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Carbon Footprint of Flour Production in Poland

Magdalena Wróbel-Jędrzejewska *, Ewelina Włodarczyk and Łukasz Przybysz

Department of Technology and Refrigeration Techniques, Prof. Wacław Dąbrowski Institute of Agriculture and Food Biotechnology—State Research Institute, 92-202 Łódź, Poland; ewelina.wlodarczyk@ibprs.pl (E.W.); lukasz.przybysz@ibprs.pl (Ł.P.)

* Correspondence: magdalena.jedrzejewska@ibprs.pl

Abstract: The importance of carbon footprint (CF) analysis in the agricultural and food industries as a fundamental element of the means to achieve sustainable food production is emphasized here. In this study, flour production in Poland and the technological processes were characterized. This study's aim was to determine and compare flour production CF for different companies. The production stages were examined, and aspects related to transportation and storage were analyzed. The obtained data made it possible to identify areas of potential improvement to increase the efficiency of production and logistics processes and reduce greenhouse gas (GHG) emissions. The results showed that flour production CF_{av} ranges from 0.042 to 0.080 kg CO_{2eq}/kg of product (in different companies). The results obtained for individual plants did not differ. One method of reducing CF was through the use of renewable energy sources. Photovoltaics (share of 17–20%) has significantly reduced flour production CF by 13–15%. The decrease was significant from March to October due to the country's climatic conditions. The work highlights CF's importance as a tool to reduce environmental impacts and optimize production costs while pointing out the need to customize the calculation methodology to the specifics of the product and process.

Keywords: flour carbon footprint; renewable energy sources; flour production; CSRD directives; greenhouse gas emissions reduction

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1. Introduction

Food production, distribution, and storage generate more than one-third of the global greenhouse gas (GHG) emissions, according to a report by the Global Alliance for the Future of Food (GAFF) [1]. The use of fossil fuels in the agri-food industry is considered a significant problem. In light of the projected 56% increase in global food demand by 2050, recommendations include the following: phasing out agrochemicals produced with fossil fuels, using renewable energy to transform food systems, and using natural agents in equipment [1]. One of the important products in a balanced human diet is cereal products, as they provide many nutrients that are important for the health and functioning of the organism [2]. According to the European Food Chain Report, the European Union (EU) produced 271 million tons of grain in 2022. Poland, on the other hand, accounted for 12.9% of the EU's grain production, with only Germany (16.1%) and France (22.1%) producing more. In contrast, it is estimated that agriculture will be responsible for as much as 10.7% of greenhouse gas emissions in 2021 [3]. In Poland, grain production is one of the main agricultural sectors. Globally, grains account for about 20% of the value of agricultural production. In Poland's agricultural areas, grains account for about 74% of the total area. Over the past few years, Poland's grain harvest has remained between 26.5 and 31.8 million tons [4]. Cereal grains are an extremely important plant raw material that is used in the production of various types of food.

Poland is known for its high-quality flour, and its products are exported to many countries around the world. The grain and milling industry plays an important role in Poland's economy and is important for the bakery and confectionery industries. The flour production process is subject to sanitary and quality regulations to ensure food safety and product quality for consumers. The milling processes of cereal grains produce various types of flours, groats, and flakes. The largest share of this production is flour, which is divided by purpose. The production of wheat flour requires the proper selection of grain with appropriate quality characteristics, such as shape, grain size, hardness, and ash content [5].

The environmental footprint of milling is most influenced by grain production. The carbon footprint, a collection of life cycle assessment (LCA) data, is used to quantify the impact of greenhouse gas (GHG) emissions [6]. Researchers at European Flour Millers [7] found that wheat cultivation accounts for the largest share of the environmental footprint of wheat flour production (more than 60%) based on a cradle-to-gate assessment of one ton of flour. Wheat flour production accounts for about 20% of the environmental footprint of bread production. The CF of flour (for 1 ton) is calculated as the sum of inventory data related to wheat cultivation, transportation, processing at the mill, and delivery to the customer. However, milling is only the first stage of processing, and wheat is the raw material. Therefore, in order to consider the CF of bread production, it is necessary to take into account all stages up to secondary processing (the baking process) [8]. Calculating the CF of products is a complex process that requires a very detailed approach. It is important to use a consistent methodology to ensure accurate, reliable results that can be compared to those of other organizations or products. For the milling sector, the most appropriate approach is to use the physical allocation method according to ISO 14044 [9].

The current green revolution in the economy and the realization of climate goals require industries and the agricultural sector to take actions that place a low burden on the environment [10]. They will enable them to adapt to climate change and introduce low-carbon technologies. A set of initiatives to redirect towards a green transformation is contained in the "European Green Deal" strategy [11]. It includes a range of measures on greenhouse gas emissions reduction, use of renewable energy, energy efficiency improvements, closed-loop economy, and biodiversity conservation, among others. An industry's impact on climate change is assessed using the carbon footprint (CF) indicator [12]. Analysis of the indicator enables comparisons of GHG emissions between different products or activities, which in turn enables informed decision-making to reduce them. Calculations of the carbon footprint are required by law and are a result of the introduction of the Corporate Sustainability Reporting Directive (CSRD) into the reporting obligation for manufacturers (UE 2022/2464) [13]. Carbon footprint is also gaining importance in the context of increasing the competitiveness of companies in the context of a developing low-carbon economy [14]. There is also a need to develop uniform standards for analyzing the carbon footprint of food products based on market needs. Scientific support for green farming and agri-food processing is key. Industrial solutions should have a low environmental impact, be low-carbon, and aim for zero waste [15]. Research in this area should focus on analyzing current processes, identifying problems, and developing new technologies to reduce the carbon footprint of food production. The main objective was to determine and compare the carbon footprint of flour production, taking into account national production methods, and allowing uniform CF analysis systems for specific products. The results of the obtained work are to be used to develop methodological standards for measuring the carbon footprint for the flour milling industry. The research also focused on transportation-related aspects, covering means of transport and storage conditions to protect product quality as it moves through the supply chain.

2. Research Material

The research material was flour production produced at domestic production facilities (mills). This work focused on analyzing flour production using key information provided by cooperating plants and from production line metering. The flour production process at four production factories for the periods 2022 (factories 1, 2, 3, and 4) and 2023 (factories 3 and 4) was analyzed. The various stages of production were analyzed in detail from the selection of raw materials through the processing process, to obtaining the finished product. The technology of flour production, although a distinctive process in its basic form, can vary significantly from one industrial factory to another. Each mill has its own methods, technologies, and infrastructure that affect the final quality and characteristics of the flour produced. After analyzing flour production at the four mills, the general guidelines of the process were characterized in the context of determining the carbon footprint. The entire flour production process begins with the preparation of grain for milling in the cleaning plant, and then goes through the stages of cleaning, conditioning, and milling in the mill proper. The final result is a variety of flours, groats, middlings, and bran. The production cycle with unit processes is shown in the diagram (Figure 1). So, the production process begins with the preparation of grain for milling in the cleaning room. The first stage is grain cleaning, which aims to remove impurities and undesirable parts, such as fruit and seed coats. This is followed by grain conditioning, which involves moistening and aging the grain. This is a process that affects the ease of milling and the quality of the resulting flour. After conditioning, the next stage of cleaning is carried out to thoroughly remove any remaining impurities clinging to the surface of the grain. Once the grain has been properly cleaned and prepared, it moves on to the actual milling stage in the mill. This process involves grinding the grain. During milling, the flour is repeatedly sifted to separate coarse and fine particles, which leads to the final product—flour. After milling different types of grains, different types of flours, groats, middlings, and bran are obtained, which are then sorted. In order to more accurately separate adhering fragments of the fruit and seed coat, porridges and middlings undergo additional sorting and cleaning on special porridge separators. The product coming out of the grain mill is not homogeneous, so it requires sorting. Sorting between different milling products is done based on particle size using sifters such as porridge sifters or flat sifters.

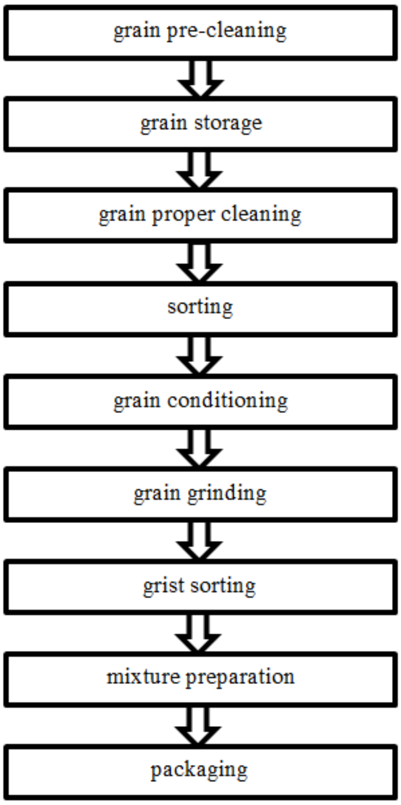


Figure 1. Diagram of unit processes of flour production.

The basic multi-species milling is tri-species milling, which leads to the production of various flours, such as light flour type 550 (up to 65% extraction), bread flour type 750 (75–80%), semolina (1.5%), crisp flour (2%), and cake flour (0.5%). The process is complex and precise, and its efficiency and the quality of the flour directly affect the final quality of bread and other food products made with the flour [16–19]. The basic division of flour into types is given by the Polish Standards: PN-A-74022:2003 Cereal preparations. Wheat flour and PN-A-74032:2002 Cereal preparations. Rye flour. In addition to the Polish Standards, there may be standards or factory specifications by which flour manufacturers can determine their flour types, such as wheat flour type 500 or type 850, which are excluded from the current Polish Standard [20,21].

3. Research Methodology

A carbon footprint is defined as the sum of all GHG emissions released into the atmosphere over the life cycle of a product, process, or technology. GHGs include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6). Each of these gases has a different impact on climate warming, and their impact is measured in relation to carbon dioxide (CO_{2eq}), using an index called Global Warming Potential (GWP) [22]. By using GWP, it is possible to express the emissions of a variety of greenhouse gases in uniform units of CO_2 equivalent. Detailed guidelines for the analysis of CF and the method of its calculation are provided in the relevant normative documents [23]. Using the principles of life cycle assessment (LCA), the CF analysis is performed according to the following steps: defining the research methodology, establishing the boundaries and scope of the research, collecting emission data, calculating the carbon footprint and verifying it, taking into account all stages of the product life cycle, and finally presenting the results and identifying the areas with the greatest impact on greenhouse gas emissions [24]. LCA considers all life stages of a product, service, or process—from the extraction of raw materials through production and use, to the end-of-life stage, including recycling or disposal. The LCA methodology is defined in ISO 14040:2009 [25] and ISO 14044:2009 [9]. Such an analysis makes it possible to identify the stages in a product's life cycle that have the greatest impact on the environment, and thus to identify areas where changes can be made to reduce negative environmental impacts. The carbon footprint (CF) value is given in equivalent quantity (CO_{2eq}), while the CF footprint of a product, process, or technology is the sum of all direct and indirect emissions identified throughout the cycle or scope of the analysis [26].

Working with manufacturing companies made it possible to closely examine the internal processes and understand what companies are doing to ensure quality. The analysis focused on identifying areas where there is potential to optimize or make improvements to increase the efficiency of production and logistics processes. The research work also included a detailed analysis of technological processes and the development of diagrams of the various stages of production. After a detailed description of the technological processes, measurement ranges for the carbon footprint, the functional unit, and the boundaries of the measurement system were defined. An analysis of input and output streams within the defined boundaries and for the entire product life cycle was conducted. A methodology was developed to calculate the carbon footprint of a process, taking into account all elements of the life cycle. In addition, a concept was developed for measuring and collecting the necessary data on, among other things, greenhouse gas emissions and production levels. On this basis, a database for calculating the carbon footprint was developed that takes into account the diversity of production volumes. These measures are intended not only to increase efficiency but also to contribute to reducing the environmental impact of production and logistics activities by minimizing greenhouse gas emissions.

4. Results and Discussion

After characterizing the technological processes, the identification and analysis of activities related to emissions (direct and indirect) of greenhouse gases in the production and transportation stages of the factories were carried out. These included the production and consumption of energy carriers to determine the carbon footprint. The conversion rates of the energy carriers used were used (Table 1). Data were obtained for four production facilities. A database was developed to collect production and consumption data for energy carriers, with aggregate data for 2022 and 2023. The article presents a sample database for only one facility—factory 4 (Table 2). The obtained production data of the factory concern the production of different types of assortment (12 different types of flour (1850 W50, 450P, 500 W25, 500 W50, 550P, 650L, 650 W50, 750 L, 750 W50, 500L, and 500P) and 2 types of bran—bulk bran and W25 bran) over the analyzed two-year period. The following two sources of emissions were identified: direct (fuel combustion) and indirect (electricity). Table 3 summarizes the share of electricity generated from photovoltaics in total energy. Based on the analysis, it was found that the share of photovoltaics in reducing electricity consumption was significant in the months of March through October. It ranges from 14 to 43% for 2022 and from 14 to 31% for 2023, and the corresponding average values for a given year of reduction in electricity consumption are 17% for 2022 and 20% for 2023.

Table 1. Conversion factors of applied energy carriers for analysis of flour production at factory 4.

Energy Media	Indicator Value	Source
Diesel oil (liter)	2.66 kg CO_{2eq}/liter	[27]
Electrical energy (kWh)	0.708 kg CO_{2eq}/kWh	[28]

Table 2. Database for factory 4 in 2022 and 2023.

Production Volume (t)							
Month in 2022	1850 W50	450P	500 W25	500 W50	550P	650L	650 W50
January	0.00	50.44	0.00	2.98	0.66	2970.36	0.00
February	0.00	66.05	1.85	0.79	1.32	2811.24	0.00
March	0.00	152.55	0.92	3.20	4.28	2522.72	1.24
April	0.00	64.11	0.00	2.60	0.35	2399.84	1.74
May	0.11	8.86	1.18	4.23	0.00	3306.10	26.62
June	0.08	35.92	1.72	0.00	0.15	3043.00	0.00
July	0.00	39.36	0.00	1.74	0.66	2879.38	0.00
August	0.00	64.18	0.92	3.27	1.53	3002.50	0.00
September	0.00	61.96	1.06	0.93	1.98	3142.20	0.00
October	0.00	59.32	2.28	0.00	0.76	3112.98	27.42
November	0.05	115.40	2.81	0.00	1.98	3119.72	0.00
December	0.03	48.56	3.20	0.00	1.37	3332.78	0.00
Total	0.27	766.71	15.94	19.74	15.04	35,642.82	57.02
Month in 2022	750L	750 W50	500L	500P	Bran loose	Bran W25	Total production of the whole assortment
January	1033.54	2.74	0.00	14.52	886.24	0.20	4961.68
February	1092.36	5.04	0.00	17.82	847.72	0.20	4844.39
March	1420.22	3.54	27.42	39.80	934.35	0.20	5110.44
April	1008.28	3.50	0.00	14.21	773.80	0.40	4268.83
May	904.44	7.82	0.00	0.00	901.03	0.20	5160.59

Table 2. *Cont.*

Production Volume (t)							
June	900.06	2.92	0.00	5.43	884.63	0.20	4874.11
July	890.61	2.28	0.00	21.12	855.27	0.47	4690.89
August	926.14	3.95	0.00	11.43	1008.73	0.20	5022.85
September	1012.76	2.62	0.00	19.14	924.38	0.20	5167.23
October	659.77	2.84	0.00	26.45	874.71	0.40	4766.93
November	875.34	1.14	0.00	21.78	897.92	0.20	5036.34
December	606.24	3.71	0.00	10.82	904.17	0.40	4911.29
Total	11,329.76	42.10	27.42	202.52	10,692.95	3.27	58,815.58
Month in 2023	1850 W50	450P	500 W25	500P	550P	650L	750L
January	0.08	47.94	0.92	7.33	0.00	2575.74	1022.89
February	0.00	59.82	3.96	13.20	0.00	2469.42	1268.03
March	0.05	72.25	2.97	22.64	2.18	2658.36	854.92
April	0.00	37.74	0.00	16.04	1.98	2165.76	1334.26
May	0.00	33.81	4.46	12.71	1.32	2629.35	1196.66
June	0.00	66.42	1.00	12.31	2.28	2365.64	964.48
July	0.00	40.79	3.15	9.90	1.98	2501.06	1297.92
August	0.00	91.77	2.96	28.49	3.35	3136.88	877.88
September	0.00	92.25	2.47	12.79	1.52	2666.34	1225.66
October	0.00	30.18	2.63	12.23	2.23	2662.71	866.74
Total	0.13	572.97	24.52	147.64	16.84	25,831.26	10,909.44
Month	750 W50	Waste	Feed bran	Bran loose	Bran W25	Total production of the whole assortment	
January	5.13	0.40	0.00	818.95	0.25	4479.63	
February	2.26	0.00	0.00	882.67	0.10	4699.46	
March	4.04	0.00	0.00	883.13	0.20	4500.74	
April	0.00	0.00	0.00	786.32	0.05	4342.15	
May	4.32	0.00	0.00	921.73	0.80	4805.17	
June	0.00	0.00	15.14	832.20	0.00	4259.47	
July	4.19	0.00	66.16	872.06	0.40	4797.61	
August	0.12	0.00	22.22	954.09	0.02	5117.79	
September	3.87	0.00	18.66	937.83	0.20	4961.59	
October	0.00	0.00	18.54	781.13	0.20	4376.59	
Total	23.93	0.40	140.72	8670.11	2.22	46,340.19	
Characteristics of consumption of energy carriers							
Month	2022	2023					
	Electricity	Disel	Photovoltaic electricity	Electricity	Disel	Photovoltaic electricity	
	kWh	litr	kWh	kWh	litr	kWh	
January	318,496	23,296	0	284,509	24,617	5460	

Table 2. *Cont.*

Characteristics of consumption of energy carriers						
February	279,986	20,439	13,840	270,728	22,624	26,820
March	259,604	22,336	60,230	243,615	23,525	44,710
April	226,381	19,329	47,950	223,784	21,685	54,620
May	226,763	21,225	80,240	232,821	23,476	67,560
June	194,450	20,286	83,620	212,220	21,147	57,520
July	237,288	20,263	71,230	210,684	18,001	64,290
August	248,918	20,860	74,860	265,606	24,560	70,310
September	282,209	22,119	45,380	257,647	22,737	63,650
October	297,690	18,912	40,210	258,839	22,341	35,900
November	312,312	21,643	12,760	-	-	15,720
December	300,543	26,223	2770	-	-	6490
Total	3,184,640	256,931	533,090	2,460,453	224,713	513,050

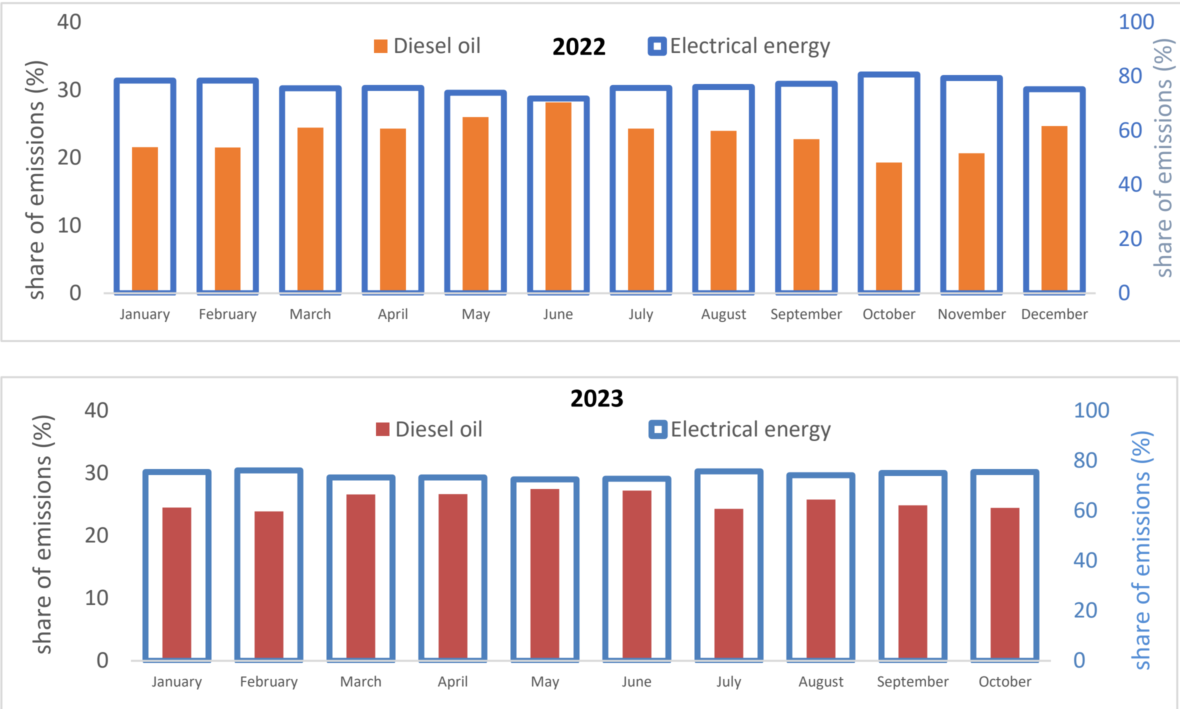
Table 3. Reduction in electricity consumption through photovoltaics.

Month	**2022**		**2023**	
	Electricity after Reduction	**Share of Photovoltaic Energy**	**Electricity after Reduction**	**Share of Photovoltaic Energy**
	kWh	**%**	**kWh**	**%**
January	318,496	0.00	279,049	1.92
February	266,146	4.94	243,908	9.91
March	199,374	23.20	198,905	18.35
April	178,431	21.18	169,164	24.41
May	146,523	35.39	165,261	29.02
June	110,830	43.00	154,700	27.10
July	166,058	30.02	146,394	30.51
August	174,058	30.07	195,296	26.47
September	236,829	16.08	193,997	24.70
October	257,480	13.51	222,939	13.87
November	299,552	4.09	-	-
December	297,773	0.92	-	-
Total	2,651,550	16.74	1,969,613	19.95

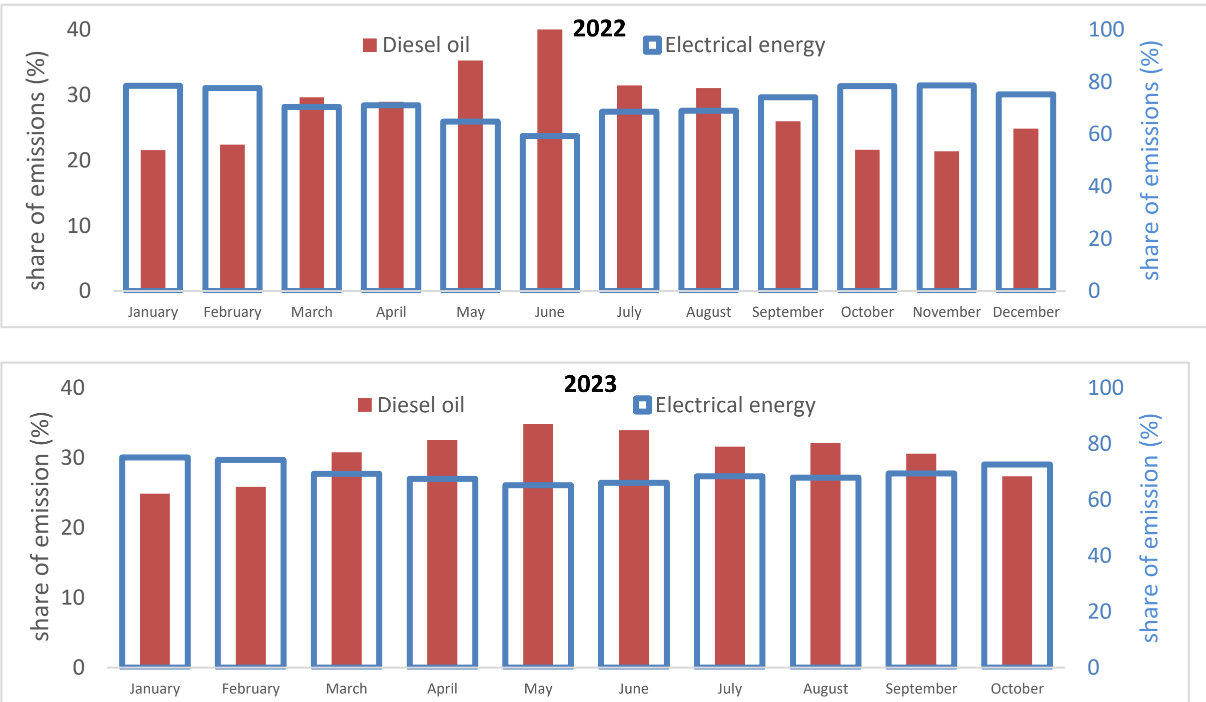
On the basis of the data on the consumption of energy carriers, GHG emissions were calculated (Table 4), and the percentage share of individual sources was determined for factory 4 (Figure 2). Taking into account the results obtained, the carbon footprint was determined for individual months in the analyzed years (Table 5). The determined carbon footprint of flour production at factory 4 (scope of analysis: production and transportation, not including photovoltaics) in terms of unit weight was 0.0393–0.0579 kg CO_{2eq}/kg (for 2022) and 0.0411–0.0596 kg CO_{2eq}/kg (for 2023), and an average CF of 0.0500 kg CO_{2eq}/kg (for 2022) and 0.0505 kg CO_{2eq}/kg (for 2023). Including photovoltaics, it was 0.0272–0.0579 kg CO_{2eq}/kg (for 2022) and 0.0316–0.0587 kg CO_{2eq}/kg (for 2023), and there was an average CF of 0.0435 kg CO_{2eq}/kg (for 2022) and 0.0430 kg CO_{2eq}/kg (for 2023). It was found that there is a relationship between the carbon footprint of flour production and the season (Figure 3) for the years considered (2022 and 2023). In addition, no significant relationship was found between the carbon footprint and monthly production volume (Figure 4). The average production-related GHG emissions came mainly from indirect emissions (electricity consumption excluding PV) and accounted for 76.74% (for 2022) and 74.45% (for 2023) of total emissions. GHG emissions related to transportation (diesel consumption) were constant throughout the analyzed year and averaged only 23.26% (for the first year) and 25.55% (for the second year). The average GHG emissions related to production continued to come mainly from indirect emissions (electricity consumption, including photovoltaics) and accounted for 73.31% (for 2022) and 70% (for 2023) of total emissions. GHG emissions related to transportation (diesel consumption) were constant throughout the year analyzed, averaging only 26.69% (for 2022) and 30% (for 2023).

Table 4. GHG emissions (kg CO_{2eq}) associated with the consumption of energy carriers for factory 4 for 2022 and 2023: I—excluding photovoltaics; II—including photovoltaics.

Month	2022		2023		Total Emissions
	Emissions: Electrical Energy	Emissions: Diesel	Emissions: Electrical Energy	Emissions: Diesel	
I					
January	318,496	61,967	201,432	65,481	647,376
February	279,986	54,368	191,675	60,180	586,209
March	259,604	59,414	172,479	62,577	554,074
April	226,381	51,415	158,439	57,682	493,917
May	226,763	56,459	164,837	62,446	510,505
June	194,450	53,961	150,252	56,251	454,914
July	237,288	53,900	149,164	47,883	488,235
August	248,918	55,488	188,049	65,330	557,785
September	282,209	58,837	182,414	60,480	583,940
October	297,690	50,306	183,258	59,427	590,681
November	312,312	57,570	-	-	369,882
December	300,543	69,753	-	-	370,296
Total	3,184,640	683,436	1,742,001	597,737	6,207,814
II					
January	225,495	61,967	197,567	65,481	550,510
February	188,431	54,368	172,687	60,180	475,666
March	141,157	59,414	140,825	62,577	403,973
April	126,329	51,415	119,768	57,682	355,194
May	103,738	56,459	117,005	62,446	339,648
June	78,468	53,961	109,528	56,251	298,208
July	117,569	53,900	103,647	47,883	322,999
August	123,233	55,488	138,270	65,330	382,321
September	167,675	58,837	137,350	60,480	424,342
October	182,296	50,306	157,841	59,427	449,870
November	212,083	57,570	-	-	269,653
December	210,823	69,753	-	-	280,576
Total	1,877,297	683,436	1,394,486	597,737	4,552,956



Excluding Photovoltaics



Including Photovoltaics

Figure 2. Monthly share of energy carriers emissions for factory 4.

Table 5. Monthly carbon footprint values for factory 4 in 2022 and 2023.

Month	2022			2023		
	CF (kg CO_{2eq}/kg)		CF Reduction (%)	CF (kg CO_{2eq}/kg)		CF Reduction (%)
	without Photovoltaics	with Photovoltaics		without Photovoltaics	with Photovoltaics	
January	0.0579	0.0579	0	0.0596	0.0587	1.45
February	0.0521	0.0501	3.88	0.0536	0.0496	7.54
March	0.0476	0.0392	17.53	0.0522	0.0452	13.47
April	0.0496	0.0416	16.04	0.0498	0.0409	17.89
May	0.0421	0.0310	26.18	0.0473	0.0373	21.05
June	0.0393	0.0272	30.89	0.0485	0.0389	19.72
July	0.0473	0.0366	22.73	0.0411	0.0316	23.10
August	0.0461	0.0356	22.87	0.0495	0.0398	19.65
September	0.0501	0.0438	12.42	0.0490	0.0399	18.55
October	0.0548	0.0488	10.90	0.0555	0.0496	10.47
November	0.0553	0.0535	3.24	-	-	-
December	0.0575	0.0571	0.69	-	-	-
$CF_{average}$	0.0500	0.0435	12.85	0.0505	0.0430	14.85

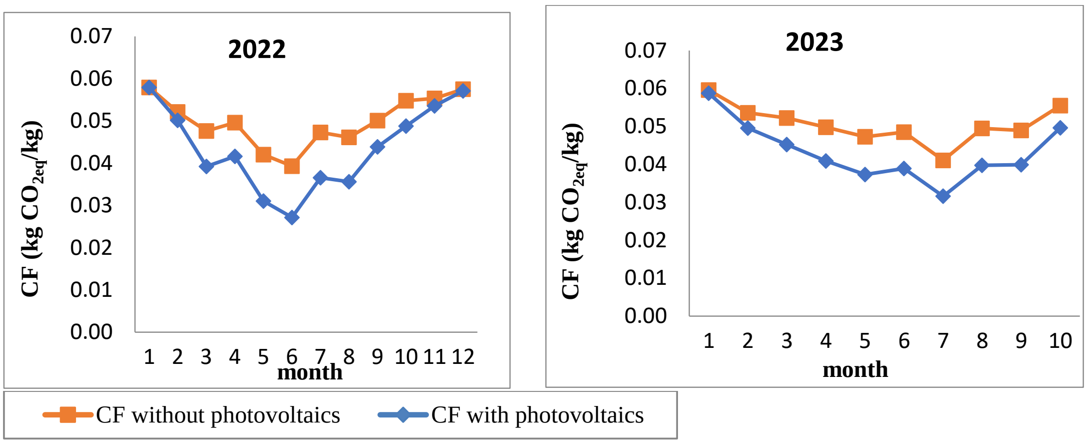


Figure 3. Monthly CF for factory 4 in 2022 and 2023, without and with photovoltaics.

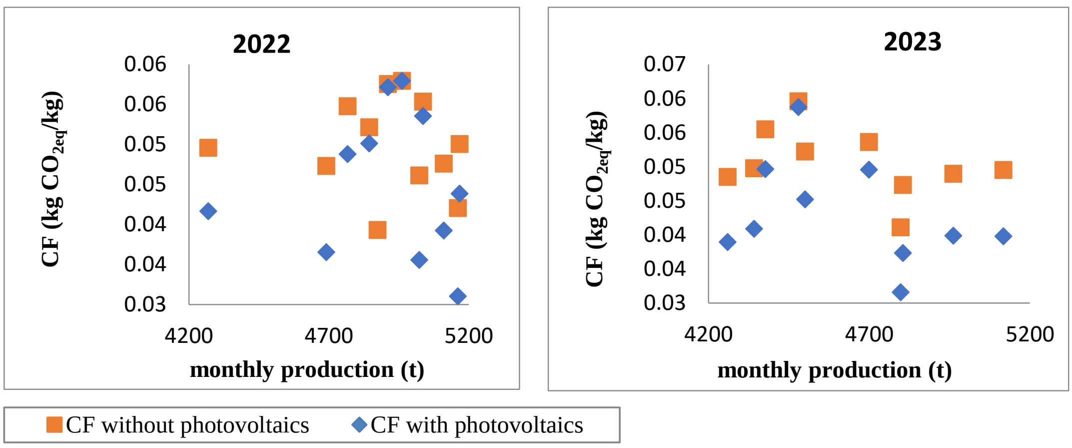


Figure 4. Dependence of CF on monthly production volume for factory 4 in 2022 and 2023, without and with photovoltaics.

The contribution of photovoltaics to reducing electricity consumption averages between 17% and 20%. For the designated carbon footprint, the contribution of photovoltaics to its reduction is also significant in the months of March through October and ranges from 11 to 31% for 2022 and from 11 to 23% for 2023, and the corresponding average annual CF reduction values are 13% for 2022 and 15% for 2023.

The CF of flour production (scope of analysis: production and transportation) was determined for the four factories (1–4), which ranged from 0.0422 to 0.0505 kg CO_{2eq}/kg (Table 6). The largest GHG emissions came from electricity comparing the four production plants (Figure 5).

Table 6. Monthly carbon footprint values (kg CO_{2eq}/kg) for plants in 2022 and 2023.

	Factory 1	Factory 2	Factory 3		Factory 4	
Month/Year	**2022**	**2022**	**2022**	**2023**	**2022**	**2023**
January	0.0454	0.0796	0.0460	0.0458	0.0579	0.0596
February	0.0430	0.0811	0.0471	0.0482	0.0521	0.0536
March	0.0431	0.0845	0.0446	0.0447	0.0476	0.0522
April	0.0427	0.0787	0.0440	0.0438	0.0496	0.0498
May	0.0411	0.0856	0.0418	0.0425	0.0421	0.0473
June	0.0414	0.0792	0.0414	0.0431	0.0393	0.0485
July	0.0429	0.0826	0.0428	0.0437	0.0473	0.0411
August	0.0399	0.0754	0.0431	0.0437	0.0461	0.0495
September	0.0413	0.0776	0.0450	0.0431	0.0501	0.0490
October	0.0415	0.0776	0.0453	-	0.0548	0.0555
November	0.0413	0.0850	0.0451	-	0.0553	-
December	0.0430	0.0788	0.0468	-	0.0575	-
$CF_{average}$	0.0422	0.0804	0.0444	0.0443	0.0500	0.0505

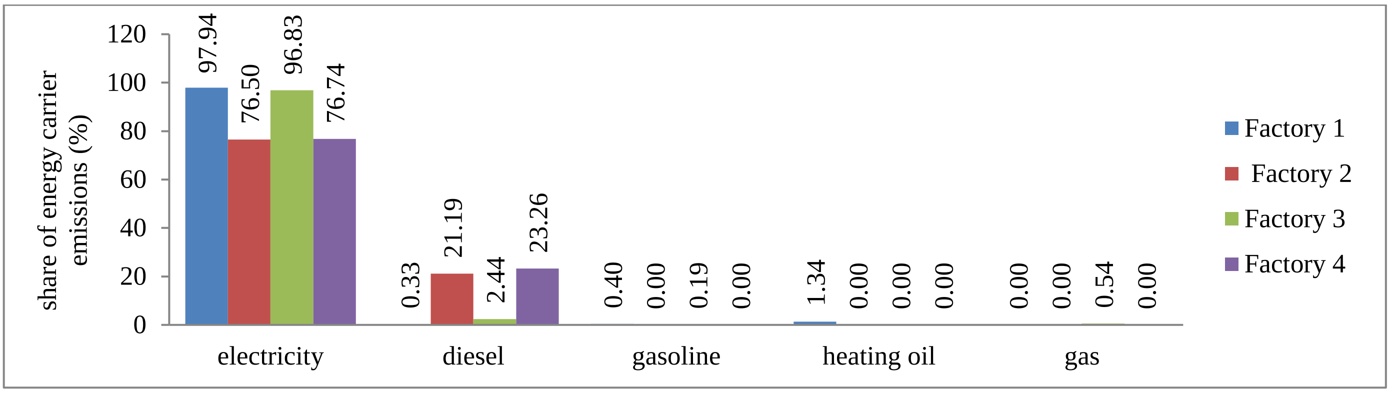


Figure 5. Comparison of the contribution of GHG emission sources for four factories.

The carbon footprint of flour production depends on a number of factors, including the type of grain grown, processing, energy consumption, and transportation. In general, flour production generates GHG emissions such as carbon dioxide and methane, although the amount of these emissions can vary depending on several factors. The main factors affecting the carbon footprint of flour production are the type of crop and agriculture. Cereal cultivation is the first stage of flour production. The type of crop, the agricultural practices used (such as the use of fertilizers and pesticides), and soil management affect the amount of greenhouse gas emissions [23]. Organic farming can generate lower emissions compared to conventional farming practices. Another important factor is the process of threshing, drying and cleaning grains, which requires energy inputs. Using energy from fossil fuels, such as coal or natural gas, can significantly increase the carbon footprint of flour production. Mills using renewable energy or more efficient sources can significantly reduce GHG emissions. The transportation of grains to mills and flour to end users has an impact on the carbon footprint. Long transportation can generate higher emissions, especially if low-fuel-efficiency vehicles are used. The use of advanced and efficient technologies during the threshing and processing processes can reduce energy losses and increase efficiency, which can reduce GHG emissions [29].

Taking grain cultivation and processing into account, the carbon footprint of flour ranges from 0.65 kg CO_{2eq}/kg [30] to 0.78 kg CO_{2eq}/kg [31]. In these papers, there are no detailed data on the grain milling process itself in the production plant, which makes it impossible to directly compare them with the results obtained for four different plants. According to other researchers [32], grain cultivation is an important stage in the entire chain that has the greatest environmental impact. Based on a cradle-to-gate analysis of one ton of wheat flour, it was found that agriculture contributes about 60% to the CF of flour, and production at the mill is responsible for about 30% of the final results of the carbon footprint of the final product [32]. Considering the above literature data, the estimated carbon footprint of flour production alone at the mill ranges from 0.195 to 0.234 kg CO_{2eq}/kg. According to [32], the carbon footprint of flour production from wheat with different grain hardness can vary. The CF of flour obtained from hard wheat is higher than that of common wheat, at 0.495 and 0.468 kg CO_{2eq}/kg. Also, the contribution of the various stages of grain milling to the formation of the carbon footprint can vary depending on the quality of the grain delivered to the mill. The largest contributions to the carbon footprint in the milling plant itself are grain milling (about 40%), flour sifting and entoleter application (about 25%), grain cleaning (about 8%), and the preparation of flour blends (about 15%) [32]. Therefore, the designated CFs of poppy production in Polish plants are significantly lower (0.042–0.080 kg CO_{2eq}/kg), indicating the use of low-carbon technologies and significant efforts towards sustainable production. In order to further reduce the carbon footprint of flour production, the flour milling industry must strive to adopt more sustainable practices, such as using renewable energy sources, optimizing transportation, and minimizing losses in the production process [33]. These actions will help reduce greenhouse gas emissions and contribute to greener flour production.

5. Conclusions and Summary

Carbon footprint is one of the most effective tools for assessing processes and reducing greenhouse gas emissions in business operations. Thus, companies can not only minimize their environmental impact but also optimize production costs and increase their competitiveness in the market. The analysis of the flour milling industry made the following statements: Based on carbon footprint studies for four factories, it was shown that the average CF rate of flour production ranges from 0.042 to 0.080 kg CO_{2eq}/kg of product. Reproducible results were obtained for two years of production (2022 and 2023). The carbon footprint values for flour production at the analyzed plants vary depending on the equipment used, technology, and location of the plant. This result can provide a benchmark for measures to reduce GHG emissions in the production process. One method of reducing the carbon footprint was shown to be the use of renewable energy sources. The use of renewable electricity (photovoltaics) (at an average share of 17–20%) has significantly reduced the CF of flour production by an average of 13–15%. The reduction is significant in the months from March to October, due to the country's climatic conditions.

Promoting knowledge of carbon footprints serves as a strong motivation to introduce solutions that increase efficiency among both consumers and manufacturers. In each production segment and for each product, it is necessary to conduct a thorough analysis and adapt the carbon footprint calculation methodology to individual requirements. The characteristics of the product and the technologies used in its production must be taken into account. Adapting the method of calculating the carbon footprint to the specifics of the product and process allows for a more accurate identification of the sources of GHG emissions and the identification of areas where reductions are possible.

The optimization of production processes and the use of low-carbon technologies are becoming key steps toward sustainable and responsible business. CF calculating is a key element in reducing adverse impacts on climate change, food production processes, and optimizing and reducing CO_2 emissions into the atmosphere by the food industry. The GHG Protocol's GHG emissions analysis covers three main scopes for an organization or business. In scope 1, we focus on direct emissions, such as those related to technological processes and refrigerants that are released directly during production. In scope 2, we deal with indirect emissions, such as those resulting from the import of electricity, heat, process steam, or refrigeration, which affect a company's total emissions balance. In scope 3, on the other hand, we look at other indirect emissions generated throughout the company's value chain. These include aspects such as the production of raw materials, waste management, and the transportation of raw materials and finished products. By considering these three areas, we can comprehensively assess an organization's environmental impact and identify areas where improvements can be made to minimize negative climate impacts.

The study of production processes in the grain and milling industry, which was conducted, provided a comprehensive understanding of these important industries. The carbon footprint calculations proved crucial, especially given the complexity of these processes and their dependence on various operating conditions. This only confirms the need to perform these calculations on a cyclical basis, enabling constant monitoring of environmental impacts and providing a basis for making modifications to food production-related technologies. Ensuring continuous monitoring makes it possible to adapt production practices to changing conditions and effectively respond to the needs of sustainability, which is crucial in the context of environmental protection.

Determining the carbon footprint of a specific technology and, based on this, carrying out measures to reduce greenhouse gas emissions, is a conscious reduction of emissions, contributing to environmental protection. In order to obtain precise data on the size of the carbon footprint of a specific food technology process, studies will be carried out over the entire range.

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