduction

During the last decade, robotic systems have gained popularity for solving tedious agricultural tasks in field operations. Agricultural field operations are quite complex and different robotic systems were developed to solve these complexities in agricultural field operations, such as seeding [1], weeding [2], harvesting [3], spraying [4], and fertilizing [5]. According to a market research firm, the agricultural robots market is expected to reach from USD 4.6 billion in 2020 to USD 20.3 billion by 2025 [6]. Considering the rapid growth expectation for the agricultural robot market, it shows that the use of robots will increase in all agricultural operations within the agriculture industry in the next 5 years. On the other hand, with the widespread use of robots, the concept of multi-robots, which are programmed to collaborate and form an ecosystem, will emerge for completing agricultural tasks.

Over the next ten years, agricultural robot research needs to focus on the multi-robot systems that collaborate to successfully execute farming tasks [7]. Multi-robot systems consist of mobile robots that work together to accomplish agricultural tasks by moving around in the agricultural environment. Multi-robot systems can accomplish tasks not executable by a single mobile robot. In recent years, several researchers have investigated the development of mobile robot technology to optimize complex operations related to farming procedures and precision treatment [8–10]. Most of the proposed techniques are based on single-robot systems, but there are important reasons to consider multi-robot systems as a more advantageous approach for agricultural tasks. Multi-robot systems will direct the agriculture of the future due to the disadvantages of the single-robot systems such as the complexity of agricultural tasks, spatially distributed tasks, and the limited capabilities of single robots [11].

The important parts of the multi-robot system are the robot management system, anti-collision system, and real-time monitoring [12]. The multi-robot system has some advantages over single mobile robots, such as their effectiveness, efficiency, flexibility, and fault tolerance in precision farming applications [13]. The multi-robot systems are divided into two categories homogeneous and heterogeneous. In a homogeneous multi-robot system, the mobile robots each have their controller with the same mechanical structures and control mechanisms. On the other hand, in a heterogeneous multi-robot system, mobile robots may have different hardware structures and control mechanisms. Nevertheless, many agricultural applications require a heterogeneous multi-robot system. Although multi-robot systems have advantages like flexibility, scalability, and robustness in solving complex tasks for precision farming and large-scale agricultural applications, there is not much research on the use of multi-robot systems in the agricultural domain. Also, there is little research conducted on internal communication and radar system to avoid collisions for the multi-robot systems in precision farming applications.

In the literature, some theoretical studies have been reported on multi-robot systems. The first real multi-robot system test has been conducted by the RHEA (Robotics and Associated High-technologies and Equipment for Agriculture) project for precision farming applications [14]. RHEA is an EC-funded research project to create a heterogeneous multi-robot system of small, collaborative ground and air robots equipped with advanced sensors, advanced end effectors, and improved decision control algorithms for both chemical and physical pest management [15]. Emmi et al. [16] developed multi-robot system architecture for both individual robots and robots working in fleets to improve reliability, decrease complexity and costs, and permit the integration of software from different developers. Also, researchers proposed a collision avoidance algorithm to avoid collisions between robots by using the wireless master-slave communication system. Conesa-Muñoz et al. [17] described a distributed multi-level supervisor system for monitoring the operation of autonomous agricultural vehicles in agricultural tasks. The system has a real-time warning system to detect a failure or potentially dangerous situations for notifying the user. In addition, the system performs the anti-collision mechanism to prevent collisions between vehicles by taking action to avoid intersecting trajectories. Gonzalez-de-Santos et al. [18] developed the multi-robot system, which consists of heterogeneous ground and aerial robots for effective weed and pest control aimed at diminishing the use of agricultural chemical inputs, increasing crop quality, and improving the health and safety of production operators.

Wireless access to telemetry data is the current trend in precision farming technology, especially autonomous mobile robots, because of providing quickness, easiness, mobility, feasibility, and flexibility. Peer-to-peer technologies such as Bluetooth [19], ZigBee [20], and WiFi [21] are used to send data wirelessly from point to point in precision farming applications. Especially in multi-robot systems, wireless data exchange is so important for monitoring and controlling the working environment.

In the literature, there are limited studies about wireless R2R communication systems for precision farming applications. Amer et al. [22] developed an autonomous agricultural robot prototype (AgriBot) for performing various agricultural tasks such as seeding,

weeding, and spraying fertilizers. The robot is communicated with the operator and other robots through a Wi-Fi communication system. Researchers reported that the basic design of an autonomous robot can work in small areas but, it can be designed to work in large areas of the field with the use of a Wi-Fi signal booster. Jian-sheng [23] proposed the WiFi wireless controlled agricultural robot system to reduce pesticides and improve spraying efficiency. The researcher used a wireless router to monitor the microcontroller core. The wireless router was used to remote control the robot and to transmit video data to the phone. The client-server-based control software was developed using Java language in the Eclipse development platform. Researchers reported that the proposed design realizes spraying pesticides by the robot without any problem and achieves good results. Brinkhoff and Hornbuckle [24] described a new agricultural sensor data gathering and logging platform based on IEEE 802.11 WiFi technology. The proposed system includes many sensor types such as weather, tank and irrigation water levels, and soil status sensing. For this reason, researchers reported that Wi-Fi is an attractive choice for their application because of the wide range of other devices that need connectivity in the system. Zant et al. [25] designed and developed a UV-Robot supervision system for controlling the robot that is used in greenhouse mildew treatment operations. Researchers reported that the position of the robot can be determined through possible Wi-Fi technology in farming areas. Pretto et al. [26] carried out a project to bridge the gap between the current and desired capabilities of agricultural robots by developing an adaptable robotic solution for precision farming that combines autonomous unmanned aerial vehicles and ground vehicles. In a designed system, each robot can communicate with others via Wi-Fi to be able to run coordinated missions between the robots. Researchers reported that the proposed solutions are easily applicable to a wide range of robots, and farm management activities.

The critical issue of the multi-robot systems is providing coordination between the mobile robots while sharing the same workspace for avoiding collision [27]. To solve this problem, mobile robots need to be informed about the temporal and spatial situations of other mobile robots working around them. Most commercial autonomous robots use different range sensors such as radar, sonar, infrared (IR) sensors, single charge-coupled device (CCD) cameras, and vision and laser scanners to detect obstacles. However, recent research shows that these sensors cannot fully detect a moving obstacle and are inadequate to acquire enough information about their environments [28]. For multi-robot systems, one of the promising solutions to improve the collision avoidance system is by integrating a two-way data exchange system R2R communication between autonomous robots.

In this paper, wireless R2R communication system architecture is proposed for eliminating the collision of mobile robots and improving the level of safety management. Also, the wireless communication system for broadcasting the mobile robots' spatial and temporal information is designed and discussed. The developed system can be applied for communication and distributed control of agricultural ground-based mobile robots using the Wi-Fi protocol.

2. Materials and Methods

The main aim of the designed system is to create a wireless R2R communication system and collision avoidance algorithm for mobile robot-based precision farming applications. The system involves four main structures:

1. Hardware structure of the communication system: This part explains the properties of hardware devices to provide WiFi (Wireless Fidelity) communication, and consists of an industrial PC, GPS receiver, and digital compass.
2. Data acquisition and WiFi communication system: This part explains the data collection and conversion procedures for data getting from a GPS receiver and digital compass. And it also describes WiFi connectivity between mobile robots.
3. Software implementation of R2R communication system: This part explains the developed server-client software to control all the functions of the wireless communication

system such as conducting communication flow control, message routing, and data monitoring.

4. Collision avoidance algorithm: This part explains and suggests a new algorithm for collision-free navigation of multiple mobile robots with differential steering systems.

The schematic of the wireless R2R communication system architecture for mobile robots in farmland is illustrated in Figure 1.

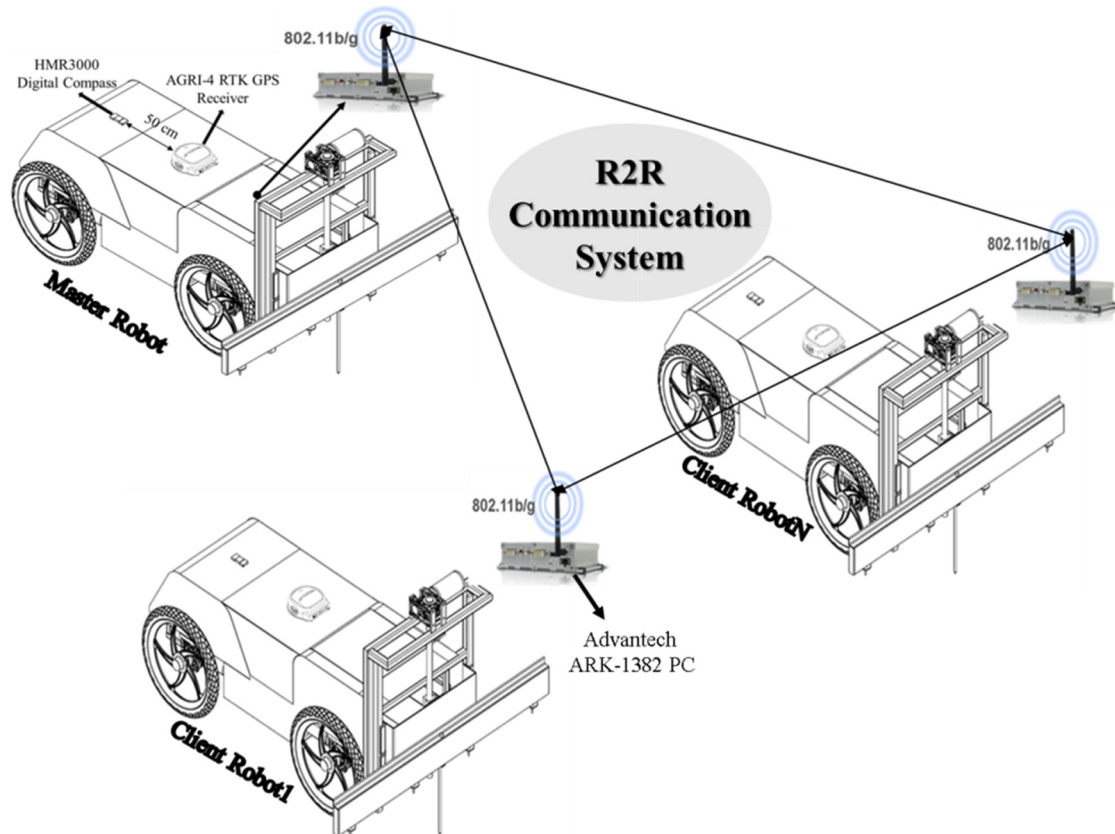


Figure 1. Whole architecture of the wireless R2R communication system.

2.1. Hardware Structure of the Communication System

The four-wheel drive agricultural mobile robot, which was developed in our previous study [29] and can be steered both autonomously and manually, was used in this study. Advantech ARK-1382 industrial all-in-one touchscreen industrial computer (Advantech Co., Ltd., Taipei, Taiwan) was used to manage and communicate with each other all of the electronic-based equipment placed on the mobile robot. The ARK-1382 fanless and ultra-compact embedded Box PC is an embedded system engaged in edge computing and highly suitable for remote monitoring, control, and mobile applications. It was designed with Intel Core Duo 1.06 GHz processor. It is equipped with an 802.11b/g WLAN (Wireless Local Area Network) card and supports a wide range of input voltages from 9 VDC to 35 VDC. It supports 4× USB 2.0, 1× Giga LAN, and 2× COM ports.

A Topcon AGRI-4 RTK GPS (Topcon Positioning Systems, Inc., Livermore, CA, USA) receiver was used to acquire the location and speed data of the mobile robot. The receiver has up to 10 Hz data output rate. It is easily upgradeable to 2 cm accuracy with RTK radio options, and NTRIP capabilities allow it to connect to Corse-TR (Continuously Operating Reference Stations-Turkey) via a phone data card (SIM Card) to receive correction signals.

Honeywell HMR3000 digital compass was used to collect the heading, pitch, and roll data of the mobile robot. It is used for different applications such as compassing and navigation, dead reckoning backup to GPS systems, marine navigation, antenna positioning, and land surveying. This electronically gimballed compass provides a fast refresh frequency

of up to 20 Hz and a high direction accuracy of 0.5 degrees with 0.1-degree resolution. The tilt range is ± 40 degrees. The hardware components used in the communication system are shown in Figure 2.

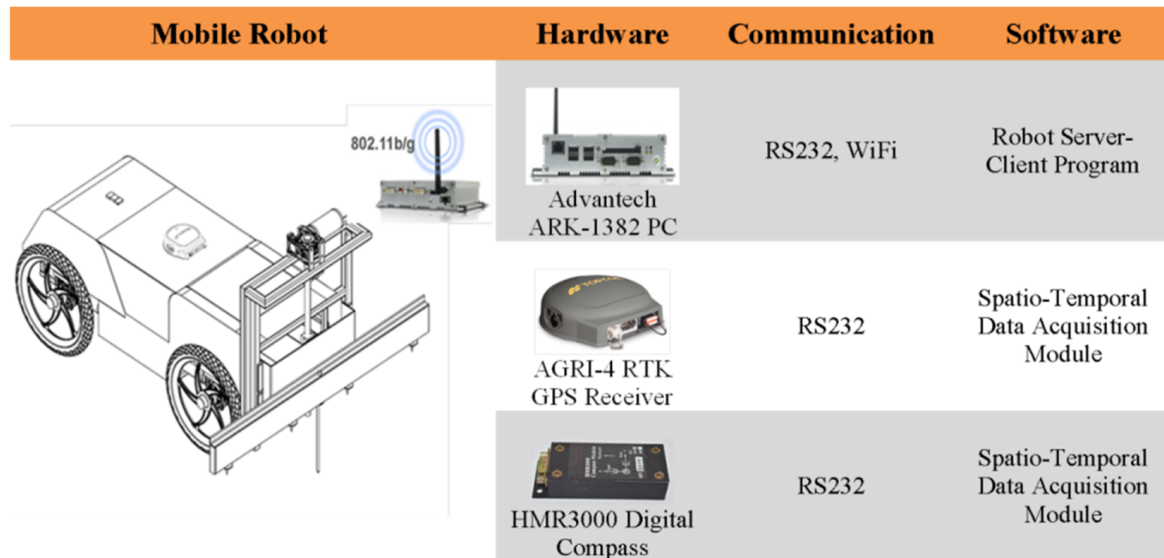


Figure 2. Hardware components used in communication systems.

2.2. Data Acquisition and WiFi Communication System

The GPS receiver was placed in the rear right corner of each robot. The digital compass was placed in front of the mobile robot. In the study, it was seen that the digital compass did not work when placed close to the GPS receiver. The industrial computer was placed inside the body of the mobile robot. The RS-232 serial communication protocol was used for connecting the industrial computer and other electronic devices and both the GPS receiver and the digital compass have serial communication ports. The serial communication speed of the GPS receiver and the digital compass with the industrial computer was set at 19,200 baud.

NMEA (National Marine Electronics Association) 0183 protocol is a combined electrical and data specification for using communication between electronic devices such as GPS receivers, digital compass, and many other types of devices. The NMEA 0183 standard uses a simple ASCII (American Standard Code for Information Interchange), serial communications protocol that defines how data are transmitted in a “message” from one “device” to multiple “devices” at a time. There are more than 80 different types of NMEA sentences for sending GPS data. Each sentence starts with a “\$” sign and the next five characters determine the sentence type. The \$GPRMC sentence type is the most important sentence and included spatial and temporal data for the navigating of the mobile robots. In this study, the GPRMC sentence was used to collect latitude, longitude, and speed data of the mobile robot. Spatial data are expressed in decimal degrees or degrees, minutes, and seconds in GPRMC sentences. Although these formats are sufficient for many applications, they should be converted to UTM (Universal Transverse Mercator) coordinates for mobile robot navigation applications, mathematical calculations, and mapping. Similarly, the HMR3000 digital compass communicates with the industrial computer using a standard serial RS 232 connection using the NMEA 0183 output sentence at 19,200 baud. The NMEA 0183 sentence specifications sent by the GPS receiver and the digital compass are shown in Table 1.

Table 1. The NMEA 0183 sentence specifications of the GPS receiver and digital compass.

Devices	Sentence Format	Specifications
AGI-4 RTK GPS Receiver	\$GPRMC, HHMMSS.SS, Q, LLLL.LL, A, YYYYY.YY, A, X.X, X.X, XXXX, X.X, A*HH	HHMMSS.SS: Time (UTC)
		Q: Status
		LLLL.LL: Latitude
		A: N or S
		YYYYY.YY: Longitude
		A: E or W X.X: Speed, knots
		X.X: Heading, degree
		XXXX: Date, ddmmyy
		X.X: Magnetic variation, degree
		A: E or W
		HH: Control
		X.X: Heading angle, degree
HMR3000 Digital Compass	\$HCHDT, X.X, T*HH<CR><LF>	T*HH: True, Control
		CR: Carriage Return
		LF: Line Feed

The IEEE (Institute of Electrical and Electronics Engineers) 802.11 standard defines the WLAN system for providing connectivity between computers or any wireless devices capable to connect WiFi over public areas networks [30]. The IEEE 802.11b/g supports high data speeds using a 2.4 GHz frequency band and provides the speed for maximum data transmission is 5 to 54 Mbps. The computer used in this study has a built-in 802.11b/g WLAN mini PCI module. For this reason, IEEE 802.11b/g was used for communication among mobile robots.

The designed mobile multi-robot system is based on the client–server model, which allows the participation of different mobile robots and the creation of a multi-robot network. The designed system consists of a mobile robot server and one or more mobile robot clients. The robot server is responsible for authenticating the connection, listening for the incoming connections, accepting mobile robot client connections, reading the incoming data, collecting all mobile robots' spatio-temporal data in an array, and sending out this array data to all robots. The mobile robot client is responsible for sending its spatio-temporal data to the server and requesting other mobile robots' spatio-temporal data from the server. Multi-robot wireless communication model is shown in Figure 3.

The client–server model is one of the most usable communication rules in networked systems. In this model, clients communicate with one server at a time. On the other hand, a server communicates with multiple clients at any point in time. There are two types of communication protocol used for client–server model, they are TCP/IP (Transmission Control Protocol/Internet Protocol) communication and UDP/IP (User Datagram Protocol/Internet Protocol) communication. In this study, TCP/IP communication was used between robot server and robot clients (Figure 4).

TCP/IP communication model provides a connection-based protocol and includes all the algorithms necessary for opening multiple connections, ensuring error-free data transfer over the network, and then closing the connections. In the designed system, the server socket that is bound to a port number on the same computer and listens to the robot client's incoming requests is an endpoint to provide a bidirectional communication link between the robot server and robot clients running on the same network. The robot client socket has to know the robot server's IP address and port number. Once the connection is established between the robot server and the robot client, they can communicate through their sockets for sending and receiving messages. After the connection is established between the robot server and the robot client, the robot server listens to the port to check if any robot client request exists. The robot client sends a message containing its spatio-temporal (UtmX, UtmY, speed, and heading) data. Every robot client connecting to the robot server should be sent this message. When the robot server receives the messages from the robot clients, it collects all data, stores it to an array variable, creates a WiFi message frame, and transfers it

to the robot clients via Wi-Fi (Figure 5). The size of the WiFi message frame is a maximum of 2346 bytes and the maximum length of the data field is 2312 bytes. In this study, both the robot server and the robot clients send a Wi-Fi message containing 33 bytes of data.

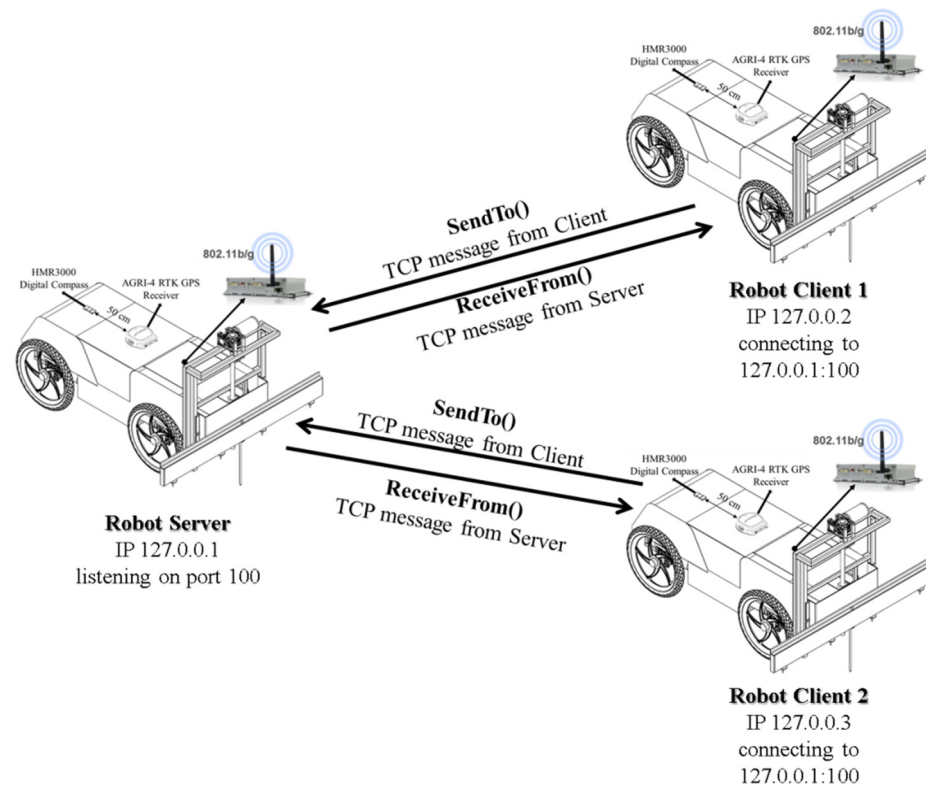


Figure 3. Multi-robot WiFi communication system.

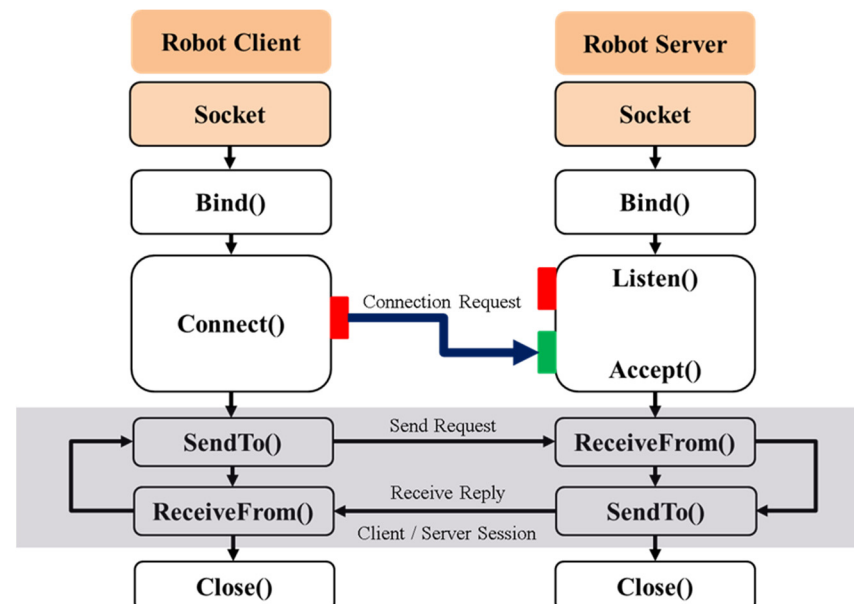


Figure 4. Multi-robot TCP/IP communication system between robot server and robot clients.

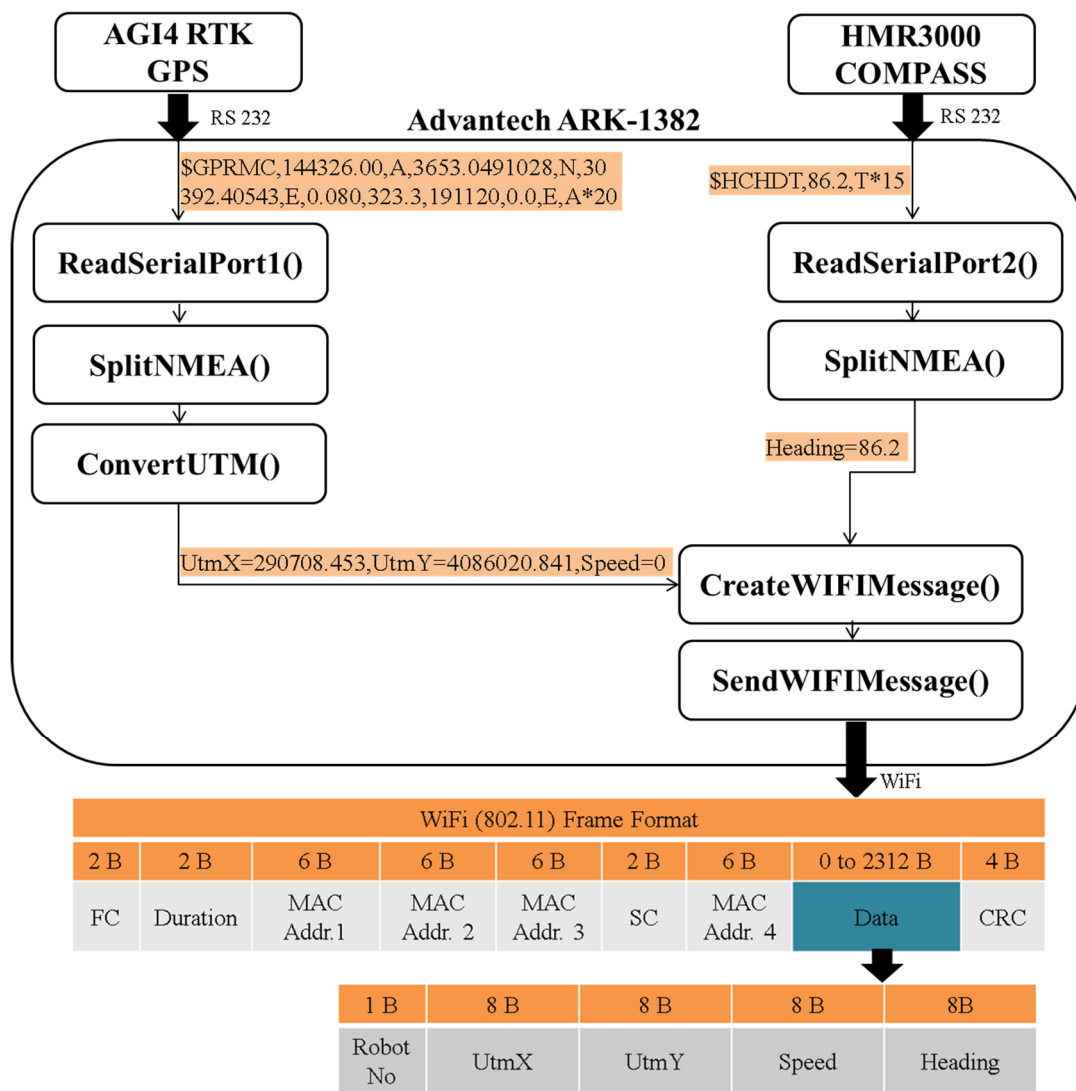


Figure 5. Data transmission from the robot client to the robot server via WiFi.

2.3. Software Implementation of R2R Communication System

Client–server-based software was developed using C#.NET programming language in Microsoft Visual Studio 2015 platform to create the WiFi communication between the mobile robot server and the mobile robot clients. C# Multithreaded Socket Programming technique was used to communicate with more than one mobile robot client at the same time in the same network in developed software. The Microsoft.NET framework provides two namespaces: System.Net for providing the TCP/IP protocol and System.Net.Sockets for providing the socket class to send and receive data over the network. In multithreaded socket programming, the mobile robot server receives a connection request from the mobile robot client side; the mobile robot server creates a separate mobile robot client thread on the mobile robot server side to communicate with that particular mobile robot client socket. That means the mobile robot client can communicate independently with their mobile robot client thread on the mobile robot server side.

The steps involved in establishing a multithreaded TCP/IP socket on the mobile robot server side are as follows:

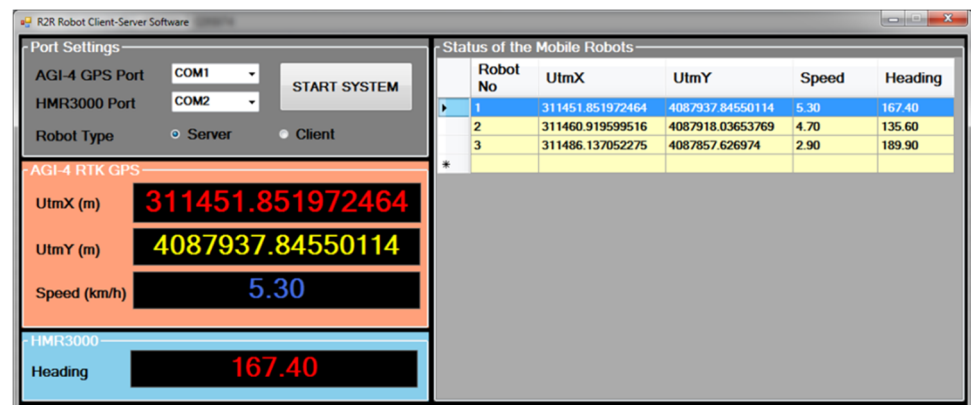
- Create a mobile robot server socket with the private static readonly Socket serverSocket = new Socket (AddressFamily.InterNetwork, SocketType.Stream, ProtocolType.Tcp) method.

- Bind the socket to an address using the `serverSocket.Bind (new IPEndPoint (IPAddress.Any, PORT))` method.
- Listen for connections with the `serverSocket.Listen(0)` method.
- Accept a connection with the `serverSocket.BeginAccept (AcceptCallback, null)` method.
- Send and receive data with the `Socket current = (Socket)AR.AsyncState` object.
- Close all connections with the `serverSocket.Close()` method.

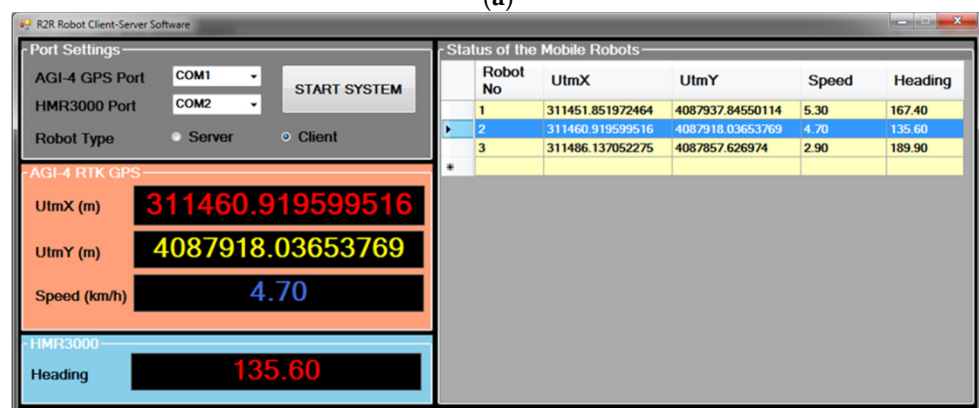
The steps for establishing a multithreaded TCP/IP socket on the mobile robot client side are the following:

- Create a mobile robot client socket using the private static readonly `Socket ClientSocket = new Socket (AddressFamily.InterNetwork, SocketType.Stream, ProtocolType.Tcp)` method.
- Connect the socket to the address of the mobile robot server using the `ClientSocket.Connect (IPAddress.Loopback, PORT)` method.
- Send data using the `ClientSocket.Send (buffer, 0, buffer.Length, SocketFlags.None)` method.
- Receive data using the `ClientSocket.Receive (buffer, SocketFlags.None)` method.
- Close the connection using the `ClientSocket.Close()` method.

Figure 6 shows the screenshot of the graphical user interface of the R2R wireless communication software. There are two radio buttons in the software window named “Server” and “Client”. If “Server” is selected, the mobile robot works as a mobile robot server, or “Client” is selected, and the mobile robot works as a mobile robot client.



(a)



(b)

Figure 6. Graphic user interfaces of the R2R wireless communication software: (a) mobile robot server side and; (b) mobile robot client side.

2.4. Collision Avoidance Algorithm

Four-wheel differential-drive mobile robots use a simple drive mechanism that provides differential speed difference between the right and left wheels. Wheels on both sides of the mobile robot can be independently driven in either a forward or reverse direction. It is assumed that no slip happens between the mobile robot's wheels and the ground during motion. A schematic illustration of a four-wheel differential-drive mobile robot is shown in Figure 7. The coordinates of points (X1, Y1) define the position of the GPS receiver of the mobile robot in a global frame. In the figure, L is the length of the robot and W is the width.

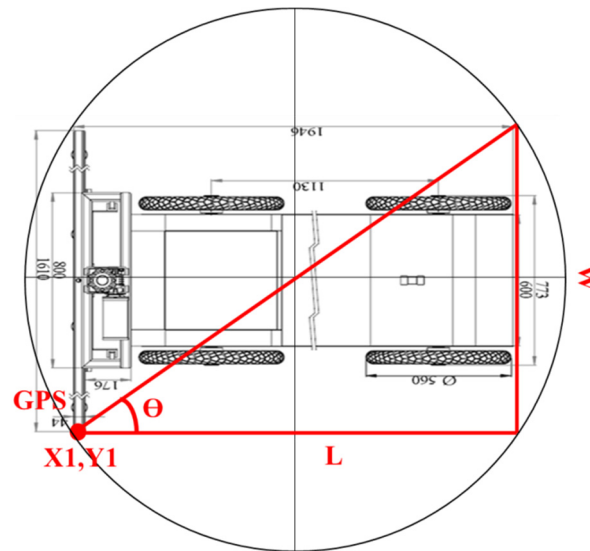


Figure 7. Schematic illustration of the metrics of a differential-drive mobile robot.

In the proposed collision-avoidance algorithm, it is assumed that all mobile robots move from the source point (X1, Y1) to the target point following a straight line. The main idea of the proposed algorithm is illustrated by taking into account the case in which two mobile robots lie in a trajectory that will lead them to collide. The mathematical operations in the proposed algorithm are based on the condition that the mobile robots moving 180 degrees opposite each other would pass tangential to each other (Figure 8).

The situation shown in Figure 8 is used to calculate the optimum reference distance and angle values to be used in the collision avoidance algorithm. The calculation of optimum reference distance (D_{Ref}) and angle ($\tan \theta_{Ref}$) values are performed using the following equations:

$$D_{Ref} = \sqrt{(2L)^2 + (2W)^2} \quad (1)$$

$$\tan \theta_{Ref} = \frac{2W}{2L} \quad (2)$$

where L represents the length of the mobile robot, W is the width of the mobile robot, and D is the longest side of the mobile robot. Mobile robots moving in the field instantly monitor the position and heading angle data of the other mobile robots via the developed R2R communication system. Within the R2R communication system, the real distances (D) and heading angles ($\tan \theta$) of all mobile robots to each other are instantly calculated. The calculation of real distance and heading angle values are performed using the following equations:

$$\Delta X = (X2 - X1) \quad (3)$$

$$\Delta Y = (Y2 - Y1) \quad (4)$$

$$D = \sqrt{\Delta X^2 + \Delta Y^2} \quad (5)$$

$$\tan \theta = \frac{\Delta Y}{\Delta X} \quad (6)$$

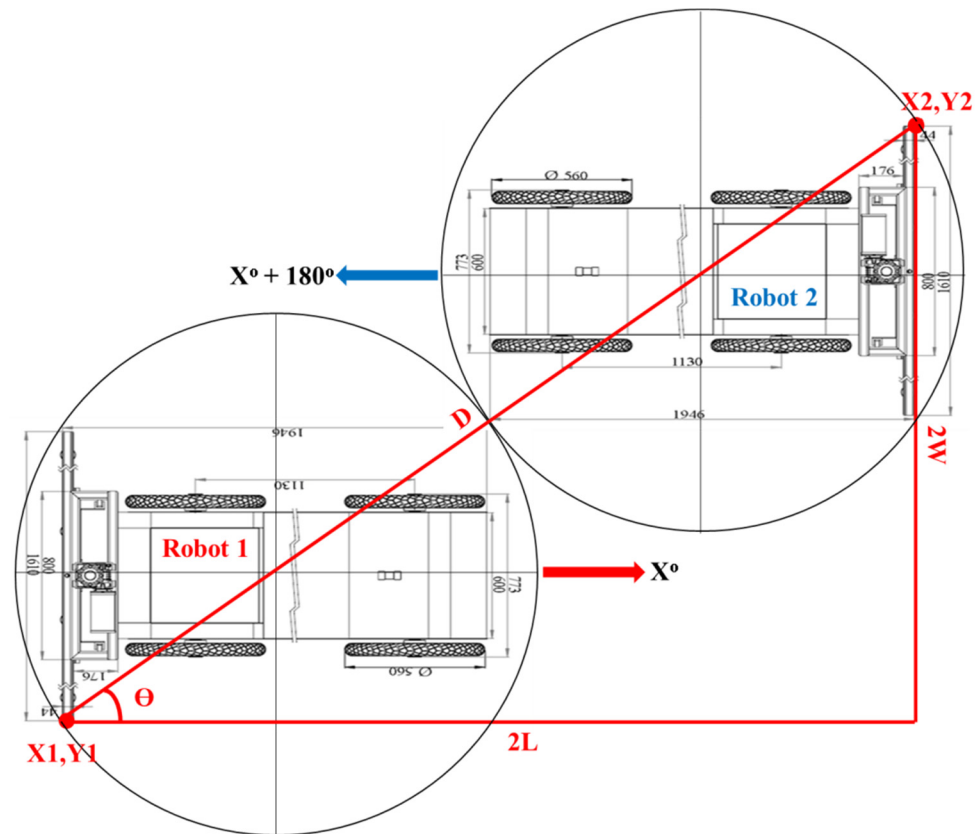


Figure 8. Illustration of the condition that the mobile robots moving 180 degrees opposite each other would pass tangentially to each other.

In the proposed collision avoidance algorithm, when the $D = D_{Ref}$ condition is met for two mobile robots coming at 180 degrees relative to each other, the mobile robots are stopped. Meanwhile, the tangent angles of the robots are calculated. If the $\tan \theta$ angle is greater than or equal to the $\tan \theta_{Ref}$ angle, the mobile robots continue to drive without collision. On the other hand, if the $\tan \theta$ angle is smaller than the $\tan \theta_{Ref}$ angle, the collision avoidance system is activated. In the collision avoidance system, all mobile robots moving in the field have mobile robot numbers from 1 to N. The basic rule in the proposed algorithm is the definition of the pass priority. Priority pass is a system that defines that the mobile robot with the lower mobile robot number than the two mobile robots in the reference boundaries has to pass superiority. In the case shown in Figure 8, Robot 1 has a pass priority over Robot 2. The schematic illustration of the collision avoidance system is given in Figure 9.

The algorithm of the collision avoidance system consists of the following steps:

Step 1. Calculation of the actual values of the variables: GPS coordinates of Robot 1 and Robot 2 ((X1, Y1), (X2, Y2)), heading angles of Robot 1 and Robot 2 (θ_1 , θ_2), the optimum reference distance (D_{Ref}) and angle ($\tan \theta_{Ref}$), the real distances (D) and heading angles ($\tan \theta$). Further inputs are the following constants: length of the robots (L), width of the robots (W).

Step 2. When the $D = D_{Ref}$ and the $\tan \theta$ angle is smaller than the $\tan \theta_{Ref}$ angle, both robots stop in their position. If the $\tan \theta$ is negative, Robot 2 turns 90 degrees to the left

in its current position. If the $\tan \theta$ is positive, Robot 2 turns 90 degrees to the right at its current position.

Step 3. The Robot 2 moves forward by the distance equal to W . Afterwards, the Robot 1 continues its movement in its direction of movement.

Step 4. When the $D = D_{Ref}$, Robot 2 moves back by the distance equal to W .

Step 5. After Robot 2 moves back by a distance equal to W , it stops.

Step 6. Finally, Robot 2 turns left or right according to its target direction of movement. And, both robots move towards their target points without collision.

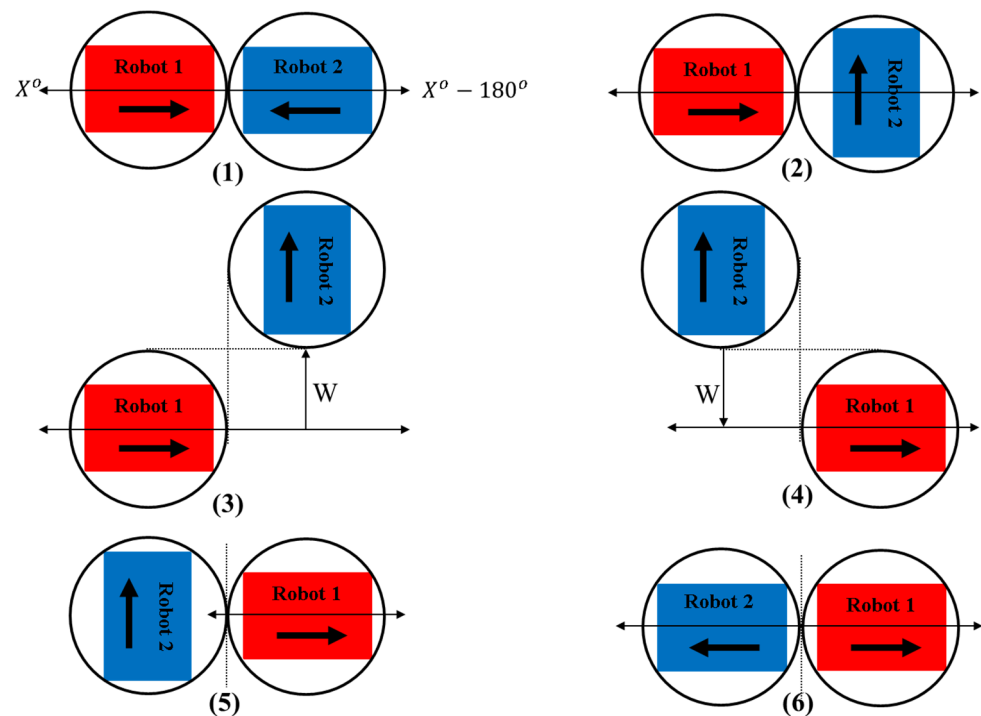


Figure 9. A step-by-step schematic illustration of the collision avoidance system (1) Step 1 (2) Step 2 (3) Step 3 (4) Step 4 (5) Step 5 (6) Step 6.

3. Results and Discussions

This work is focused on the wireless R2R communication mechanism and the collision avoidance algorithm for multi-robot applications in precision farming. The development of modern information technologies and wireless communication technologies are very important to provide connectivity for portable and mobile precision farming applications. And the development of autonomous mobile robots is continuously gaining importance for repetitive agricultural tasks in the agricultural domain. One aspect often neglected during the development of autonomous mobile robots is the communication of the multiple robots working in the same agricultural field. In this paper, a wireless R2R communication system between mobile robots was proposed to solve this aspect. The experimental wireless network contains a mobile robot server and more than one mobile robot client. The proposed mobile robot server reads the spatio-temporal data, which are sent from all the mobile client robots. It stores all the data in an array, creates the WiFi message frame, and sends it to the mobile robot clients. Figure 10 shows an algorithm for collecting and merging the spatio-temporal data of the mobile robot clients with the help of developed software.

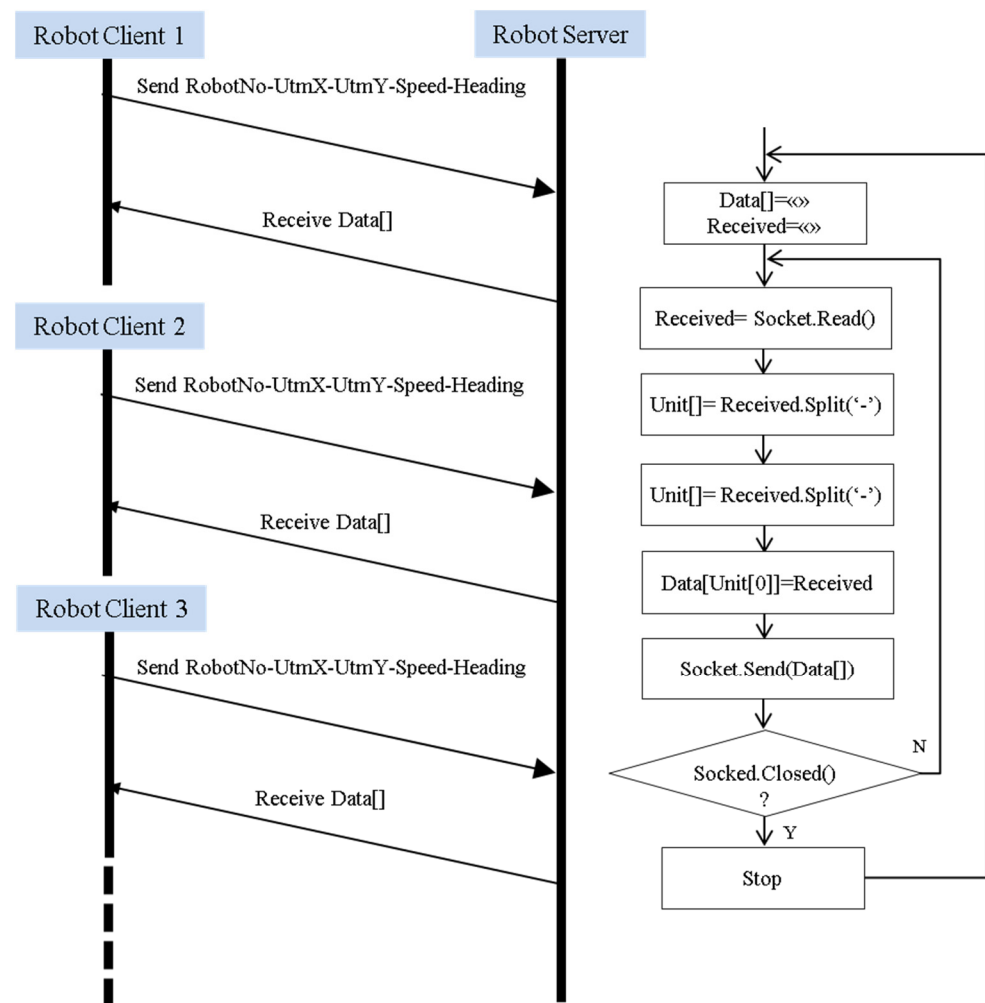


Figure 10. Algorithm for collecting and merging the WiFi message frame.

The Split() method, which is used to split a string based on the delimiters passed to the string, is part of the string class in C#. The Split() method returns an array of string (Unit[]) generated by splitting the original string separated by the “-” delimiter passed as a parameter in the Split() method. All data from mobile robot clients splits and moves to an array (Data[]) according to robot numbers. As soon as a message is received from any mobile robot client, the algorithm is run and the array containing the data of all mobile robot clients in the network is sent to the relevant mobile robot client.

The maximum length of the data field in a Wi-Fi message frame is 2312 bytes. The spatio-temporal data were sent as 33 bytes of data in this study. This means that the wireless R2R communication system is capable of supporting a maximum of 70 mobile robots per wireless network. The number of supported mobile robots seems to be satisfactory for precision farming applications. In a developed wireless R2R communication system, every mobile robot is capable of working as a mobile robot server or a mobile robot client.

Nowadays, with the increase in the number of mobile robots in farming applications, communication and coordination between robots are necessary to fulfill complex agricultural tasks. Communication plays an important role in the performance of multi-robot systems, where the robots interact with each other to exchange their spatio-temporal data and collected sensor data. In the developed wireless R2R communication system, the Wi-Fi message frame contains 33 bytes of spatio-temporal data (UtmX, UtmY, Speed, and Heading) of the mobile robots. On the other hand, this system is also capable of sending other sensor data within the remaining 2279 bytes in the data section of the Wi-Fi message frame.

The multi-robots in farm areas need to adjust their locations in real time. For this reason, the data exchange of communication among multiple robots is mainly focused on wireless communication technology. This technology mainly involves a wireless local or personal area network such as Wi-Fi, Bluetooth, ZigBee, and IRDA (infrared data association). Among them, Wi-Fi technology has been mostly preferred in agricultural multi-robots [31]. When these three wireless communication technologies are compared, Wi-Fi technology has been used in our study due to its features such as fast transmission speed, long effective distance, reliable connection, and wide coverage.

To evaluate the effectiveness and usefulness of the R2R communication and multi-robot collision system for multi-robot systems, the developed communication system and the algorithm were tested in the field. It evaluated three different cases for validating the collision avoidance algorithm in the field experiment. Firstly, the case of the real distance and the calculated distance are equal, and the real angle is greater than or equal to the calculated angle was tested (Figure 11). Secondly, the case of the positive of the calculated real tangent angle was tested (Figure 12). Lastly, the case of the negative of the calculated real tangent angle was tested (Figure 13).

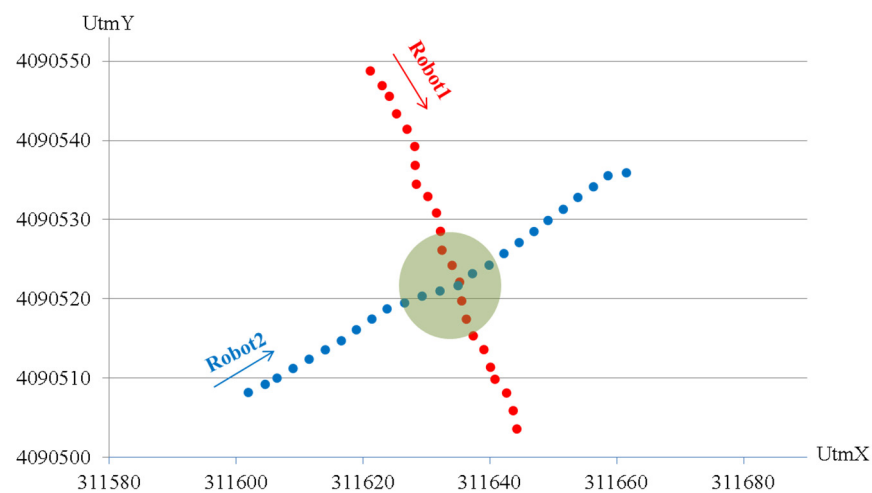


Figure 11. Test result for case 1.

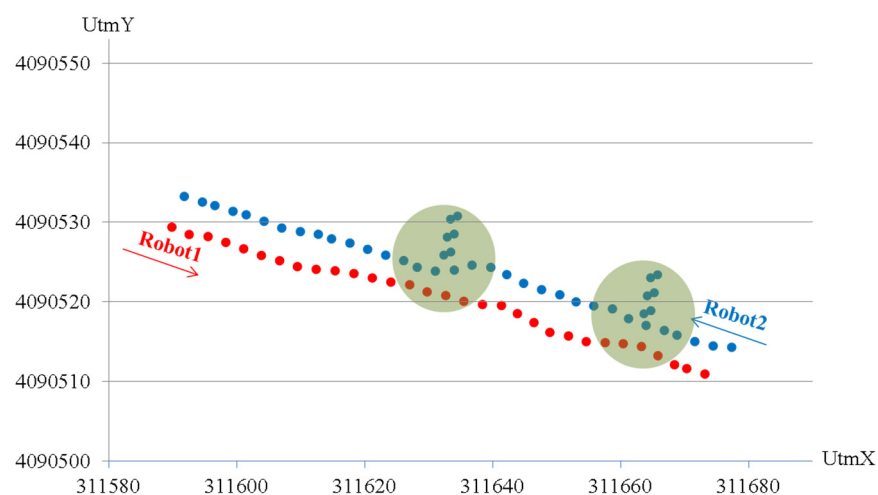


Figure 12. Test result for case 2.

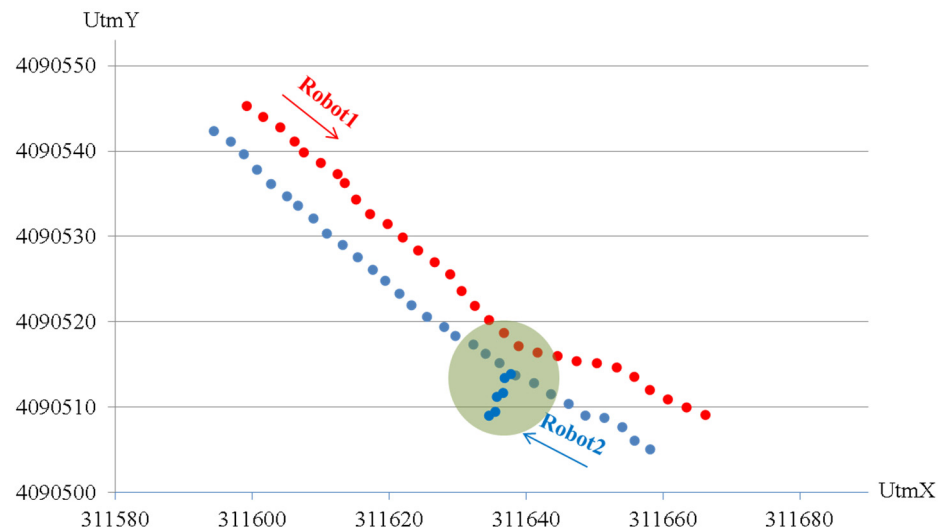


Figure 13. Test result for case 3.

Figure 11 shows the test result for collision avoidance in the case of the real distance and the calculated distance being equal and the real angle is greater than or equal to the calculated angle. Robot 1 has a passing priority due to its low robot number. Robot 1 moves with a heading angle of approximately 170 degrees. On the other hand, Robot 2 moves at an angle of about 50 degrees. When the robots reach the collision boundary, Robot 2 stops and Robot 1 moves forward. After Robot 1 is out of the collision boundary, Robot 2 resumes its movement.

Figure 12 shows the test result for collision avoidance in the case of the positive of the calculated real tangent angle. Robot 1 moves with a heading angle of approximately 290 degrees. On the other hand, Robot 2 moves at an angle of about 110 degrees. When the robots reach the collision boundary, the robots stop, and Robot 2 starts the collision avoidance maneuver. Robot 2 turns 90 degrees right and moves forward as far as its width; Robot 1 continues to move forward. After Robot 1 moves out of the collision boundary, Robot 2 moves back by its width and turns 90 degrees to the left. Then, Robot 2 continues to move in its direction.

Figure 13 shows the test result for collision avoidance in the case of the negative of the calculated real tangent angle. Robot 1 moves with a heading angle of approximately 130 degrees. On the other hand, Robot 2 moves at an angle of about 310 degrees. When the robots reach the collision boundary, the robots stop, and Robot 2 starts the collision avoidance maneuver. Robot 2 turns 90 degrees left and moves forward as far as its width; Robot 1 continues to move forward. After Robot 1 moves out of the collision boundary, Robot 2 moves back by its width and turns 90 degrees to the right. Then, Robot 2 continues to move in its direction.

Several algorithms for multi-robot collision avoidance have been proposed over the last few decades. These are potential fields [32], the dynamic window [33] inevitable collision states [34], sequential convex programming [35], model predictive control [36], priority-based planning [37], social forces [38], buffered Voronoi cells [39], barrier certificates [40], reciprocal velocity obstacle (RVO) [41], optimal reciprocal collision-avoidance (ORCA) [42], reciprocal orientation algorithm (ROA) [43], and shortest distance algorithm (SDA) [44]. However, none of the algorithms have been supported by a robot-to-robot communication system. In this paper, a new algorithm is suggested to solve the problem of multi-robot collision avoidance. The main idea of the study is to define the transition priority for the robots and to start the maneuver for collision avoidance from the two encountering robots to the one that does not have the transition priority. In this way, it is ensured that the robots for agricultural applications continue their work without leaving the route they should follow. The basis of the developed algorithm is formed by the developed robot-to-robot communication system. When the studies in the literature are evaluated, it is seen that this

study is important in terms of communication between ground-based mobile robots. In addition, the collision algorithm is unique in the software prioritization of robots.

4. Conclusions

One key element in multi-robot systems is communicating between robots and providing coordination to achieve well-defined agricultural tasks. The aim of the wireless R2R communication system was based on a client–server model where clients send the spatio-temporal data to the server and the server sends all collected robot data to all robots in a wireless network. The designed wireless R2R communication system is suitable for providing wireless connectivity between the devices which is capable of Wi-Fi communication not only on mobile platforms but also on stationary systems for precision farming applications. This system provides a flexible, reliable, adaptable, and elegant solution to connect all mobile systems in agriculture. In conclusion, the wireless R2R communication system can be used safely in both outdoor and indoor conditions for agricultural mobile systems. In this study, a new and robust collision–avoidance algorithm was introduced for multi-robot systems. This algorithm is based on the kinematics of the robot and robot-to-robot communication system. From the test results, we found that the algorithm is collision-free and straightforward. We believe that the R2R communication system and collision–avoidance algorithm are well suited for real-time computation and sensing thanks to its low computational complexity, which allows for agricultural multi-robot systems. Future work should focus on the multi-robot spraying, fertilizing, and harvesting applications using the proposed R2R communication system and algorithm.

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Article

Analysis of UNESCO ESD Priority Areas' Implementation in Romanian HEIs

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Abstract: Higher education institutions (HEIs) are adopting sustainable development (SD) in their strategies for the future. The roadmap by UNESCO is the path to follow to reach success. The approach is different for every HEI, thus the objective of this paper is to analyze the current state of education for sustainable development activities provided by HEIs through the eyes of the academic community (responders category: professors, researchers, associate professors). The method to conduct the study was an interview that had 40 enclosed questions and a free part at the end where the responders could bring additional information to the study if they considered it necessary. All the interviews were transcribed and given a code (e.g., RHEI1, RHEI 29) in order to perform the analysis using descriptive statistics with the help of the program MS Office EXCEL. The results showed some areas where the activities provided by HEIs need improvement and also revealed promising aspects through partnerships. Making the values of SD known to the academic and local community will help fulfill the true potential for change and future development. Moreover, the analysis showed the need to educate educators and improve their digital skills and teaching methods/techniques in order to achieve sustainable development. Another result revealed the need for improvements in HEI curricula that will contribute to gaining those skills/abilities that emerging jobs should have.

Keywords: higher education institutions (HEIs); education for sustainable development (ESD); UNESCO priority areas for ESD; sustainable development



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1. Introduction

The agenda adopted by the United Nations member states in 2015 contains 17 sustainable development goals (SDGs) that are people- and planet-centered to achieve prosperity and peace through partnerships for sustainable development. Starting from the principle of solidarity, the agenda for sustainable development leaves no one behind, with the support of all individuals, communities, and countries. Lately, however, global threats such as inequalities and discrimination, poverty, unemployment, scarcity of resources, environmental degradation, climate change, and global warming, etc. have intensified as never before, so humanity must find new solutions to tackle them for communities/societies not to be at risk [1].

Since then, the Sustainable Development Report has been published annually. This report is a ranking in which nations are positioned due to their progress in achieving all 17 SDGs. For example, Finland has an overall score of 86.51, being in the first position of this ranking (163 countries) in 2022. A simple analysis suggests that Finland has progressed 86.51% of the way towards sustainable development, a level obtained by very good indicators for SDG1 (No Poverty), SDG4 (Quality Education), SDG7 (Affordable and Clean Energy), SDG9 (Industry, Innovation, and Infrastructure), and SDG10 (Reduced Inequalities). Furthermore, high progress in SDG4 (Quality Education) is a key factor for the overall score of the countries in the first positions of this ranking. Romania is in the

30th place in this ranking, with a total score of 77.7. This score was obtained by very good sub-indicators of SDG1 (No Poverty) and being on an ascending track for SDG6 (Clean Water and Sanitation). Unfortunately, the achievement of SDG4 (Quality Education) for Romania is on a descending trend. In this field, Romania registers an 84.52% participation rate in pre-primary organized learning (percentage of children aged 4 to 6) (with a slightly increasing rate from 2018 to 2019), 87.3% net primary enrollment rate (quite constant from 2018 to 2019), 88.5% lower secondary completion rate (quite the same in 2019 compared with 2018), and a 99.4% literacy rate in 2018 (percentage of the population aged 15 to 24) [2].

We must state that education for sustainable development means more than SDG4 (Quality Education). Quality education is about having equitable access to education and an increase in the number of individuals who obtain appropriate skills for easier insertion into the labor market, while education for sustainable development (ESD) is a learning process meant to train individuals to find solutions to major problems humanity confronts, with a holistic approach focused on empowering learners to act responsibly in order to achieve, simultaneously, environmental, economic, and social goals for the present and future generations, taking into consideration cultural diversity [3,4].

HEIs have an important role in implementing ESD. The objective of this paper is to analyze the current state of education for sustainable development activities provided by the public HEIs in Romania through the eyes of the academic community (responders category: professors, researchers, associate professors). This paper aims at identifying Romanian universities' strengths and the opportunities related to ESD, but also the possible constraints, as well. The authors identify, through qualitative research, the Romanian higher education practice regarding ESD and the weaknesses that impede ESD in HEIs. It is also a good starting point for future research to identify the best ways of improving the communication between academic staff and university management so their actions are well known by all actors involved in a university. Romania is a major emergent country and this research can be considered a reference point for ESD in HEIs in other transition economies similar to Romania. Thus, the research hypothesis is that the academic community is aware of SDG implementation in the university and the necessity of implementation.

2. Literature Review

2.1. Education for Sustainable Development in Time

Most times, formal education towards sustainable development starts with great initiatives in primary school focusing on ecological/environmental education. After a few years of primary school, it seems that education for sustainable development stops suddenly. Many studies state that there are neither strategies, policies, or specific legislation for education for sustainable development in the higher education system, nor standards for integrating sustainability both in university lectures and professors' training in higher education [5–18]. Each university is free to define its curriculum according to its domain and the experience of its human resources. At the same time, higher education institutions are in a continuous process of adapting their curriculum and practices taking into consideration the sustainability goals for 2030 [18,19].

In this context, environmental education (EE) might be considered the beginning of ESD which is from quite far in the past (1977) at the United Nations Conference on Sustainable Development, Stockholm, and the UNESCO and UNEP Intergovernmental Conference on Environmental Education, Tbilisi. It was stated then that environmental problems should be solved by individuals and societies through education in this field (knowledge, skills, attitudes, experience, involvement, and social responsibility) [20]. Additionally, education for sustainable development (ESD) is more transversal, starting with promoting quality education, building awareness for individuals and communities, and reshaping educational programs to focus on practical training. Therefore, starting from EE and moving towards ESD, humanity confronts three types of challenges: (a) sustainability concerns: people have to tackle diverse problems that cover a wide range of life aspects and threaten sustainability (from scarcity of resources to gender equality, from biodiversity loss

to desertification, from health to energy issues); (b) values: people have to have a dynamic approach to customs, beliefs, and mentalities and to find solutions to combine past, present, and future when it comes to ESD; (c) placing ESD above all other education priorities at the international level (or at least comprising all of them): Millennium Development Goals, Education for all, United Nations Literacy Decade [21,22]. ESD can be defined as a frame of mind that can nurture the positive behavior needed for achieving sustainable development [23].

In 2022, 5 years after the United Nations Agenda was adopted, it became very clear that we need new tools for achieving sustainable development. UNESCO came up with a roadmap that identifies five priority areas to facilitate a way of achieving all 17 SDGs through education for sustainable development (ESD): (1) policy; (2) learning environments; (3) building the capacities of educators; (4) youth; and (5) local level action [24]. These areas mean a promise of contemporary societies to implement education for sustainable development.

The UNESCO ESD roadmap is a vision of education for the present and future whose main objective is for individuals to obtain knowledge and competencies for a sustainable way of life: critical thinking, anticipatory thinking, multidisciplinary and integrative thinking, skills for effective communication, team working, the ability to build interpersonal relations, and emotional intelligence, as can be seen in Figure 1 [24,25].



Figure 1. State of ESD in HEIs—general view. Source: Authors' interpretation.

2.2. Implementing ESD: The Great Outcome

Education is the trigger of all our actions. What we do depends on what we know and what we have learned through training, observation, and assimilation. Even if education is considered a necessity, after individuals obtain a study degree (usually a high school degree), many of them stop searching for a higher level of education [26]. Therefore, we consider that the implementation of ESD is vital for societies to be sustainable [24].

The implication of all stakeholders in all priority areas mentioned in the UNESCO ESD roadmap leads to a sustainable society based on diversity, freedom and interdependence, fairness, cooperation, and responsibility. From the perspective of sustainable development, all actors involved in education have to understand that the present and future are rather about skills/competencies than knowledge taught and learned. They have to know that solving complex problems, critical thinking, creativity, leadership, coordination, emotional intelligence, quick decision-making, communication, negotiation skills, and cognitive

flexibility are very important in personal and professional lives and must consider them key factors for a sustainable life [24].

We consider that the main outcome of implementing ESD is to achieve a sustainable way of life. It is not simple to implement it because a global and transdisciplinary approach is needed. Moreover, it is not simple because in poor societies even education is considered difficult to implement, especially ESD. There are some points of view that state that ESD is what economics considers a normal or even luxury good [27]. Normal goods are those for which demand is higher and higher when the income of the consumer is higher and higher. In other words, the higher the economic/financial power of a society, the higher its capacity to implement ESD. We strongly believe that higher education institutions (HEIs) play a major role in this implementation even if they are different regarding the capacity for the implementation of ESD. Even countries are different when it comes to their performance in ESD [28].

The core of ESD is the concept of sustainable development, but it will be effective only if all stakeholders in education have a holistic approach and do not emphasize only one single side of sustainable development (economic, social, or environmental) depending on their background or mentalities [29–31].

The world needs a systemic framework for connecting sustainable development goals (SDGs) to educational outcomes so that societies may achieve a sustainable state. This systemic approach helps stakeholders (educators, students, policymakers in education, etc.) to identify problems and gaps in education, to develop curricula, and use pedagogical tools to have great social transformation from the perspective of sustainability. If Nelson Mandela said that “education is the most powerful weapon we can use to change the world”, we may admit that education for sustainable development is the most peaceful tool we have in order to obtain a sustainable life [32,33].

2.3. Higher Education Institutions (HEIs) and ESD

Higher education has an important role in achieving Quality Education (SDG4) and for other major goals, as well, from the perspective of 2030: No Poverty (SDG1), Good Health and Well-Being (SDG3), Gender Equality (SDG5), correlated with Reduced Inequalities (SDG10), Decent Work and Economic Development (SDG8), Sustainable Cities and Communities (SDG11), Responsible Consumption and Production (SDG12), Peace, Justice, and Strong Institutions (SDG16), and Partnerships for the Goals (SDG17). Therefore, HEIs have a complex mission nowadays: teaching and learning, researching (creating knowledge), and engaging in social progress [34].

To accomplish this triple role, HEIs have to adopt a sustainability-focused approach in their development strategies related to education, research, and social responsibility [35,36]. Consequently, HEIs will be able to be a great contributor to sustainable development considering a dynamic approach regarding education, research, and good governance, being an inspiration for all individuals and communities [37]. Such HEIs are integrative organizations that are able to select the best solutions and practices appropriate for sustainable development [38].

Sustainable development goals (SDGs) represent a suitable context for integrating education for sustainable development (ESD) into a higher education institution (HEI) [39,40]. In this framework, there are studies focused on general methods, strategies, and models for the implementation of ESD in HEIs aiming at incorporating sustainability into a general education curriculum [41,42]. Other studies put emphasis on triggers and barriers to the process [43–45] and ESD initiatives in formal education, university management, and extracurricular activities [46–49].

In this context, regarding ESD, only one course about sustainable development in the university curriculum is far from being sufficient to develop the competencies mentioned previously (solving complex problems, critical thinking, creativity, leadership, coordination, emotional intelligence, quick decision making, communication and negotiation skills, cognitive flexibility) [50]. A general and common framework is needed, in which curricula in

HEIs are adapted and developed in such a manner to focus on ESD competencies integrated into teacher education programs, followed by a common framework for evaluating the efficiency of this process [51–56]. Furthermore, other studies evaluate the impact of HEIs on sustainable development focusing on the effects of HEIs outside its borders: economy at micro- and macroeconomic levels, policy-making, environment, culture, and demography, both in the short and long term. Short-term effects are considered direct (the knowledge the students acquire about sustainability) and the long-term effects are considered indirect (mentality changes and the adoption of a sustainable way of life) [57,58]. Furthermore, HEIs' impact on sustainable development comes from either their organizational behavior (activities in education and research) or the individual behavior of their main stakeholders (students and academic staff) [57–61].

3. Materials and Methods

3.1. Research Methodology and Data Gathering

To provide the answers needed for the analysis of the current state of education for sustainable development activities provided by HEIs, in this paper the results of the research were made possible by conducting interviews addressed to the higher education institutions (HEIs) in Romania. The interview was addressed to all public HEIs in Romania. We contacted every higher education institution (HEI) in Romania by sending an email in which we explained the nature of the research and the request for their participation in the study. After this step, we received very few positive answers from the HEIs responsible for implementing sustainable development strategies or leaders that make decisions related to SD, but we received many positive answers from assistant professors, lecturers, and PhD students, and some from associate professors, professors, and researchers. After discussing all the positive answers and setting some limitations—mentioned in subchapter 3.3—we thankfully began the study with 46 people, one from every institution that accepted to be a part of our research study and fit the limitations. Thus, the number of respondents was 46 and could be included in these three categories: professors, associate professors (degrees for university teachers), and researchers (scientific researchers whose activity is based only on conducting research activities in various areas), as can be observed in Table 1.

Table 1. Responders' classification.

Responders' Category	No. of Participants
Associate professors	21
Professors	16
Researchers	9

Moreover, all responders have a minimum of 15 years of experience in the HEI they represent and were/are involved in the university academic community through a series of activities. The responders were contacted by the authors in order to set a date for the audio/video interview. After both parties agreed on a date, the interview took place as established. The interviews extended over a period of 3 months, from March to the end of May 2022. The responders, according to which HEI they represented, received a code: RHEI1, RHEI2, through to RHEI46. The codes were given to respect and offer confidentiality. Happily, no interview needed to be rescheduled, and all were conducted on time.

Therefore, the methodology used is qualitative, the main aim being to see if the five UNESCO priority areas were/are/will be considered by HEIs in Romania. This method was chosen due to the fact that examples can help bring more value to research and better express the responder's additional information, thus the results and findings of this paper [62].

Because an opinion can offer great value and deeper meanings to this subject, education for sustainable development, the authors chose this approach and no other. The

interview had close-ended questions, but at the end of the interview, any other information or comment that the responders considered useful could have been mentioned and their opinions are presented in the Results and Discussion section of the paper.

3.2. Interview Design

The interview design started from the five priority areas of ESD for 2030, identified by UNESCO, that can contribute to the achievement of 17 SDGs. Moreover, the interview design was conducted by analyzing the dimensions proposed by Lozano et al. [63] and the challenges that researchers already found [64,65] in connection to ESD adoption. Because we live in an era where time is of the essence for the interview design, the time to answer the questions was a factor considered in trying not to retain the responders for more than 20 min. The answers were collected using the existing platforms that allow for distance communication, such as Zoom, MS Teams, WebEx, Google Meets, and Skype. The number of responders for every platform is highlighted in Table 2.

Table 2. Communication platform.

Communication Platform	No. of Participants for Each Platform
Zoom	12
MS Teams	11
WebEx	6
Google Meets	8
Skype	9

A particular platform was used according to the desire of the responder. The interviews were conducted one on one, each question being addressed, and the answer was written down. The number of questions addressed was 40, and every question could have been answered with “yes/no/maybe/I don’t know”. The end of the interview was represented by comments/examples/opinions/information that the responder considered important for the scope of the research and in relation to any question answered before. At the end of all interviews, the results were collected, and analysis could be performed based on the answers. After each interview, the interviewer transcribed the answers in a document that was named according to the responders’ institution code (e.g., RHEI1). At the end of the interviews, after all the transcriptions were made, the data gathered and coded were analyzed using descriptive statistics with the help of the program MS Office EXCEL (Supplementary Material). So that the analysis can be enriched, as mentioned before, the examples given by the responders are also presented.

3.3. Study Limitations

Although the interviews were structured for people/employees from the HEIs responsible for implementing sustainable development strategies or leaders that make decisions related to SD, the responders that said yes to the interviews were researchers, professors, and associate professors. In this respect, participants such as assistants and lecturers were eliminated from being possible responders because it was important to have a person answering with a solid background and experience. Their background and experience were measured in the years spent in the HEI they represent and their activity within these years. Their involvement in the HEI’s activities such as projects, regulations, and academic issues such as admissions and final exams were criteria taken into consideration when considering conducting an interview, thus limiting us in our study implementation. In Romania, there are 53 public HEIs (including military universities) and 34 private HEIs; thus, considering this, another limitation was related to the type of HEI. The private universities were not questioned about ESD. This limitation was chosen because the focus and the development of both types of HEI are different. A study conducted first just on ESD in private HEIs and

then a comparison between public and private HEIs could provide a perspective on the entire higher education system in relation to sustainable development.

4. Results

The search for answers regarding the analysis of the current state of education for sustainable development activities provided by the HEIs in Romania through the eyes of the academic community began by reaching out to the academic community, which proved to be challenging. The analysis began with agreeing to participate in the study and scheduling the interviews.

The research done in the paper through the interviews started with a few questions related to the general aspects of ESD in HEIs. As can be seen in Figure 2, the five priority areas identified by UNESCO for ESD are known by more than 80% of the HEIs. Although the priorities are known, the development of the HEIs in relation to the priority key elements and whether they are applied or not are not publicly communicated, and the levels of implementation are not available to the public. The positive aspect of these questions is related to the fact that there were no “NO” answers for the second question, which can only represent that either the HEIs are using ESD strategies, or the responders are not aware whether the HEI they represent has an ESD strategy.

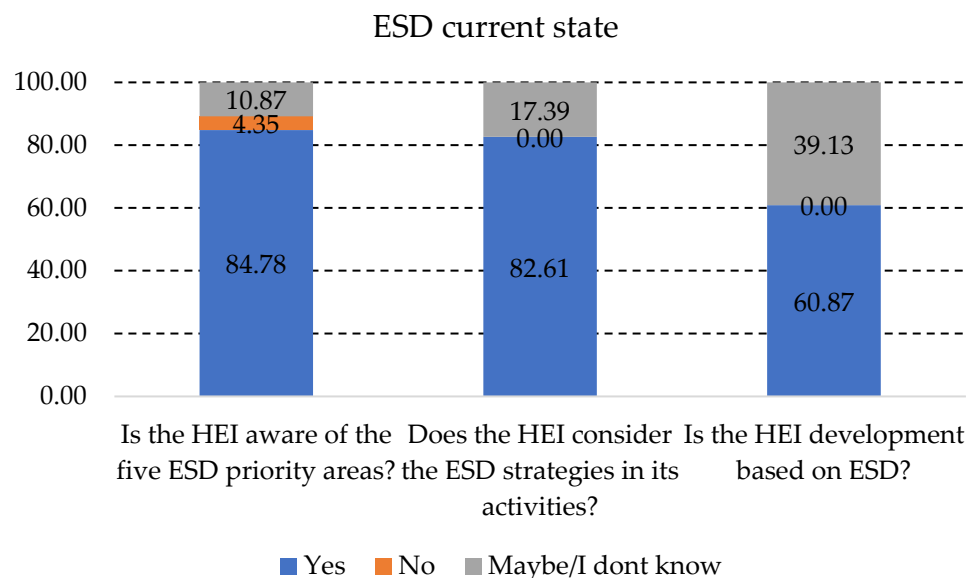


Figure 2. State of ESD in HEIs—general view.

After this part was established, the questions related to the five priority areas for ESD, identified by UNESCO, were addressed to the responders. Thus, the first priority area, “Advancing policy” was analyzed, and the percentages of the answers are presented in Figure 3.

Sustainable development starts with policies that can provide the framework necessary for the future. The policymakers, along with practitioners, need to come together and find the best way to reshape the HEI system in order to answer the requirements for sustainable development. As can be seen from Figure 3, a percentage of 52.17% of HEIs started changing their policies. About 43.48% were not aware of this aspect in the HEI they represented. The most important aspect to mention for this priority is the fact that about 82.61% of the responders do not find the policies related to ESD difficult to apply, which leads us to the conclusion that most of them are willing to support educational change. One other encouraging aspect to mention is the quality of education that was taken into consideration for the ESD policies developed by the HEIs.

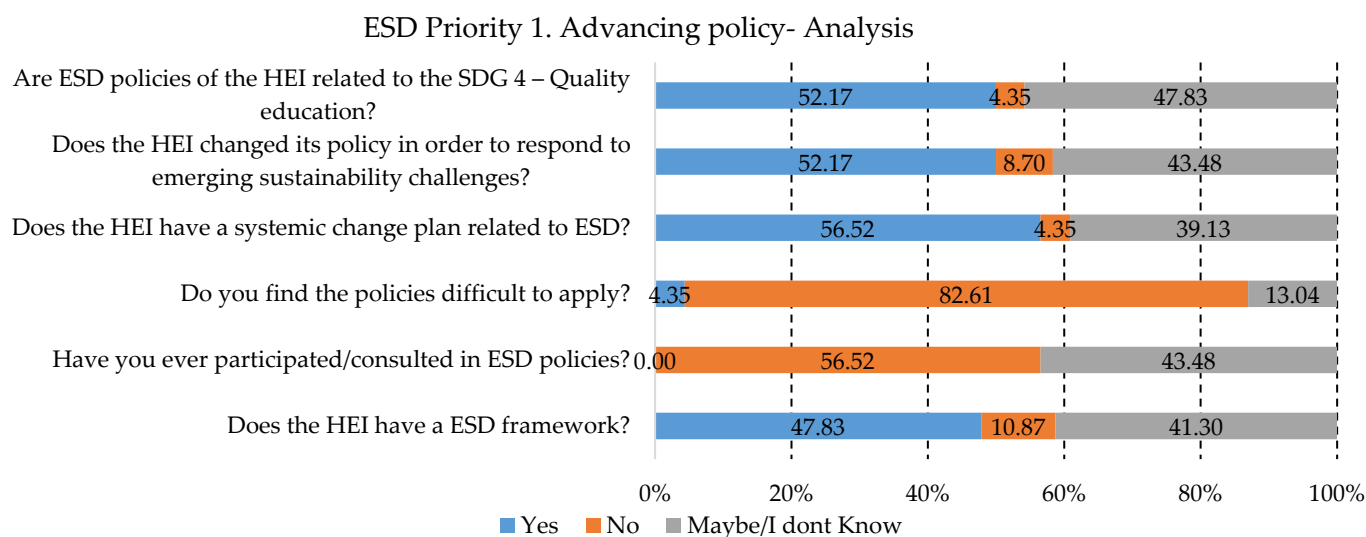


Figure 3. Priority area No. 1 results.

Continuing the analysis for the second priority area, “Transforming learning and training environments”, analyzed from the higher education point of view, the results can be seen in Figure 4. An important element that can lead to positive outcomes is the fact that approximately 98% of the students are willing to change their way of learning and, from the point of view of the responders, are open to new learning environments. Changing the way a class is taught or using technology becomes more appealing to students. Their involvement in class activities, individual research, and innovation contribute to the willingness of students to contribute to change. The change that has to be achieved, according to the results, is related to the curriculum, 33% of which is still using the classic learning environment.

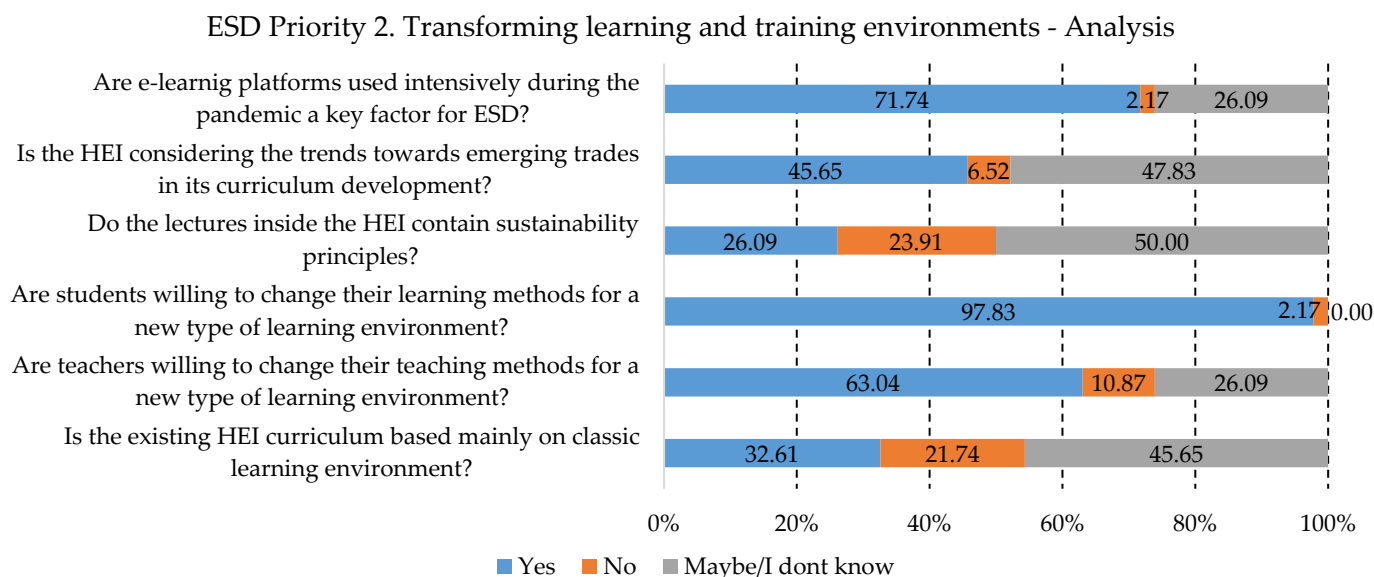


Figure 4. Priority area No. 2 results.

If we analyze Figure 5 to see the results for the third priority area, we can observe that there are many answers that do not provide a clear view of the aspects connected to it. There are many answers of “Maybe/I don’t know”, which can be a result of the fact that the responders are not part of the decisional authorities in the HEI or part of the structure responsible for sustainable development. One aspect that the responders mainly agreed on

was the fact that teachers need digital skills and the HEIs should provide the means for it. Moreover, the change in the curriculum from the previous priority area is highlighted in this analysis because there are more “NO” answers than “YES” for applying sustainable principles to teaching styles. Along with special programs/lectures/training for teachers related to ESD, the values of ESD for SDGs should be promoted for a better commitment to achieving the goals for 2030.

ESD Priority 3. Building capacities of educators and trainers - Analysis

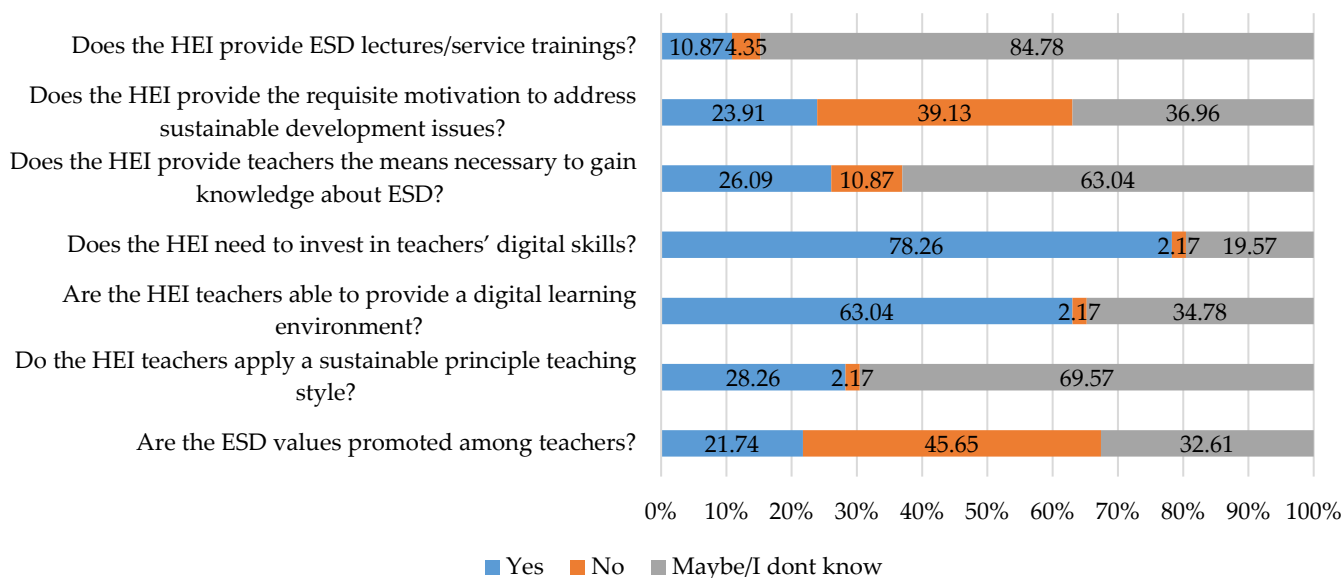


Figure 5. Priority area No. 3 results.

When a current advancement is made at the expense of future generations, this is also known as unsustainable development. For instance, poor planning and resource exploitation can degrade the environment and harm ecosystems by producing waste and pollution. Mobilizing youth to contribute to changing an unsustainable pattern can help diminish the lack of appropriate education and awareness for sustainable development, with students being an important part of the higher education system.

Also, a question that requires change inside the HEIs is related to SD internships. As can be seen in Figure 6, the responders are not aware of such activities. Moreover, the HEI does not continue the curriculum from secondary education, thus creating another gap that can only become bigger if the education system does not consider a continuous process through all stages of the education system.

Continuing the analysis with the fifth and last priority area, it can also be observed that some questions do not reflect sustainable development. The work done on the curriculum and the teachers' skills reflects the ability of the students to answer the challenges faced in contemporary society, whether we are looking at a local, regional, or national level. There are still 32.61% of the responders of the opinion that student skills are not what the business and social environments need. This environment requires students to have the ability to adapt to every situation, face the challenges that come, and be more proactive. All these can be achieved by engaging students in university activities and by putting them in situations that can need different characteristics in order to be solved. An encouraging aspect is that partnerships with public/private entities are being developed at a percentage of more than 84%. These results can be observed in Figure 7.

ESD Priority 4. Empowering and mobilizing youth - Analysis

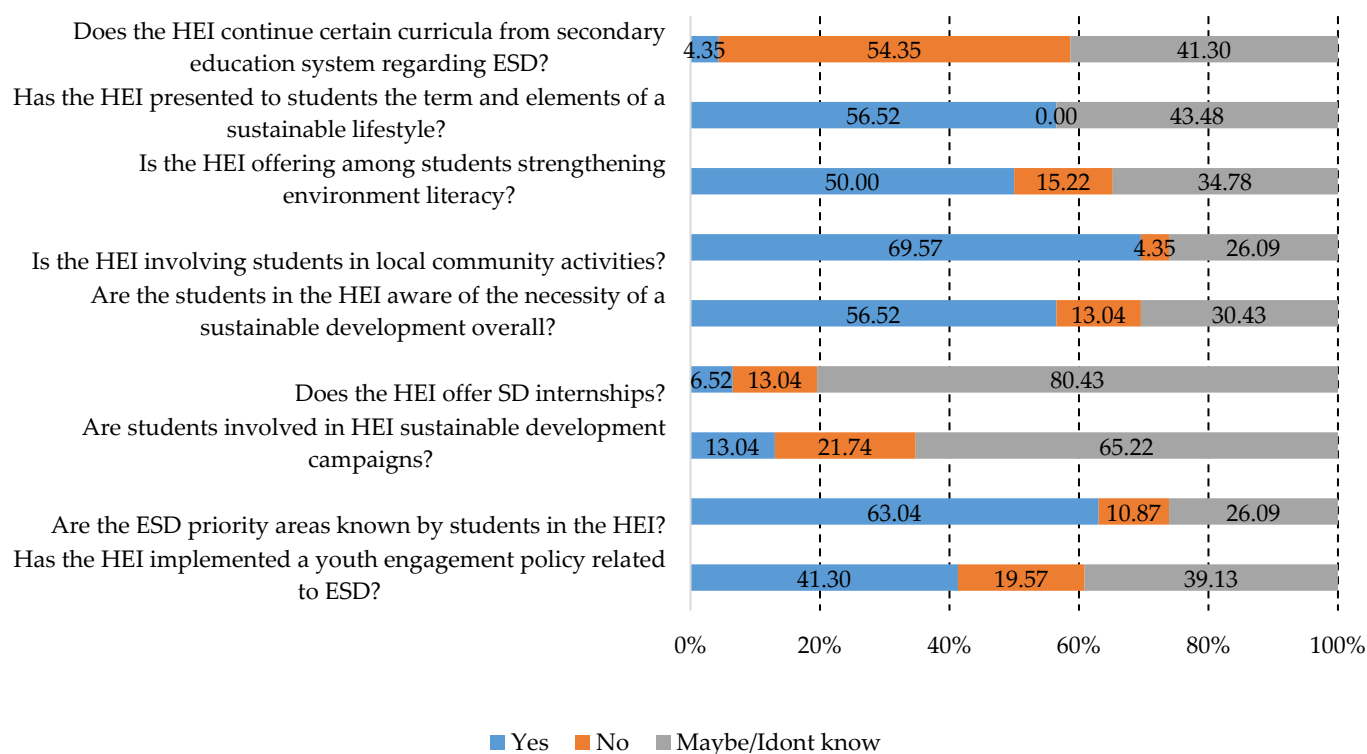


Figure 6. Priority area No. 4 results.

ESD Priority 5. Accelerating sustainable solutions at local level - Analysis

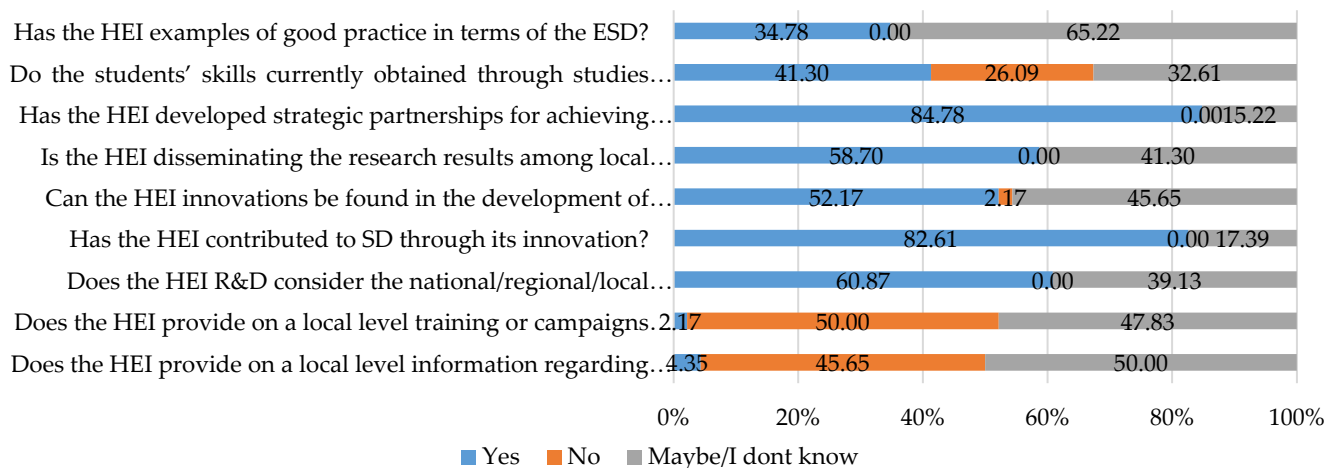


Figure 7. Priority area No. 5 results.

Moreover, this is not enough—the need for awareness and information campaigns are determined by activities that any HEI should consider at a local level in order to answer together for sustainable development goals. To ensure that the most recent theories and methods for sustainable development are applied to advance the local agenda, active cooperation between educational institutions and the community should be encouraged.

Demonstrating how people from all professions or stages of life can come together to study and take action in the search for sustainable futures is the idea of cooperation

and education for all, the idea behind the “Accelerating sustainable solutions at local level” priority.

As mentioned before, the last part of the interview was addressed to information/opinions/aspects that the responders considered important to be mentioned. Most of the comments are on the direction of sustainable development and that it will require time to achieve the goals of the SDGs.

RHEI5: “The HEI is acting in the direction of sustainable development. We are at the start of a department development that will be responsible for overseeing the implementation of policies, awareness campaigns, activities for teachers and students, that can all contribute to ESD.”

RHEI23: “Although we did not have a dedicated structure for sustainable development, we tackled these issues in every management plan developed for the university, and on top we changed and we are still in the process of changing some inside policies that can only lead to future development”

RHEI37: “We are taking some steps in the area of sustainable development, and we started this process through becoming a part of a consortium that can mean a good practice example, because through meeting/project, we can bring closer the element that can contribute to achieving the goals for every priority”.

Other aspects that were mentioned by the responders were related to the willingness of teachers to change their teaching style. More than half of the respondents said that there are gaps between younger teachers compared to older ones. The desire to grow, to learn new ways of teaching, to apply various methods, or to change overall can be seen most of the time in teachers between 25 and 45 years old, unlike those over 45 years old who are used to doing things in a certain way.

RHEI16: “A desire for a new teaching environment or to adopt another teaching method was expressed by our younger teaching staff. They mentioned the need for upgrading the environment that can also fulfill the needs of the socio-economic domain.”

RHEI41: “When you try to change the teaching environment of a professor, is like you are diminishing his entire life’s work. Most of the time, unfortunately, they do not see it as an evolution, but rather as a step back, and not just this, but as way of saying we don’t need you anymore.”

It seems that from the free answers given, an opinion that is mainly the same for every responder is that teachers need to improve their digital skills. The COVID-19 pandemic contributed to this, forcing them to learn, but there is still a lack of experience related to digital skills.

RHEI8: “Although most of us use electronic devices every day, this does not mean that everybody knows how to use them. In our HEI, a need for digital skills development which is on our short-term goals has been identified.”

RHEI19: “I am sorry to say this, but during the COVID-19 pandemic most of the teachers started using for the first time an e-learning platform, which was highly reflected in the quality of the teaching process. There were cases where everything would work just as it should have, but there were cases where it required training and even then, there still were elements unknown.”

The last thing that needs to be mentioned is that some of the responders said that they are aware of the commitment that is needed for sustainable development, but the lack of action of the leading authorities enforces skepticism when considering the future of education for sustainable development.

RHEI26: “I don’t think that the HEI alone will succeed in reaching the goals of the five priority areas, this can be possible just together with other leading authorities”

RHEI33: *“The Education Ministry should clearly contribute to the objectives set for education regarding sustainable development. Not just that, but emerging trades should be taken into consideration when trying to improve the curriculum. Also, the business environment should be a part of this transformation, together with specialists from the socio-economic environment.”*

5. Discussion

Most European countries are on the right track when considering the transition to ESD, but there are still numerous obstacles to overcome, which can only mean that there should be more coordination across all education stakeholders to improve the transition to ESD, especially for low-performance countries [66].

The results reveal the need for greater attention on all aspects related to sustainable development. Even though significant steps to improve the education system towards sustainable development have been achieved, there is still room for improvement. As mentioned by the responders, not every institutional framework considers all five priority areas of ESD identified by UNESCO. Thus, as RHEI9 stated, *“the framework needs additional improvement to answer all areas and to be able to obtain all the aims desired also in the 17 SDGs”*. As a result, a framework with relevant measures should be taken into consideration for tracking the EU27’s progress towards efficient ESD. The elements that together constitute a priority chosen for each line of intervention are intended to capture both quantity and quality, and by including both, our notion differs from existing conceptual frameworks [28].

In Romania, access to education is unlimited because a sustainable society is built on a sustainable education system. Adults and children alike are motivated to advance their knowledge and abilities [67]. Thus, both priorities two and three can be fulfilled due to the education culture that is prepared for a long-lasting future, as the responders mentioned. RHEI31 said that the desire to change the future through building capacity and attractive learning environments is a part of the teachers’ values. Unfortunately, the budget allocations make it impossible to compare Romania to other European countries in this regard [68]. The need to empower the young generation and make them the factors of change can be achieved through the teacher’s capacity [62].

Although in previous research papers, the results revealed no interest in adding ESD competencies to the curriculum [69], now, through partnerships or by adding to their strategy in the University Charter for Sustainable Development, steps have been taken in this area [70]. The overcrowding of curricula, the apparent lack of significance to the curriculum, educational legitimacy, and limitations are cited as the key causes of institutions’ unwillingness to participate in sustainable education [62]. According to other researchers, for universities to become the drivers of sustainability issues and change agents, they must make sure that the needs of both the present and the future generations are better understood and built upon. This will allow professionals and teachers with expertise in SD to educate students of “all ages” in ways that will support the shift to “sustainable societal patterns,” as stated in frameworks [52–54,63,71,72]. Moreover, these findings are in agreement with our research and with the statements made by responders, that teachers must build their capacity and acquire the training they need to be able to contribute to change (just 27% of lectures include sustainability principles; a wide range of responders—more than 84%—are not aware of if the HEI is providing lectures related to SD; more than 39% of HEIs do not provide the requisite motivation necessary for addressing sustainable development issues). Moreover, teacher skills and professional improvement were addressed in this paper [73], revealing an interest in the study by the participants to discuss practices, teaching methods, and SD principles that can be integrated into ESD, which is in accordance with our findings—more than 63% of the teachers embracing change.

Regarding priority 4, it must be said that many young people in rural regions believe that migrating to the city is a better alternative for a better life, since they see the alternative as the more difficult option [74]. The UN, through its studies and activities, revealed that volunteering can be considered a method to develop pertinent skills and capacities able to

guarantee that the Sustainable Development Goals are implemented in an inclusive and localized manner. As a result, in some regions of the world, there have been requests for the inclusion of volunteerism in the academic curricula, to encourage civic engagement and student leadership from an early age [75]. Our findings also show that unfortunately, the students are not that involved in local community activities or campaigns that can lead to sustainable development (priority 5 results). Moreover, this is consistent with results from other countries, for example, Sweden, where, according to a study, the results showed the need for ecosocial youth empowerment, which urges individuals to connect to social work practice, in order to have a greater understanding of both youth empowerment through SD and ecosocial work [76]. Moreover, our findings are in accordance with other results related to the development of sustainability abilities as strategies for navigating the diversity of the present era, which need to be aided by university degrees, youth empowerment, and community activity [42].

As mentioned before, HEIs can be the drivers of sustainability, not just through their teachers and students, but also through research. HEIs can shape a new path for the future of the world by delivering innovation to society [77]. According to researchers, a solution to benefit both the community and the HEI is “Living Labs” [59–61,77–79], which can ensure the connection between the socio-economic environment and the university in order to identify research and innovation opportunities, problems that could be solved, the development of strategic projects, etc. The partnerships appeared in our results as being addressed by the HEIs, which showed that over 84% have developed specific partnerships. Our findings are in accordance with UNESCO’s desire for the transformation of education, because by bringing together a range of stakeholders from most areas, a solution for sustainable education can be achieved and implemented [1,2]. Regarding research and innovation, just 58% and 52%, respectively, of the responders mentioned that their results can be found in the development of local-level areas, although more than 82% of the responders mentioned that their HEI’s innovation can contribute to sustainable development [80]. Moreover, awareness campaigns for the local/regional/national community can be considered an element of social marketing techniques that can lead to changes in thinking and behavior towards a specific social problem. Thus, a need that needs to be addressed, which resulted from research, is the lack of local-level training or campaigns for SD awareness, which, in turn, affects long-term SD change.

6. Conclusions

The SDGs’ implementation, socioeconomic recovery and progress, efforts to empower and develop societies in need, and the sustainability of any possible advancements prompted by the SDGs will all be impacted by the neglect of higher education. Without education that utilizes correct methods, tools, and objectives and equally targets all society segments, sustainable socioeconomic empowerment is difficult to attain.

Therefore, the analysis based on the five priority areas for ESD, identified by UNESCO in HEIs, sought to highlight the steps made by HEIs in creating an environment that can answer the challenges and meet the targets for sustainable development.

The study revealed a few implications and also several aspects that need improvement. Regarding the acceptance of change, both teachers and students are willing to embrace new skills and teaching abilities that contribute to the creation of new learning environments.

Regarding the implementation framework and adopting policies, there is still room for advancement and creation, mainly by decision-makers, which will affect HEIs’ policies in the future, in order to respond to emerging sustainability challenges.

Regarding the transformation of learning environments, it can be said that improvements in HEI curricula will help in answering the characteristics/skills/abilities needed for emerging traits, which, in the context of Industrial Revolution 4.0, automation through digitization, are subjected to permanent technological transformations, requiring a complex set of skills. The ability to adapt will bring society closer to sustainable development. For this objective, HEI teachers need to build their capacity, because their digital skills need

improvement, and the HEIs need to provide the required motivation to address sustainable development issues; in one word, to “invest” in the academic community.

For the last priority, it can be said that the study revealed very few implications from HEIs in local community development, although they do contribute to solving issues through innovation. A good start can be seen through the high percentage of developed partnerships, which will lead to sustainable development.

Future research is recommended, and the study needs to be redone by applying the interviews to people inside the HEIs who are a part of developing sustainable development strategies or are involved in the decision-making process related to SD. The proper knowledge about ESD and its implementation inside HEIs will provide valuable insights as to the future steps that HEIs should take and, through best practices if there are any, how to take them.

This paper presented the situation of ESD in the academic community, with no authority point of view (professors, researchers, assistant professors) and the limited knowledge that these people have in relation to HEIs’ strategies for ESD. This article simply aimed to emphasize the current state and thus open the door for contemplation and future investigation, which the authors plan on realizing if decision-makers agree to be interviewed. By adopting sustainability into campus events including education, science, and infrastructure, one can implement sustainable university principles.

Furthermore, future research should examine whether some of the actions intended to help with achieving ESD really had an impact, and also to question and find if the adaptation of the curriculum changed the concept of SD for both teachers and students. Moreover, society overall is another path to follow for future analysis.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/ijerph192013363/s1>, Interview architecture.

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Review

Effective Valorization of Anaerobic Digestate—A Sustainable Approach to Circular Economy

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Abstract

Lately, anaerobic digestion has become a promising method for producing bioenergy from organic waste and is considered a model of the circular economy. At the same time, the concept of circular economy has gained particular attention in environmental policy agendas supporting the transition towards climate neutrality and the promotion of clean energy sources. Although the main objective of anaerobic digestion is to produce biogas, a significant part of the used substrate is converted into digestate, a by-product. Digestate is composed of organic and inorganic matter, which are considered dangerous contaminants for the environment if not properly treated, but also potential renewable resources if properly recovered. Digestate has enormous potential as an organic fertilizer, soil improver and landfill cover soil, but its disposal and use present significant challenges. The main aim of this review paper is to present the current routes for solid and liquid anaerobic digestate valorization according to circular economy principles and to highlight the relation between anaerobic digestion processes and circular economy models. It further focuses on the aspects regarding anaerobic digestate processing technologies, standards and regulations for digestate use and environmental benefits of its use as soil fertilizer.

Keywords: digestate valorization; anaerobic digestion; circular economy; sustainable development; sustainable agriculture



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1. Introduction

Lately, global waste generation has increased dramatically, with the main contributing factors being human population growth, accelerated urbanization, rapid industrialization and numerous anthropogenic activities [1]. Statistics show that more than two billion tons of municipal solid waste are produced annually worldwide, and this amount is estimated to increase by about 70% by 2050 [2]. This massive increase in waste contributes significantly to environmental degradation and has become a worldwide concern [3,4].

In addition, the burning of fossil fuels, improper waste disposal and unsustainable agricultural activities pose a threat to the future of humanity and ecosystems [5].

Improper waste management practices, including uncontrolled waste disposal, continue to remain a global threat to climate change. In this context, the implementation of

effective waste management techniques is essential to reduce the amount of waste land-filled, thus contributing to a sustainable future [3]. Waste management plays an essential role in supporting the principles of sustainable development, as can be seen in various international directives and agendas, such as the 2030 Agenda, Transforming our world: the 2030 Agenda for Sustainable Development [6,7]. In addition, the concept of circular economy is strongly linked to sustainable development, focusing on continuous resource use, minimizing waste and maximizing resource efficiency [8].

In this context, worldwide, many countries have established targets to decrease waste disposal and increase recycling rates, transforming organic waste into bioenergy. In the European Union (EU), anaerobic digestion (AD) and composting are the most popular methods for treating organic waste [9]. AD is a well implemented and widely utilized technology used both for treating sludge produced in wastewater treatment plants and for managing organic waste [10]. Thus, AD is positioned at the intersection of wastewater treatment and effective management of organic waste, offering an integrated approach for both the valorization of organic waste and the generation of renewable energy.

In comparison with thermal and chemical methods, AD represents an effective solution for organic waste valorization, due to its merits, such as reducing the environmental impact by minimizing the volume of stored waste and energy recovery. In addition, AD is also used as a treatment method for stabilizing sewage sludge [11]. In the AD process, organic substrates are decomposed by complex microbial consortia to produce biogas, a renewable energy source, and a nutrient-rich digestate as by-product, which can be used to produce bio-based fertilizers [12–14]. The biogas and digestate are the most promising alternatives to fossil fuels and biofertilizers. Furthermore, the AD process provides a practical approach to waste management, energy recovery and nutrient recycling, being in accordance with the EU directives involving waste reduction and recovery and promoting clean technologies. Thus, AD is a promising solution that combines several economic and environmental benefits [15–17]. The specialized literature includes studies focusing on the anaerobic digestion process of organic waste and digestate production, as well as their integration into the circular economy. Seruga et al. [9] presented an anaerobic digestion method as a component of circular bioeconomy. Their results indicated that the average biogas production rate of 120 Nm³/ton of fresh waste can be achieved. Furthermore, the reduction of CO₂ emissions was between 25.3 and 26.6% total, considering the fact that using biogas is environmentally friendly. In his review article, Huang X. [10] highlights the importance of the circular economy in achieving low-carbon goals. In addition, the author presents a comprehensive overview of the advances and challenges of anaerobic digestion technology in waste treatment plants, identifying critical challenges, such as high investment costs, technical inefficiencies, and regulatory barriers, particularly in developing countries. In another paper, Rizzioli et al. [13] reviewed several technologies in terms of nitrogen recovery for various bio-based fertilizers.

In 2020, according to data provided by the European Biogas Association (EBA), over 20,000 biogas installations were operating in Europe. Furthermore, EBA has estimated the total amount of digestate produced in Europe for the years 2030 and 2050; namely, 75 million tons (Mt) of dry matter (DM) of digestate can be produced by 2030, while 177 Mt DM is the total digestate potential for 2050 [18,19]. Due to its properties, the main utilization of digestate produced in biogas plants is as a bio-fertilizer in agriculture, but, depending on the application type, different processing techniques, such as solid–liquid separation, dehydration, biological and thermal processes may be required [20]. However, without proper treatment, the discharge of digestate threatens the environment and produces significant amounts of greenhouse gas emissions. [21]. Other significant environmental risks associated with untreated digestate include the potential presence of pathogenic

microorganisms, heavy metals—particularly in digestate produced by biogas plants that process sewage sludge—and antibiotic resistance genes, especially when antibiotics have been used in the treatment of sick animals [22,23].

The main aim of this review paper is to present the current routes for solid and liquid anaerobic digestate valorization in accordance with circular economy principles and to highlight the relationship between AD processes and circular economy models. It further focuses on the aspects regarding anaerobic digestate processing technologies, standards and regulations for digestate use and environmental benefits of its use as soil fertilizer.

2. Anaerobic Digestion and Circular Economy Model

The concepts of waste management and circular economy are interconnected, and both are essential for promoting sustainable development. Today's economy mainly follows a linear model, based on the "take-make-use-dispose" principle, in which resources are extracted, utilized and ultimately disposed of as waste. The transition from the current linear economy to a circular one involves extending the life cycle of products through actions such as reuse, repair and recycling. The implementation of the circular economy concept is based on preventing and minimizing waste generation [24,25]. This means that this concept is based on the fact that waste generated from a technological process can be used as raw material for other processes, which supports the notion of waste elimination. Thus, adopting a circular economy model allows for the assessment of the degree of circularity in waste management, while also promoting sustainable development [26]. In 2020, the European Commission adopted the circular economy action plan, aiming, among other objectives, to promote the use of secondary raw materials, what will support sustainable development [27].

Different strategies have been proposed to support the transition from linear to circular economy. The concepts supporting these strategies include, among others: sustainable and eco-friendly product design, energy efficiency, the application of the 3R's strategy (reduce–reuse–recycle), sometimes extended to the 9R's strategy (refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle or recover), and industrial symbiosis (by-products of one industry form raw materials for another industry) [28–31].

Applying the circular economy concept also promotes environmental protection while supporting economic growth, in line with sustainable development [32]. Thus, a sustainable way to mitigate current environmental challenges is to turn waste into renewable energy [5]. The waste valorization process allows the integration of circular economy principles, based on the conversion of waste into valuable products, thus leading to a considerable reduction in the carbon footprint [33].

The EU's energy and climate policies have encouraged the promotion of renewable energy resources. The Renewable Energy Directive (RED II) [34] and the EU Action Plan on Circular Economy [27] promote both the sustainable use of biodegradable waste and the transition to renewable energy sources such as biogas. In this context, AD has become one of the most promising methods to recover energy from organic waste. In Europe, biogas is produced by anaerobic fermentation in anaerobic digesters using agricultural waste, municipal organic waste, manure, energy crops and sewage sludge as feedstock [9,35]. The process of AD not only generates energy from biogas but also helps reduce greenhouse gas emissions, recover nutrients and reduce dissolved oxygen, thus contributing to the achievement of SDGs [36].

Biogas serves as the primary vector for producing bioenergy from organic waste through anaerobic digestion (AD) in the modern bioeconomy [37]. This process not only generates renewable energy but also yields a by-product known as digestate—a solid–liquid residue with a high moisture content and rich in nutrients. As a result, AD contributes to the

production of a stable and agronomically valuable organic fertilizer [5,38]. The valorization of organic waste through AD aligns with circular economy principles by transforming waste into bioenergy and value-added products, thereby supporting the transition to a low-carbon future [37,39]. Consequently, the overall sustainability of AD plants relies not only on energy production but also on the efficient and responsible management of digestion residues [40]. In particular, the high water content of the anaerobic digestate leads to high transportation volumes and costs, transportation distances depending on the location of the biogas plant [41]. Consequently, sustainable digestate management systems need to be developed, including options for digestate processing within the biogas plant or ex-situ digestate processing [42]. To overcome this limitation, the digestate is separated into two phases: the liquid fraction and the more fibrous solid fraction, to decrease the volume and, hence, the transportation cost [43]. Digestate is frequently used as a soil amendment due to its nutrient content or as a substrate for pyrolysis and gasification processes to produce biochar. However, the variety of microorganisms found in digestate may help to increase the range of possible uses for it. Digestate has proven to contain agronomically beneficial microorganisms, such as nitrogen-fixing bacteria, denitrifying and nitrifying bacteria, saprophytic fungi and soil methanogens. Moreover, microorganisms obtained from digestate can also be used in the soil bioremediation process, due to their ability to degrade aliphatic hydrocarbons from oil-polluted soils [44]. Based on corn production, the liquid digestate fraction from food waste, corn silage co-digestate and swine manure can replace commercial N fertilizer with greater environmental advantages, particularly for soil health. In addition, the liquid fraction of the digestate can be diluted and used as a medium for the cultivation of micro- and macroalgae, which are subsequently used as feedstock for biofuel production. On the other hand, the solid fraction of the co-digestate can be composted to enhance the quality of the digestate [45].

3. Anaerobic Biogas Digestate: Production and Processing

AD is a biological process where microorganisms break down organic matter (such as agricultural residues, food waste, animal manure or sewage sludge) in the absence of oxygen, producing biogas (a mixture of methane and carbon dioxide) and a nutrient-rich residue called digestate [46].

Most biogas plant owners are mainly focused on maximizing revenues from biomethane or electricity production, while digestate is considered a by-product. In line with this, the EU has introduced, within the Circular Economy Package, essential principles for sustainable digestate management. Thus, from a circular economy perspective, the nutrient and stable organic carbon content of digestate are valuable resources that can be recovered [47,48].

The digestate resulting from the AD process is taken out of the digester tank and placed in special containers. It is essential to note that the amount of produced digestate is directly related to the quantity and type of utilized substrate for biogas production, their susceptibility to decomposition, as well as the technologies used for pretreatment and fermentation. The quantity of digestate produced usually represents 70–90% of the feedstock weight [49]. Moreover, the composition of biogas digestate varies depending on the feedstock used for digestion, the process conditions and the efficiency of the AD process [50]. However, the composition of the anaerobic digestate is influenced by various factors, including the operating conditions of the biogas plant, how the digestate is stored and, most importantly, the substrate used [51]. The type of substrate used in the anaerobic digestion process is an essential factor in biogas production, as it can determine the efficiency of the process, but also the properties of the digestate. The main types of feedstocks used in digesters are animal manure, agricultural residues, food waste, energy

crops, wastewater sludge and the organic fraction of municipal solid waste. Apart from used feedstock, temperature and pH represent other important parameters that determine the efficiency and stability of the anaerobic digestion process. The optimal temperature range for the mesophilic regime is between 35 and 40 °C, while that for the thermophilic regime is between 50 and 55 °C [50]. The optimum range for the substrate pH is between 6.8 and 7.5.

Typically, anaerobic digestate contains organic compounds (carbon (C)) that could not be degraded in the fermentation process, macronutrients (such as nitrogen (N) and phosphorus (P)), micronutrients (potassium (K), sodium (Na), calcium (Ca) and others), organisms' biomass and water [21,52]. The moisture content of the digestate is influenced by the AD process type, which can be wet or dry [53].

To prevent environmental risks, anaerobic digestate must be treated appropriately, as it may contain heavy metals, such as cadmium (Cd), chromium (Cr), copper (Cu), lead (Pb), nickel (Ni), zinc (Zn) and arsenic (As), and generates greenhouse gas emissions [54].

For example, Golovko et al. [55] examined the characteristics of anaerobic digestate based on food waste from three biogas plants in Sweden. The heavy metal concentrations reported by the authors for the tested biofertilizer samples are presented in Table 1. These values were compared with the European Union standards specified in Regulation (EU) 2019/1009 for organic fertilizers [56].

Table 1. Heavy metals concentrations in digestate and comparison with EU limit values [55,56].

Parameter	Measured Value [55] (mg kg ^{−1})	EU Standard Limit [56] (mg kg ^{−1} Dry Matter)
Cadmium (Cd)	0.34–0.37	1.5
Copper (Cu)	41–100	300
Zinc (Zn)	180–540	800
Lead (Pb)	2–7.4	120
Nickel (Ni)	7.2–15	50
Mercury (Hg)	<0.1	1

The anaerobic digestate produced annually in a typical 1 MWe agricultural biogas plant can reach tens of thousands of Mg. These are huge quantities that can be managed profitably [57].

Generally, there are three types of anaerobic digestate, namely the solid fraction (rich in C and P), the liquid fraction (rich in K and N) and whole digestate (combination of the two fractions in sludge form) [38,58].

Depending on the substrate used, digestates are classified into two different component material categories (CMCs) [13]:

- CMC 4 for digestates derived from crops exclusively intended for biogas production (e.g., energy crops);
- CMC 5 for digestates derived from (i) biowaste according to Directive 2008/98/EC [59] and (ii) derived products according to EU Regulation 1069/2009 [60], which includes, among others, manure and digestion residues.

3.1. Solid–Liquid Separation

Separating anaerobic digestate into a solid and liquid fraction is a simple and economical process that is often performed prior to any additional digestate post-treatment [61]. The solid–liquid phases are obtained by separation processes using mechanical separators, centrifuges, stripping, drying or evaporation [38]. Thus, solid–liquid separation represents the first step in digestate processing. The separation of anaerobic digestate results in two

phases, namely a liquid fraction with a higher moisture content and a solid fraction, which is a fibrous material with a lower moisture content. Both need to be stored and handled separately [62].

Thus, after the solid–liquid separation, the liquid fraction of digestate was found to contain a high percentage of organic N and K in the form of K ions and ammonium, and the solid fraction of digestate contained a high content of P and N [50,53,63].

A few of the most popular mechanical separators used for digestate separation are the belt press, sieve drum, screw press, sieve centrifuge and decanter centrifuge. Figure 1 presents two of the most common equipment used for liquid–solid separation of the digestate, namely the screw press and the decanter centrifuge. The working principle of the screw presses is based on separating particles by their geometric dimensions. This means that the digestate is forced through a sieve with a mesh that only allows liquids and solid particles smaller than the mesh size to pass through; they will form the liquid fraction. In the case of decanter centrifuges, the separation is based on the particle's density. Thus, the digestate is fed into a rotating drum and an internal screw conveyor leads the solid particles to the solids discharge port. Comparing these two pieces of equipment, it can be concluded that decanter centrifuges are able to recover smaller-sized particles than screw presses [64].

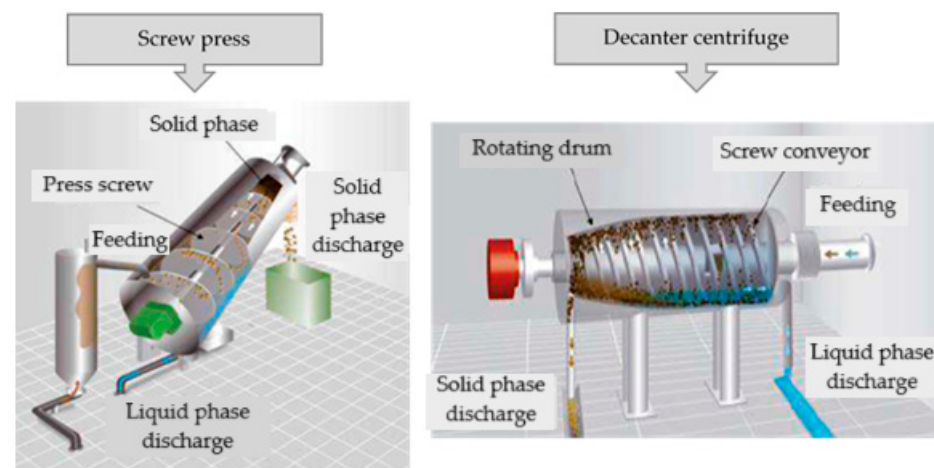


Figure 1. Schematic diagram of solid–liquid separation by screw press and decanter centrifuge (adapted from [65,66]).

Carraro et al. [41] reported that centrifuges are able to separate 60% more DM and total P than screw presses.

Chemical methods, such as precipitation and flocculation, allow the formation of larger particles and thus aid in the separation phase. Thus, the performance of solid–liquid separation can be improved by adding different products into digestate, such as flocculants or organic polymers (acrylamide) and precipitating agents (ferric sulfate, $\text{Fe}_2(\text{SO}_4)_3$; aluminum sulfate, Al_2SO_4 ; ferric chloride, FeCl_3 ; and lime $\text{Ca}(\text{OH})_2$). Furthermore, functionalized chitosan may be used to increase the effectiveness of solid–liquid separation, according to recent research [38,67–69].

Another solution for digestate processing is to dry the digestate. The method can use the heat generated in cogeneration, but this solution is rarely used since raw digestate has a high moisture level. Another attractive method is digestate thickening using an evaporator that rapidly evaporates water under low pressure at temperatures below 60–75 °C [49].

Several separation techniques were tested, and the efficiency of solid–liquid separation and the quality of the fractions were evaluated [23,62,70]. Nowak's research regarding the screw presses showed that there is a strong relation between the dry matter concentration

of the digestate and how well it can be separated. It showed that only around 60% of the original liquid fraction can be extracted. However, when the pulp has a dry matter content of 5%, up to 95% of the liquid fraction can be separated [23]. Lyons et al. [62] evaluated two mechanical separation technologies (screw press and decanting centrifuge) that could be used in the agro-zootechnical and AD sectors for enhancing manure sustainability and improving anaerobic digestate management. According to the study's conclusions, screw press separation is the more cost-effective choice when approving the export of small quantities of P off-farm. On the other hand, decanting centrifugation is an effective option if greater amounts of P removal are needed.

Tambone et al. [70] studied the effect of solid–liquid separation of anaerobic digestate on DM, nitrogen (TKN), phosphorus (P_2O_5) and heavy metals distribution into these two phases. After chemical characterization, the authors reported that liquid fraction can be used as a substitute for mineral N fertilizers because of its high N content, while solid fraction can be proposed as an NP-based organic fertilizer.

3.2. Digestate Fractions: Liquid and Solid

The liquid fraction of anaerobic digestate may contain a higher proportion of macro- and micronutrients; however, it is not recommended to apply it directly to the soil because of the presence of pathogens (such as *Salmonella* and *Campylobacter*), greenhouse gas emissions, odors, phytotoxic volatile fatty acids and high humidity (70–80%), which make soil application difficult [50].

Akhlar et al. [71] analyzed how substrate origin, process parameters and solid–liquid separation techniques affected the residual compounds in the liquid fractions of digestate. According to the authors, the used substrate and the combined effects of the solid–liquid separation method mostly affect the characteristics of the residual organic matter in the liquid fractions of digestates. The liquid fraction of the anaerobic digestate can be used to dilute the new amount of feedstock fed into the biogas plant reactor. In this way, the beneficial microorganisms involved in AD are added to the process, in addition to saving large amounts of water [49]. Moreover, its richness in micronutrients, organic matter, and plant macronutrients such as N, K, P and sulfur (S) makes it excellent plant fertilizer [67].

In parallel, the solid fraction, also known as pressed cake, concentrates nutrients, mostly organic N and P, and DM (between 20 and 30%) and is usually applied as a soil fertilizer [61]. In order to improve the safety use of digestate, many treatment methods have been proposed [38,45,72]. For example, the solid fraction of digestate can be converted into biochar by thermal treatment (gasification and pyrolysis), or biostimulants such as humic and fulvic acids can be obtained. Biochar is a solid product with a porous structure that can contribute to climate change mitigation by sequestering CO_2 , making it a valuable product. When added to soil, biochar improves microbial activity, water holding capacity and nutrient retention [38]. Composting digestate is another way to add value to it. This method reduces the number of pathogens, increases biological stability and produces organic fertilizers that can be used in agriculture [45].

On the other hand, depending on the type of anaerobic digestion process used for biogas production (wet or dry fermentation), the resulted digestate can be classified as wet or dry. Wet digestates are flowable and can be applied to fields for fertilization, since wet digestion techniques are used for substrates with total solid concentrations less than 10%. Dry digestion methods are used for materials that have a 15–35% total solids concentration. Dry digestate is richer in nutrients and fiber, making it suitable for processes such as composting [72].

Thus, the two separated fractions of anaerobic digestate, the solid and liquid fraction, support the circular bioeconomy and sustainable agricultural practices.

4. Anaerobic Digestate Valorization According to Circular Economy

The growing number of biogas plants throughout Europe is creating an increasing issue in digestate management [73]. In the EU, about 180 million tons of digestate are produced each year. The majority of the digestate generated (120 million tons) comes from agriculture; the organic component of urban solid waste produces approximately 46 million tons; at least 7 million tons comes from biowaste separated by source; and sewage sludge and by-products from the agri-food sector provide about 1.7 million tons each [61].

As the volume of digestate from biogas plants increases rapidly, it becomes imperative to develop effective protocols for its handling. The strategic location of local biogas plants near areas with large amounts of organic waste facilitates efficient collection from regional producers. In addition, the resulting digestate can be used to enrich the soil of surrounding farms, thus reducing transportation costs [50,74]. For digestate from biogas installations to be classified as a ‘product’ and not ‘waste’ and to comply with the regulations, it must undergo biological or physico-chemical treatment [75]. Due to its high micro- and macronutrient content, anaerobic digestate is an optimal alternative for reducing the application of chemical fertilizers. However, digestate may affect soil and growth of plants if it is used incorrectly. For example, applying digestate too early, combined with a prolonged retention period in the soil before plant uptake may result in nitrate (NO_3) emissions into groundwater or nutrient loss and migration to deeper soil layers [76]. Moreover, the concentration of nutrients in the digestate is variable and an excess of a particular element can lead to soil pollution [38]. The presence of pollutants such as pathogens, heavy metals, pesticides and steroid hormones can also pose a drawback for soil application (Figure 2) [77].

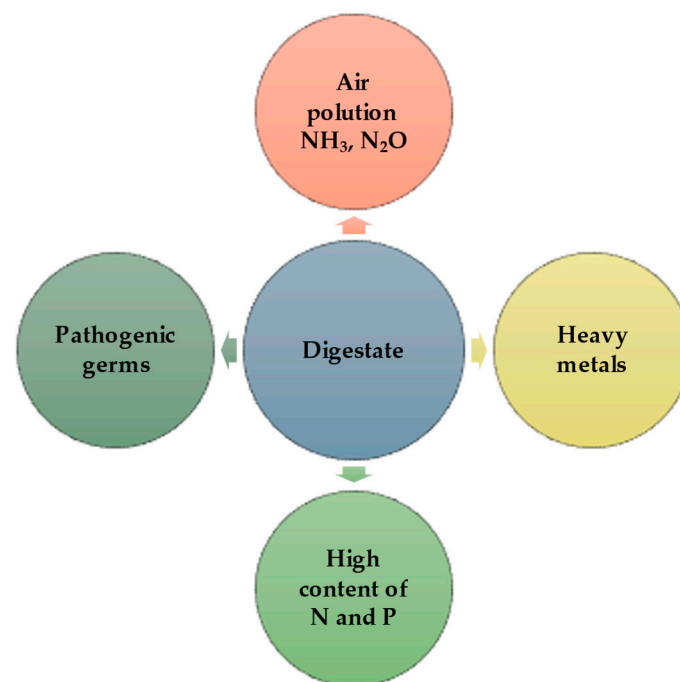


Figure 2. Environmental risks associated with the use of raw digestate (own creation).

In addition, transportation costs, nutrient surplus, market acceptance and seasonal agricultural demands are the main barriers to the use of digestate for agricultural purposes. Other disadvantages of the improper use of digestate are unpleasant odors and uncontrolled leachate flow into the soil and groundwater, emissions of ammonia or greenhouse gases such as carbon dioxide (CO_2) and methane (CH_4) into the atmosphere [78].

Consequently, studying different methods for the management and utilization of digestate is essential [75].

Treating digestate before application to the soil is fundamental to ensure its optimal use as a fertilizer. The processing of the solid phase includes methods such as composting, drying/pelletizing and thermochemical conversion (gasification, hydrothermal carbonization and pyrolysis). On the other hand, the liquid fraction can be treated using, among others, the following methods: membrane filtration, vacuum evaporation, ammonia stripping and struvite precipitation [61,63,79].

From the point of view of circular bioeconomy, field application is the simplest and most economical way to valorize anaerobic digestate. However, excessive field application of digestate can lead to N pollution and the eutrophication of the aquatic environment [54].

Apart from land applications, there are various ways to reuse digestate, as shown in Figure 3, depending on the quality and source of the raw material used in the anaerobic fermentation process, which defines the digestate's primary properties [21,80].

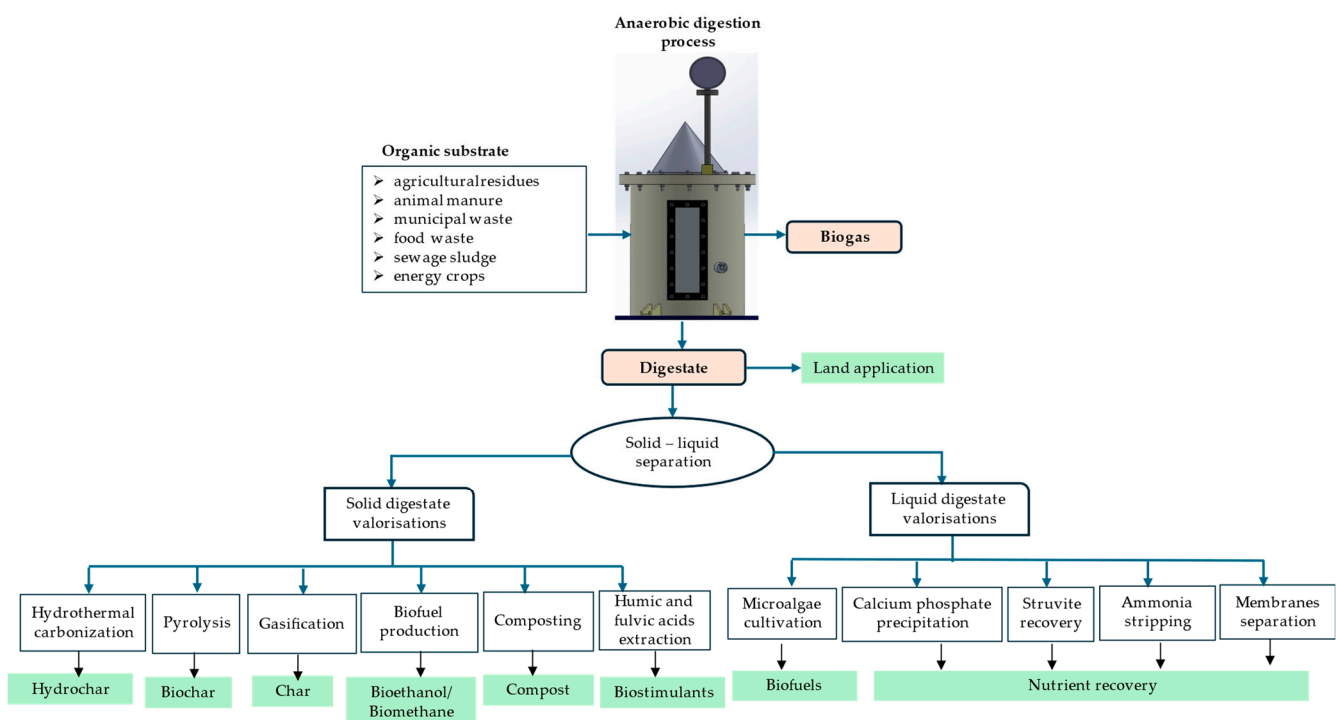


Figure 3. Directions of digestate valorization based on [38,50,54,81].

Proper digestate management is a key element in the efficient operation of biogas plants, reducing greenhouse gas emissions, odor problems and nutrient leaching [50].

4.1. Digestate as Fertilizer

Due to its high content of N, P and K, the most common use of anaerobic digestate is its application to the soil as a fertilizer and soil amendment [38,80].

Before being used as a fertilizer, the chemical composition of digestate must be carefully evaluated to avoid contamination of the soil and thus of the human food chain [76].

Numerous investigations have demonstrated that digestate is a valuable source of nutrients for agriculture [52,82], and that the digestate's chemical properties are mostly determined by the feedstock and the operating conditions of the anaerobic digester [83].

According to the study conducted by Panuccio et al. [84], two digestate fractions, liquid and solid, were investigated for their effects on tomato growth and the nutritional value of cultivated tomato fruits. The results demonstrated that both digestate types had

beneficial effects on tomatoes' nutritional content, as evidenced by higher levels of essential health components such as vitamin C, phenolic compounds and flavonoids. The authors reported that the solid digestate fraction obtained from a digester fed with animal manure, at a concentration of 20%, doubled the number of flowers compared to the control group. In contrast, the solid digestate fraction from a digester fed mainly with olive waste and citrus pulp had a significant effect on the leaf area, which registered a 150% increase compared to the control group.

In another study, Ferdous et al. [85] evaluated the effect of biogas slurry combined with synthetic fertilizer on tomato (*Solanum lycopersicum* L.) yield. The highest fruit yield was obtained, according to the authors, from the application of synthetic fertilizer and poultry bio-slurry. According to [86], the use of solid and liquid digestate enhanced plant growth in hydroponic baby leaf lettuce (*Lactuca sativa* L.) culture. Digestate has also been used in alfalfa cultivation, and analyses have shown an increase in the content of macro-nutrients in alfalfa leaves [87].

4.2. Thermochemical Methods of Solid Digestate Valorization

The main thermochemical methods of solid digestate valorization are pyrolysis, gasification and hydrothermal carbonization. Pyrolysis is a thermochemical process that produces non condensable gases, bio-oil, and solid carbon-rich residues (biochar) from organic materials in an oxygen-free medium [88]. Digestate has recently been used in the production of biochar, a process considered essential for reducing negative environmental impacts and increasing the financial viability of AD plants [89]. Due to its efficacy, the "slow pyrolysis" method is recommended for producing biochar, which enhances P availability and immobilizes metals [90]. Biochar has a very wide range of applications due to its sorption properties, including fertilization, composting, wastewater treatment and environmental protection. Biochar facilitates the absorption of nutrients and organic materials in soil, functioning effectively as a natural fertilizer [91]. In addition, biochar has been shown to improve digestate quality when added to AD processes, especially in terms of nutrients conservation, higher C/N ratio and decreased nutrient leaching [92].

In a study conducted in 2016 [93], Shariff and collaborators observed that the highest biochar yield is obtained at the lowest temperature. The same was observed in the paper [94]. Liu J. and colab. [89] evaluated food waste solid digestate resulted from AD process as a potential source for biochar preparation by pyrolysis. The authors reported that the obtained results offer a different approach for waste disposal resulted from the AD of food waste. Other studies indicate that biochar derived from solid digestate exhibits enhanced qualities in terms of raising pH and increasing adsorption capacity compared to biochar directly produced from raw biomass [95,96].

Gasification is another thermochemical method used to valorize anaerobic digestate. The gasification process takes place in the presence of an oxidizing agent at temperatures ranging from 600 to 1300 °C. The final products include tar, a condensable product, composed of aromatics compounds, a solid carbonaceous material with a porous structure called char, and syngas, a gaseous combustible product [88]. Gasification char is an economical alternative to activated carbon in multiple applications, such as catalysis and adsorption [97].

The hydro-thermal carbonization process involves heating biomass in a water environment at temperatures between 160 and 280 °C while applying pressure ranging from 2 to 10 MPa. In this process, the resulted products are a solid product, which is called hydrochar, liquid and gaseous phases. The hydrochar can be used as soil fertilizer due to the nutrient content, as solid fuel and as adsorbent for environmental remediation [98,99]. In another study [100], heavy metals in the digestate were effectively immobilized during hydrother-

mal dehydration and pyrolysis processes, which contributed to obtaining a quality biochar, with the optimal pyrolysis temperature being set at 500 °C.

Belete Y.Z. et al. [101] investigated the hydrothermal carbonization of raw manure and anaerobic digestate manure with water or whey as the liquid phase in order to recover energy and nutrients. The authors reported that manure hydrochar is suitable as an energy product, with energy properties similar to lignite (manure + water), while digestate hydrochar is more suitable for soil amendment. The results showed that among the produced hydrochars, the calorific value of the hydrochar derived from whey was the highest at 19.4 MJ kg⁻¹, followed by that obtained from manure and from digestate (16.0 MJ kg⁻¹). On the other hand, the hydrochar derived from digestate contained up to 1.8% phosphorus, which was higher than that of the hydrochar derived from manure, which reached a maximum of 1.5%.

4.3. Biofuel Production

An additional viable approach for the valorization of liquid and solid digestates is the synthesis of bioethanol via biological fermentation [77]. A few studies highlight the potential of anaerobically treated waste as a feedstock for bioethanol production, due to the remaining hydrocarbon components [102]. In study [103], digestate was used instead of fresh water and fertilizers in bioethanol production. The results showed that ethanol output increased by up to 18% compared to the production using freshwater.

Chen et al. [104] evaluated the effects of digestate recirculation on the performance of two-stage thermophilic–mesophilic co-digestion of swine manure and rice straw. The authors reported that digestate recirculation improved the performance of the two-stage anaerobic co-digestion by increasing the methane production by 9.92%. In addition, digestate recirculation improved the performance of the co-digestion process by increasing the abundance of *Methanosarcina* (from 4.1% to 7.5–10.7% and 35.7%). In another study [105], bio-hydrogen and bio-methane production from food waste were studied to observe the effects of digestate recirculation on energy efficiency and process stability. The results showed that stable hydrogen and methane production was obtained by the recirculation rate at 0.3. At this recirculation rate, maximum hydrogen and methane production were obtained (3 L L⁻¹d⁻¹ and 2.9 L L⁻¹d⁻¹). Compared to a system without recirculation, digestate recirculation reduced the need for alkali addition to maintain the pH in the H₂ reactor by 54%.

4.4. Compost Production

Composting is one of the most widely used and effective methods for stabilizing digestate and reducing the concentration of volatile organic compounds [50]. Digestate contains N and P, which are important for plant growth, so the resulting compost can replace or reduce the need for synthesized fertilizers. In addition, using compost instead of synthetic fertilizers saves energy and water used in fertilizer production [106]. However, the high moisture content and low C/N ratio of the digestate are factors that influence its efficient composting. Thus, mixing with different types of waste is necessary to enhance the digestate composition before composting [107]. Song et al. [108] investigated the co-composting of food waste digestate with sawdust and mature compost. Their results demonstrated that, within two weeks of co-composting, combining food waste digestate with sawdust, either alone or in combination with mature compost, can result in high-quality compost with a high seed germination index (>80%) and low NH₄⁺-N (<700 mg kg⁻¹ DM).

In other paper, Weldon and colab. [109] used biogas digestate, garden waste and biochar in the composting experiment. The authors reported that the addition of biochar

improves the digestate composting, without further negative effects on plants. Furthermore, using biochar decreased cumulative N₂O emissions by 65–70%, but it had no noticeable effect on CO₂ or CH₄ emissions.

4.5. Humic and Fulvic Acid Extraction

Humic substances are usually classified into three subcategories according to their solubility: humic acids, fulvic acids and humins. Among them, humic and fulvic acids are of interest because they can be obtained from anaerobic digestate. Humic substances are the most important natural soil improvers due to their ability to improve the chemical and physical properties of the soil, thus promoting plant growth [38,110].

The digestate resulting from AD processes is rich in both essential macronutrients (N, P and K), and humic acids, which play a fundamental role in ecological processes and terrestrial lives. Humic acid, used as a biostimulant in horticulture, can improve processes such as seed germination, root development and overall plant growth [111]. Biostimulants are defined as substances or microorganisms that have beneficial effects on the growth and development of plants, independent of any nutritional properties [112].

Humic acids contribute to stimulating root growth by supplying essential metals needed for plant development, while fulvic acids facilitate micronutrient mobilization and absorption, especially iron [113].

In the study by Anielak et al. [114] humic substances were recovered from digested sewage sludge. The recovered humic substances contained relatively high amounts of plant nutrients (including N and P), making them suitable for use as biostimulants.

In the work of Chaves et al., conducted in 2025 [112], the biostimulant properties of several fractions derived from raw digestate on winter rye were evaluated: humic and fulvic acids obtained through alkaline-acid extraction, their mixture (humic substances), the water-soluble fraction, as well as the raw and liquid digestate. The results demonstrated that, in hydroponic settings, the recovered fulvic acid greatly increased the winter rye's root DM (0.381 g plant⁻¹), root carbon quantity (163 mg plant⁻¹), root N levels (8.06 mg plant⁻¹) and its projected leaf area (80.5 cm²).

4.6. Nutrient Recovery

Mineral fertilizers of fossil origin have N, P and K as their main components. Given the non-renewable nature of the resources from which they come, the production of these fertilizers is considered unsustainable, raising concerns about their long-term availability [13]. In 2023, Europe used 9.3 Mt of mineral fertilizers (N and P) for agricultural production, which represents a 3.7% annual reduction and a total loss of 20.5% from the comparable peak in 2017 [115]. In this context, the agricultural digestate resulting from AD processes is recognized as a potential valuable material for the recovery and valorization of biofertilizers [13].

The recovery of nutrients from the anaerobic digestate involves several methods, such as vacuum evaporation, ammonia stripping, adsorption, struvite precipitation, membrane filtration and reverse osmosis. The performance of nutrient recovery methods varies depending on the type of waste, processing conditions and the specific recovery technology used [13,50,110]. The most widely developed technologies are ammonia stripping and struvite precipitation, which allow an average removal and recovery efficiency of 80–90% for both N and P [13]. Under current regulations, the recovery of nutrients from digestate is a priority for AD plants. Nutrient recovery from digestate can thus play a significant role in reducing dependence on mineral fertilizers based on N and P, while supporting the implementation of the principles of circular economy [116].

4.6.1. Ammonia Stripping

Ammonium (NH_4^+) is the main N compound in the liquid digestate. During the ammonia-stripping process, ammonia (NH_3) is separated from the liquid fraction of the digestate by means of a gas stream, usually air, in an ammonia-stripping reactor, which results in the transfer of NH_3 from the aqueous phase to the gaseous phase. The released NH_3 is removed in a chemical air scrubber by washing it with a concentrated acid solution, such as sulfuric acid or nitric acid. The reaction between NH_3 and sulfuric acid (H_2SO_4) leads to the formation of ammonium sulfate, and the reaction with nitric acid (HNO_3) generates ammonium nitrate. Having a high N content, both products obtained can be used as N fertilizers [117]. Brienza et al. [118] evaluated the performance of a full scale digestate processing cascade that includes an innovative vacuum side stream NH_3 stripping and scrubbing system. According to mass and nutrient balances, 57% of the ammonium N contained in digestate was recovered as 22% ammonium sulfate, while 7.5% was recovered in the form of a liming substrate. In another study, Abba et al. [119] investigated the performance and energy consumption of a full-scale ammonia stripping plant. Stripping tests were carried out on the liquid digestate fraction, and the results showed that AD coupled with stripping was a suitable solution for removing up to 81% of the NH_4^+ without the need for external energy input or reagent dosage. However, the efficiency of ammonia stripping depends mainly on pH, temperature, air–liquid ratio and feed characteristics. In 2022, ammonia recovery from anaerobic digesters via side-stream stripping was investigated by Palakodeti and colab. [120]. Ammonia recovery was controlled to maintain a constant ammonia concentration. During the experiment, methane yields of 60–80 mL (gVS.d)^{−1} and volatile fatty acid concentrations of 0–500 mg L^{−1} were reported.

However, ammonia stripping has been reported to be economically feasible only when ammonia N concentrations are greater than 1500 mg/L [121].

4.6.2. Struvite Precipitation

Struvite precipitation is an established method that is used mainly for P recovery. Struvite is a crystalline mineral composed of magnesium (Mg), NH_4^+ and phosphate (PO_4) with the chemical formula $\text{MgNH}_4\text{PO}_4 \cdot 6\text{H}_2\text{O}$. This product can be considered as a slow-release fertilizer [121,122]. Moreover, the struvite precipitation process facilitates the simultaneous recovery of NH_4^+ and orthophosphate, conditional on the presence of an external source of Mg [116].

Trotta et al. [116] tested a method which combines struvite precipitation and ammonia stripping to observe the efficiency of nutrient recovery/removal from cow manure digestate. Their results indicated that more than 60% of total P was removed as struvite, which can be used in N–P fertilizer, thus substituting synthetic mineral fertilizers. In a study published in 2023, Pepe Sciarria and collaborators [123] analyzed the possibility of P recovery in the form of struvite from the liquid fraction of digestate from pig manure, having a high total solid content. The study results indicated that at a total solids content of 4.5% and a molar ratio Mg/P of 2:1, the highest recovery of phosphorus was 85%, and that of nitrogen was 52%. Further, the authors assessed the generated struvite's fertilizing capacity by comparing it with poultry dung and traditional phosphate mineral fertilizers. Brassica rapa chinensis was used in agronomic experiments. Struvite showed comparable performance to conventional fertilizers in terms of N, total biomass and P (mineral fertilizers: 5.6; poultry manure: 5.7; struvite: 5.9 g kg^{−1}).

4.7. Microalgae Cultivation

Recently, the decline in fossil fuel resources, coupled with rising greenhouse gas emissions, has led to a transition to renewable energy sources, with a particular focus on microalgae biofuels [124]. During microalgae cultivation, in addition to water, CO₂ and light, nutrients must also be supplied. Thus, the cultivation of microalgae in the digestate resulting from the anaerobic fermentation process represents a sustainable alternative to the artificial nutrients currently used. However, growing microalgae on digestate is cost-effective, as it reduces the cost of nutrients needed for biomass growth, but it is still a challenge, as the liquid fraction of digestate is characterized by turbidity and bacterial contamination, which could negatively affect cultivation [125]. In this case, the liquid fraction of the digestate must be processed before its use as a nutrient source for microalgae culture. Depending on its composition, the most commonly used methods are centrifugation to remove solids and ammonia stripping and dilution for the adjustment of nutrient concentrations [126,127]. Fernandes et al. studied the performance of a digestate resulting from the AD of food and kitchen waste, treated by dilution, settlement and membrane processing technologies. The treated digestate was subsequently tested as a nutrient source for *Chlorella vulgaris* cultivation. The authors reported that the treated digestate was a suitable substrate to support the growth of *Chlorella vulgaris* [128]. In other studies [125,129], *Chlorella sorokiniana* and *Chlorella vulgaris* microalgae were cultured using ultrafiltered digestate.

4.8. Standards and Regulations for Digestate at EU Level

The aim of introducing the digestate management regulation is to protect human health and the environment by setting standards for the production and use of anaerobic digestate in certain applications [53]. Moreover, digestate management legislation is important for determining sustainable practices in the biogas industry [79]. Policies governing digestate at EU level include the Waste Framework Directive, the Animal By-products Regulation, the Fertilizers Regulation, the Nitrates Directive and the Sewage Sludge Directive [19]. The European Union approved legislation on biofertilizers in 2019 through the Fertilizers Regulation 1009/2019, which promotes safe circular digestate management [56]. The EU began regulating the application of digestate in 1991 with the European Council Directive (EC) concerning the protection of waters against pollution caused by nitrates from agricultural sources, also known as the Nitrates Directive. According to this directive, the amount of manure applied to the land each year shall not exceed 170 kg of N per hectare [130].

The existing EU regulation on fertilizers (EC, 2003/2003) [131] only stipulates the placing on the market, and therefore the trade, of mineral fertilizers in the EU market [74].

The European Union has set standards for certifying the quality of digestate. The main quality parameters in the standards include nutrients, heavy metals, pathogens, organic/inorganic pollutants and digestate stability/maturity. Most standards specify that digestate should include no more than two viable seeds per liter and no more than 0.5 g/kg of pollutants (plastic, glass and metal). In addition, to maintain hygiene, *Escherichia coli* should be less than 1000 CFU/g and *Salmonella* sp. should not be present in 25 g of fresh digestate [132,133].

Table 2 summarizes the relevant standards related to anaerobic digestate quality.

Table 2. Standards for digestate certification.

Standard/Certification	Description	Reference
Regulation (EU) 2019/1009 of the European Parliament and of the Council	Sets out the requirements for placing fertilizing products on the EU market, including limits for contaminants and product function categories (PFCs) of EU fertilizing products and component material categories (CMCs)	[56]
ECN-QAS (European Compost Network—Quality Assurance Scheme)	European Quality Assurance Scheme for Compost and Digestate	[134]
British Standards Institution (BSI) Publicly Available Specification (PAS110:2014)	Specification for whole digestate, separated liquor and separated fiber derived from the anaerobic digestion of source-segregated biodegradable materials	[135]
SPCR 120—Sweden	Certification rules for digestate from biowaste by the quality assurance system of Swedish Waste Management	[136]

5. Effect of Anaerobic Digestate Application on Agricultural Soil

As the application of mineral fertilizers on agricultural land is associated with a negative impact on the environment, more and more activities are focusing on the use of organic fertilizers [137]. Due to its high nutrient content, mainly N, anaerobic digestate can be successfully utilized as a fertilizer. Incorporating anaerobic digestate into the soil involves adding organic matter and N, which can increase the humification process [51,57]. Applying digestate as fertilizer not only closes the nutrient loop, but also reduces the demand for mineral fertilizer, which requires a high input of raw materials and energy for production [74].

The use of anaerobic digestate as fertilizer in the agricultural sector is a solution recommended by numerous studies conducted worldwide. In his study, Czekala [57] determined the content of total nitrogen (N_{tot}) and its selected fractions ($N\text{-NH}_4$, $N\text{-NO}_3$ and N_{organic}) in the raw and processed digestate derived from five agricultural biogas plants. The author reported that the tested digestate can be considered a multi-component fertilizer, with the content of N_{tot} in the tested samples ranging from 1.63 g kg^{−1} to 13.22 g kg^{−1} fresh matter.

Cichy et al. [138] used direct soil testing to analyze the influence of fish sludge and liquid digestate from the AD of food waste on the growth of *Lepidium sativum* and *Triticum aestivum* plants. According to the results, applying this digestate delayed the germination process and had a negative impact on the plants' early growth in the first days of the experiment, but this effect progressively diminished.

In another study, Slepetiene and colab. [51] showed that different rates of separated liquid and solid phases of anaerobic digestate influenced the contents of carbon and N in different layers of *Fluvisol*. The authors reported that the application of solid digestate increased the soil organic carbon content in the 0–10 cm layer, and the liquid digestate significantly increased the soil organic carbon content in the deeper layers, specifically the 20–30 cm layer. The treatment fertilized with 170 N rate of both digestates had a noticeably higher concentration of soil organic carbon in the examined soil layer (0–30 cm).

In another investigation, Jurgutis et al. [78] assessed the fertilizing potential and chemical composition of several types of digestates coming from eight agricultural biogas installations. The results obtained show that spreading solid and liquid digestate to low-fertility soils near biogas plants can increase the amount of biomass suitable for biogas by up to three times. In addition, the digestate's value was assessed to be between EUR 2.88 and 7.89 Mg^{−1} for liquid digestate and EUR 7.62 and 13.61 Mg^{−1} for solid digestate, based on the market prices of commercial fertilizers.

Nabel et al. [139] assessed the potential of the *Sida hermaphrodita* energy plant to grow in a marginal sandy soil. The authors used different fertilization treatments in their experiment, either digestate from biogas production or a commercial mineral NPK fertilizer. Their results showed that the anaerobic digestate was the best performing fertilizer because it produced similar yields as the NPK fertilization but minimized nitrate leaching.

6. Life Cycle Assessment and Greenhouse Gas Emissions in the Valorization of Anaerobic Digestate

Life cycle assessment (LCA) is a technique for evaluating the environmental impact of services and products, including the entire life cycle from the extraction of raw materials to the disposal of waste. For each stage of LCA, resource use, emissions and waste generation are quantitatively described. LCA has various uses, such as determining a country's waste treatment strategies [140]. LCA is an essential tool for optimizing digestate production by establishing impacts on the environment, promoting the transition to a circular economy through sustainable waste management and the generation of value-added products. In the case of anaerobic digestate production, LCA identifies emissions generated within the system during feedstock handling, digestate post-treatment, storage, field application, anaerobic digestion process and transport. These steps contribute significantly to energy consumption and greenhouse gas emissions [141].

In the literature, studies have been conducted to investigate the effects of anaerobic digestion on the environment. Some studies have compared anaerobic digestion methods with other solid waste treatment methods using LCA [142–145]. The anaerobic digestion process produces renewable energy and organic fertilizer, which can reduce greenhouse gas emissions from energy production, agriculture and waste management [146]. Compared to mineral fertilizers, digestate can be more environmentally friendly regarding the greenhouse gas emissions associated with the production of synthetic fertilizers. Sarec et al. [147] investigated the influence of two digestate application methods (disc injection and band spreading) on permanent grassland over a four-year period. Among the analyzed hypotheses, the authors investigated whether, independent of application technique, greenhouse gas and ammonia (NH₃) emissions increase proportionately with increasing digestate rates. The authors reported that disk injection reduced NH₃ emissions by over 66% on average, although this was in comparison to digestate band application. However, the most effective approach to minimizing emissions while maintaining good agronomic performance was the combination of split-dose fertilization and disc injection. The results showed that NH₃ and CO₂ emissions increased proportionally with the digestate dose. Regarding CH₄, the flux did not increase significantly with higher application doses.

Timonen et al. [146] used different techniques to evaluate the climatic emissions of the complete AD chain, from the purchase of raw materials to the use of energy and digestate. The authors conducted a life cycle analysis of three anaerobic digestion scenarios using pig slurry and various secondary feedstocks. The comparative analysis of the scenarios with different co-substrates showed that the highest total emissions associated with digestate were recorded in scenario S1 (8.4 kg CO₂ eq kg⁻¹ N), while the lowest were observed in scenario S2 (8.2 kg CO₂ eq kg⁻¹ N). Although the difference is modest, it highlights the sensitivity of emission outcomes to the chosen allocation method, particularly when 100% of the emissions during phase 1 of anaerobic digestion are attributed to energy production. In another study [148], the authors reported that compared with direct land application, mono-digestion of pig manure decreases direct greenhouse gas emissions by 48% (190 tons CO₂ eq). On the other hand, co-digestion with grass silage increases the total energy recovery by 226% (1592 MWh) compared to mono-digestion.

The authors of [149] investigated the decrease in greenhouse gas emissions that can be achieved by replacing mineral fertilizers with the digestate resulting from agricultural biogas plants utilizing various co-substrates. They reported that the calculated reduction in greenhouse gas emissions was 27.9–61.6 kg CO₂ eq Mg^{−1} of digestate. This indicates that fertilizing with a yearly quantity of digestate from the biogas plants being studied lowers emissions by almost 570 Mg CO₂ eq for the smallest biogas plant and by more than 3000 Mg CO₂ eq for the largest biogas installation.

7. Future Directions

While significant progress has been made in the valorization of AD within the framework of a circular economy, several technical, economic and environmental challenges remain unaddressed. Current limitations include the variability in digestate composition, the inefficiency of conventional separation methods, low nutrient recovery rates and the lack of standardization for end-use applications. Therefore, future research should prioritize the development of efficient, cost-effective and scalable technologies for the physical and chemical separation of digestate fractions, alongside advanced nutrient recovery strategies. Moreover, innovative pathways for generating value-added products—from biofertilizers and soil amendments to bio-based materials—should be explored to enhance market viability. Equally important is the integration of digestate into modern precision agriculture systems, supported by digital tools and site-specific application techniques, which can maximize nutrient use efficiency and minimize environmental risks. Furthermore, advancing the use of smart sensor technologies and real-time monitoring tools—capable of tracking key parameters such as pH, volatile fatty acids and ammonia—will be essential for improving process stability and enabling more responsive, data-driven control of anaerobic digestion systems. These advancements should be complemented by comprehensive economic assessments and the establishment of clear regulatory frameworks to ensure safe, sustainable and widespread implementation.

8. Conclusions

This review provided a comprehensive overview of sustainable routes for the efficient valorization of digestate resulting from biogas plants. Adequate digestate management is crucial for the effective utilization of nutrients and for environmental protection. This review contributes to the understanding of sustainable management of digestate generated from the anaerobic fermentation process in the context of the circular economy and carbon neutrality, providing perspectives for future research.

Lately, the AD of organic waste has been intensively promoted under the current EU legislative framework. In addition to generating renewable energy, this biological treatment method also permits the recycling and recovery of organic matter and nutrients contained in biodegradable waste. AD is considered a circular economy model that produces energy in the form of biogas from organic waste while recycling nutrients in the form of digestate. Discharging digestate without adequate treatment poses a threat to the environmental quality and leads to significant greenhouse gas emissions. Various methods, such as pyrolysis, gasification, hydrothermal carbonization, ammonia stripping and struvite recovery, offer economical ways to transform anaerobic digestate into valuable resources. Applying these digestate value-adding techniques reduces waste and its negative effects on the environment while promoting a more circular and sustainable agriculture system. Thus, the AD process can improve the circular economy through proper management and valorization of digestate.

Anaerobic digestate can be used as a fertilizer in agriculture and for soil improvement, thus replacing the use of manure and mineral fertilizers for these purposes. Moreover,

the biogas digestate is produced from renewable sources, thus supporting sustainable production by taking into account climate change and limited fossil resources. Thus, the recovery of anaerobic digestate represents an effective approach within the circular economy by increasing resource efficiency, minimizing the quantity of organic waste and reducing the carbon footprint related to waste management processes. These benefits promote sustainable agriculture and significantly decrease greenhouse gas emissions.

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