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PROSPECTS OF SUNFLOWER RESIDUES USE FOR ENERGY

The present position paper №25 of the Bioenergy Association of Ukraine belongs to the planned series of publications on the main issues of bioenergy development in Ukraine.

UABIO's Position Paper presents the results of technical and economic analysis of harvesting by-products of sunflower production for energy. The theme is topical due to an increase in the gross sunflower production in Ukraine in recent years, which creates the possibility for introducing technologies for the harvesting of sunflower by-products for their further processing into solid, liquid and gaseous biofuels. The energy potential of sunflower by-products is assessed for Ukraine's regions. Fuel characteristics of sunflower stalks and heads are analyzed. Prerequisites for the sustainable development of the value-added chains for sunflower production by-products are presented.

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1.1. Current state of sunflower production in the world and in Ukraine

Sunflower is the main oil crop in Ukraine. It is grown to obtain seeds that contain 30-35% of oil, and kernels contain 50-60%[1] of oil. In terms of the amount of oil extracted from the seeds, sunflower ranks first among the oil crops; regarding taste, sunflower oil is considered one of the best. In large quantities, sunflower seeds are processed into edible fats, and the worst varieties are used for technical purposes. Sunflower is of great fodder value. The cake received while processing of seeds contains 20-35% of proteins and is considered quite good concentrated feed for animals.

In addition, sunflower is important for the energy sector. Thus, the processing of sunflower seeds produces about 15% of husk, which is mainly burned for energy and processed into fuel pellets and briquettes. By-products of sunflower seeds production can also be used as biomass for energy. The ash obtained by burning sunflower stalks is rich in potassium and is used for potash production, as well as applied as a potassium fertilizer.

Fig. 1.1. Sunflower field

Since 2012, Ukraine has become the world leader in sunflower production. According to preliminary USDA data given in **Table 1.1**, the gross harvest of sunflower in Ukraine in 2019/2020 MY amounted to 16.5 million tons, which is almost 30% of the world production. Other largest producers of sunflower are Russia (15.31 million tons) and the EU (9.75 million tons). It should be noted that the first place in the world in terms of sunflower sown area is occupied by Russia (8.36 million hectares in 2019/2020 MY, or 31.6% of the sunflower sown area the world); however, the yield of this crop is less there than the world average. In the EU, in terms of the gross sunflower production in 2019, the leaders were Romania (3.45 million tons), Bulgaria (1.9 million tons), Hungary (1.7 million tons), and France (1.32 million tons) (**Fig. 1.2**).

[1] http://nsfond.gov.ua/index.php?option=com_content&view=article&id=25&Itemid=24&lang=uk

Table 1.1. Main producers of sunflower in the world (by MY) [2]

No	Country / region	Area, million ha			Yield, t/ha			Production, million t		
		2017/ 2018	2018/ 2019	2019/ 2020	2017/ 2018	2018/ 2019	2019/ 2020	2017/ 2018	2018/ 2019	2019/ 2020
1	**Ukraine**	**6.80**	**6.50**	**6.40**	**2.01**	**2.31**	**2.58**	**13.70**	**15.00**	**16.50**
2	Russia	7.15	7.94	8.36	1.45	1.60	1.83	10.36	12.71	15.31
3	EU	4.39	4.12	4.35	2.30	2.31	2.24	10.13	9.51	9.75
4	Argentina	1.68	1.88	1.59	2.11	2.04	2.14	3.54	3.83	3.40
5	China	1.17	0.92	1.25	2.69	2.71	2.60	3.15	2.49	3.25
6	Turkey	0.70	0.72	0.73	2.21	22.52	2.40	1.55	1.80	1.75
7	Kazakhstan	0.88	0.85	0.82	1.02	1.00	1.13	0.90	0.85	0.92
8	USA	0.54	0.49	0.50	1.80	1.94	1.75	0.97	0.96	0.88
	World	**25.92**	**25.93**	**26.48**	**1.85**	**1.95**	**2.09**	**47.85**	**50.55**	**55.25**

Notes: 2018/2019 MY – preliminary data, 2019/2020 MY – forecast (April 2020).
The marketing year starts on 1st of September and ends on 31th of August.

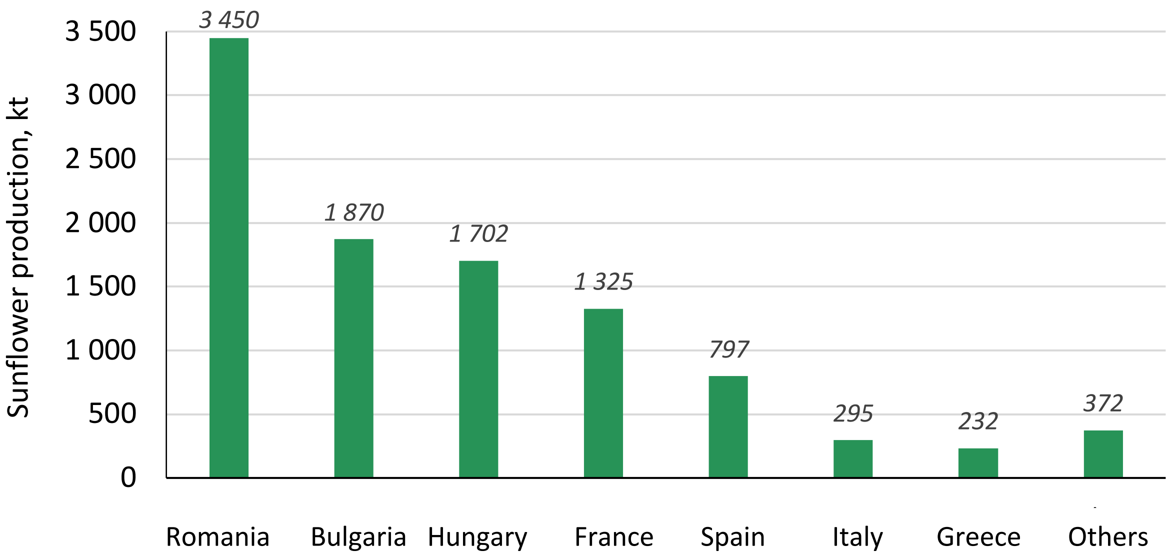

Fig. 1.2. Sunflower production in the EU (2019) [3]

The yield of sunflower has increased considerably, which is shown in **Fig. 1.3**. From 1961 to 2019, the average world yield of sunflower doubled – from 1.0 t/ha to 2.1 t/ha. The average yield in Ukraine exceeds the world average one; in 2019, it exceeded the average yield of the EU countries. However, the potential for sunflower production has not yet been fully used in Ukraine, especially in the Forest-Steppe and Polissya zones[4]. Today, the efforts of scientists are aimed at improving the technology of sunflower growing, breeding precocious varieties and hybrids, which will expand the growing areas.

[2] World Agricultural Production, USDA Reports https://apps.fas.usda.gov/psdonline/circulars/production.pdf
[3] https://ec.europa.eu/eurostat/data/database
[4] https://propozitsiya.com/ua/suchasni-sorti-ta-gibridi-sonyashniku

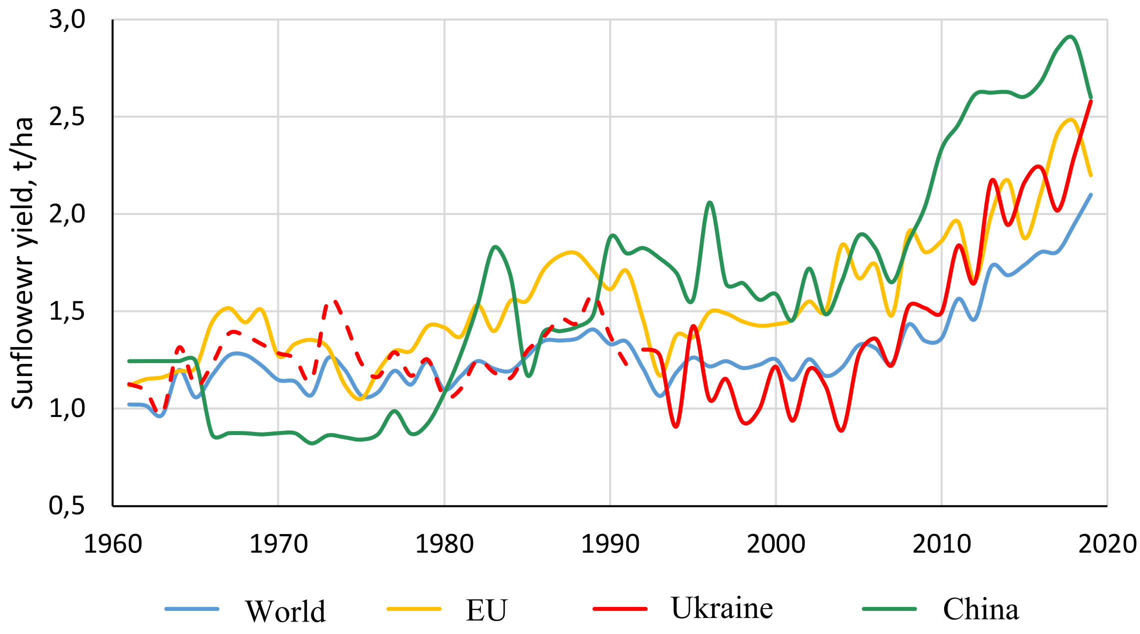

Fig. 1.3. Increasing of sunflower yield from 1961 to 2019 [5]

From 1990 to 2016, the area under sunflower increased more than 3.5 times in Ukraine. This is due to the development of the domestic oil and fat complex, which has ensured a stable demand for sunflower seeds in the domestic market. A powerful sector of processing sunflower into a value-added product (oil) was created, in contrast to other areas of crop production, where the harvest is mainly exported as raw material. In 2018, 5.6 Mt of sunflower oil to the sum of 4.1 billion USD were exported[6].

Several times sunflower became the most profitable crop in the country. According to the State Statistics Service of Ukraine, in 2018, the profitability of sunflower production by enterprises amounted to 32.5%, while the profitability of their whole activity was 13.5%[7]. In 2015, the profitability of sunflower production reached 78.4%, the profitability of the whole activity of enterprises being 30.4%.

Regional distribution of the gross sunflower production, harvested areas, and yields in Ukraine are given in **Table 1.2**.

Table 1.2. Production of sunflower in Ukraine's regions in 2015-2019 [8]

Region	Gross harvest (production), kt					Harvested area, 1000 ha					Yield, m.c./ha				
	2015	2016	2017	2018	2019	2015	2016	2017	2018	2019	2015	2016	2017	2018	2019
Vinnytsya	503.6	819.8	725.8	808.1	846.1	187.0	266.7	248.2	259.9	246.2	26.9	30.7	29.2	31.1	34.4
Volyn	5.2	15.6	39.5	69.5	94.5	2.5	6.4	15.9	23.6	31.4	20.6	24.3	24.7	29.4	30.1
Dnipropetrovsk	**1198.6**	**1264.1**	**1202.8**	**1283.2**	**1448.6**	**536.3**	**631.4**	**625.1**	**592.7**	**593.2**	**22.4**	**20.0**	**19.2**	**21.6**	**24.4**
Donetsk	528.3	620.0	555.5	531.0	685.7	316.8	332.5	335.0	311.1	314.6	16.7	18.6	16.6	17.1	21.8
Zhytomyr	141.5	231.7	247.6	298.6	324.6	60.6	91.9	107.4	142.7	117.9	23.3	25.2	23.1	20.9	27.5
Zakarpattia	4.7	6.9	6.8	5.4	8.0	2.7	3.2	3.1	2.7	3.8	17.6	21.8	21.7	19.7	21.4
Zaporizhzhia	**961.8**	**985.2**	**866.4**	**720.5**	**1020.6**	**536.1**	**601.9**	**571.3**	**568.8**	**535.6**	**17.9**	**16.4**	**15.2**	**12.7**	**19.1**
Ivano-Frankivsk	27.3	53.1	76.9	57.6	61.1	12.1	23.1	31.6	24.8	23.9	22.4	23.0	24.4	23.2	25.5

[5] http://www.fao.org/faostat/en/#data
[6] Ukraine's foreign trade. Statistical yearbook, 2019.
[7] Agriculture of Ukraine. Statistical yearbook for 2018.
[8] Data of the State Statistics Service of Ukraine.

Kyiv	292.1	452.6	397.5	570.1	508.0	116.0	165.6	164.8	191.7	159.4	25.2	27.3	24.1	29.7	31.9
Kirovohrad	**1170.1**	**1293.8**	**1091.9**	**1458.7**	**1540.3**	**547.8**	**577.4**	**553.7**	**588.8**	**572.9**	**21.4**	**22.4**	**19.7**	**24.8**	**26.9**
Luhansk	484.8	670.1	566.1	720.9	860.6	308.4	339.5	361.1	361.2	375.7	15.7	19.7	15.7	20.0	22.9
Lviv	27.8	67.6	73.7	79.8	72.7	11.0	26.3	35.1	34.1	25.5	25.4	25.7	21.0	23.4	28.6
Mykolaiiv	**938.7**	**1162.3**	**875.8**	**1087.2**	**1063.4**	**475.6**	**558.5**	**532.6**	**559.9**	**499.2**	**19.7**	**20.8**	**16.4**	**19.4**	**21.3**
Odesa	755.3	1004.2	903.9	886.3	693.4	418.0	468.6	453.8	413.6	364.7	18.1	21.4	19.9	21.4	19.0
Poltava	848.4	824.4	730.9	943.9	979.3	315.2	312.5	311.7	329.8	323.6	26.9	26.4	23.5	28.6	30.3
Rivne	9.6	37.0	67.0	58.4	77.9	4.2	13.2	24.6	24.2	27.7	22.8	28.0	27.3	24.1	28.1
Sumy	471.2	488.4	516.3	621.0	777.1	175.2	196.9	201.7	213.4	236.7	26.9	24.8	25.6	29.1	32.8
Ternopil	74.7	149.1	234.2	190.6	215.6	30.9	55.1	82.1	70.8	59.9	24.1	27.0	28.5	26.9	36.0
Kharkiv	**1172.2**	**1352.2**	**1103.0**	**1468.2**	**1480.6**	**402.8**	**486.6**	**484.9**	**529.0**	**528.0**	**29.1**	**27.8**	**22.7**	**27.8**	**28.0**
Kherson	486.5	613.1	499.2	552.8	641.2	300.6	383.3	356.6	341.7	353.0	16.2	16.0	14.0	16.2	18.2
Khmelnytskyi	105.9	346.7	438.7	484.1	513.4	40.0	115.8	146.2	157.5	140.2	26.4	30.0	30.0	30.7	36.6
Cherkasy	541.6	576.0	504.7	640.9	673.7	190.1	203.4	203.4	201.9	201.4	28.5	28.3	24.8	31.7	33.4
Chernivtsi	20.8	55.5	43.6	52.4	34.3	10.4	19.6	17.3	19.6	12.5	20.0	28.4	25.3	26.8	27.3
Chernihiv	410.4	537.5	467.7	576.0	633.7	165.9	207.3	193.5	203.0	211.9	24.7	25.9	24.2	28.4	29.9
UKRAINE	**11181.1**	**13626.9**	**12235.5**	**14165.2**	**15254.1**	**5166.2**	**6086.7**	**6060.7**	**6166.5**	**5958.9**	**21.6**	**22.4**	**20.2**	**23.0**	**25.6**

Traditionally, most of sunflower is grown in the Steppe and Forest-steppe. However, in recent years, sunflower fields have also appeared in Polissya. In 2019, the largest areas were sown with this crop in Dnipropetrovsk region (harvested area was 593 th. ha), Kirovograd region (573 th. ha), Zaporizhzhia region (536 th. ha), and Kharkiv region (528 th. ha). In terms of the gross harvest in 2019, Kirovohrad region (1540 kt), Kharkiv region (1481 kt), and Dnipropetrovsk region (1449 kt) were in the lead in Ukraine. In terms of the yield in 2019, Khmelnytskyi region (36.6 m.c./ha), Ternopil region (36.0 m.c./ha), Vinnytsia region (34.4 m.c./ha), Cherkasy region (33.4 m.c./ha), and Sumy region (32.8 m.c./ha) were in the lead.

Sunflower yield depends on favourable soil and climatic conditions for growing the crop, the quality of seed material and agro-technological methods. Timely and high-quality harvesting is an important final stage of growing crops. An important factor for increasing the harvest is the correct timing of the beginning of harvesting. The main criterion for the beginning of harvesting is the moisture content of seeds, which depends on the ripening phase and weather conditions. The increase in the mass of seeds and oil ends in 35-40 days after mass flowering. Next is the physical evaporation of water, after which economic maturity comes. Pre-harvest drying of sunflower with the help of chemicals (desiccation) in the phase of physiological maturity accelerates ripening and dries the seeds, allowing starting harvesting 8-12 days earlier. The optimal harvest time comes when 20-25% of all crops are yellow and yellow-brown, and other plants are dry and brown. At this stage, the moisture of seeds decreases to 11-13%, moisture of heads to 69-75%, and that of stalks to 60-70%[9].

One can start harvesting at a seeds moisture content of 20-22%, provided that the farm has drying equipment and a large sown area of sunflower. It should be taken into account that only seeds of less than 7-8% moisture content are suitable for long-term storage. At higher moisture, seeds are oxidized, and the oil becomes unfit as food.

The optimal duration of sunflower harvesting is 5-6 days. If one begins to harvest sunflower in the phase of full ripeness, then the losses from seed falling increase by 2 times on the fifth day, and by 12

[9] https://agroexp.com.ua/uk/kak-pravilno-ubirat-podsolnechnik-chtoby-uvelichit-urozhay

times on the 15th day[10]. In Ukraine, the period of sunflower harvesting begins in August and ends in November, the main amount being harvested in September-October.

Fig. 1.4. Sunflower field awaiting harvesting

Sunflower is harvested with combine harvesters with special or universal reapers. One can use adapters, special attachments (sunflower attachments) for grain reapers. Reapers can be with or without a stalk shredder. The use of the shredder will reduce productivity and increase fuel consumption during harvesting but will save on mulching[11]. Classic reapers are designed for the traditional technology of sunflower growing with a row spacing of 70 cm. The cut line that contains cutting machines of a reaper should be 20-25 cm below the heads. A combine harvester moves in the field, usually along crops, in rows. This facilitates collection with a sufficiently high operating speed (up to 9 km/h) and maximum efficiency. The cut heads and the seeds partially fallen out of them are fed to the threshing and separating system of the combine[12]. Stalks remain standing in the field (**Fig. 1.5**), forming the main part of the post-harvest remains of sunflower.

Fig. 1.5. Sunflower field after harvesting of the main products

[10] https://agroscience.com.ua/plant/zbyrannya-sonyashnyku
[11] https://agrotimes.ua/article/suchasne-zbyrannya-sonyashnyku-v-ukrayini/
[12] https://propozitsiya.com/ua/sonyashnik-zibrat-ne-pole-pereyti

During further technological operations with the use of specialized agricultural machines, plant residues are comminuted and distributed over the field. However, sometimes farmers burn almost everything that remains after growing sunflower in the field[13]. An alternative to the burning can be the harvesting of sunflower by-products for energy production.

1.2. Assessment of energy potential of sunflower by-products in Ukraine

1.2.1. Yield of different parts of sunflower by-products.

Sunflower of the Central Russian ecotype is grown in Ukraine. Plants are 120-190 cm tall; they do not branch; seeds are of the shell type, which determines its resistance to pests. Depending on the variety, hybrid, weather conditions, soil fertility, oil hybrid plants reach a height of almost 3 m, and silage varieties reach 3.5-4.5 m. The average daily growth of a sunflower stalk from germination to the formation of two pairs of leaves is 0.8-1.0 cm, to the formation of heads – 1.5-1.7 cm, to flowering – 3.0-4.3 cm. With the increasing weight of heads, the upper part of a stalk with the head droops in most varieties[14].

The diameter of a stalk near the soil surface can reach 5-8 cm, gradually decreasing in height. Sunflower has a strong well-branched taproot, which reaches a depth of 260-280 cm by the end of vegetation. The number of leaves on the plant may be different even within one variety: early ripening and mid-ripening varieties have 24-28 and 28-32 leaves on the plant, respectively. Formation of heads in early ripening and middle-late hybrids begins in the presence of 3-4 and 5-8 pairs of true leaves, respectively. The bulk of leaves increases in size only before the flowering of sunflower; after the flowering, the area of upper leaves near heads increases. The growth of heads continues until they turn yellow. The diameter of heads is 5-40 cm depending on the hybrid and growing conditions. At a certain age, leaves give part of the previously accumulated nitrogen to form a protein and fat complex of seeds[15]. The full maturity of the seeds comes at the last macro-stage of sunflower development, and the plant dies[16].

Post-harvest residues of sunflower include aboveground parts: stalks, leaves, heads, and chaff, which is formed during threshing, and underground part – roots. Sunflower reapers are designed to cut heads with seeds with the limited supply of stalk mass to the combine. The cutting height of the reaper is set 10-20 cm below the level of the most inclined heads[17]. The cut stalk mass and heads pass through the threshing-separating system of the combine and, at the same time, are comminuted. Such biomass can be collected in a hopper or trailer. Thus, in the 1980s, sunflower was harvested with SK-5 Niva combine with PUN-5 shredder, which provided the collection of chaff and heads into tractor trailers for animal feed. This allowed to collect chaff in the amount of up to 3-5 m.c./ha[18]. At that, technological maps of sunflower cultivation using advanced technology took into account the yield of sunflower 25-30 m.c./ha, and that of heads 40-45 m.c./ha.

[13] http://agro-business.com.ua/agro/ahronomiia-sohodni/item/8996-spaliuvannia-solomy-ta-roslynnykh-reshtok-u-poli-koryst-chy-shkoda.html

[14] Tkalich I.D. Agrotechnical measures to increase the yield of sunflower seeds in the steppe of Ukraine / I.D. Tkalich, A. D. Gyrka, O. V. Bochevar, Yu. I. Tkalich // Grain crops. – Institute of grain crops of NAAS of Ukraine, v. 2, № 1, 2018. P. 44–52. https://dspace.dsau.dp.ua/jspui/bitstream/123456789/1655/1/5bcd8b153bd1d.pdf

[15] Tkalich I.D. Sun flower (basics of biology and agrotechnics of sunflower: a monograph) / I.D. Tkalich, Yu.I. Tkalich, S.G. Rychik // Edited by I.D. Tkalich. – Dnepropetrovsk, 2011. – 172 p.

[16] https://superagronom.com/multimedia/infographics/17-infografika-rozvitok-sonyashniku-vsi-fazi-rozvitku

[17] http://agro-business.com.ua/agro/ahronomiia-sohodni/item/582-rekomendatsii-do-zbyrannia-rannikh-zernovykh-ta-zernobobovykh.html

[18] Recommendations for advanced sunflower production technology. – K.: «Urozhai», 1981. – 29 p.

Some farmers regulate the separation of seeds in the combine to increase the ingress of impurities from heads and other parts of the sunflower into the hopper. Further, clean seeds are extracted on stationary grain cleaning machines, and organic waste impurities are used as energy biomass in heat generators of grain dryers and solid fuel boilers. However, the possibility of widespread use of this technology for the harvesting of significant amounts of sunflower by-products and their sale is limited due to the reducing productivity of the combine, increasing load on it, increasing consumption of diesel fuel and rising seed moisture. At that, the obtained biomass has an inhomogeneous composition and is contaminated with various impurities, which negatively affects its fuel characteristics.

At present, the parts of heads and stalk mass comminuted with the combine are scattered over the field surface, and it is very difficult to collect such biomass. Existing agricultural technology envisages the comminution and even distribution of sunflower residues with specialized agricultural machines, which requires significant costs. This and other production factors lead to the fact that sunflower stalks remain standing in the fields until spring. Then, when these plant remains are ploughed in the soil, they do not have time to decompose and create difficulties for sowing the crop that is next in the crop rotation. To avoid this, farmers burn the remains of sunflower. Therefore, another option for harvesting, which will allow collecting larger volumes of sunflower by-products from the fields, is collection of stalk mass standing in the field (see **Fig. 1.5**), for example, using forage harvesters. An important advantage of this approach is the possible drying of stalks in the field, which results in obtaining biomass with better fuel characteristics.

According to research on sunflower in the crop rotations of the Left-Bank Forest-Steppe of Ukraine, seeds, which make up 20-23% of the total harvest weight and 10-15% of chaff, are taken away from the field. Everything else remains in the field where the sunflower was grown. The complete account of all components can be made when sunflower leaves of the lower tier begin to dry up, but still remain on the stalk. This is the time of yellowing of the heads, which means the physiological maturity of the seeds. The absolutely dry mass of one plant (height is 170-185 cm, the number of leaves is 28-30) makes up 250-280 g, on the average 265 g. At a density of plants standing at the time of harvesting of 50,000 per hectare, the absolutely dry mass of post-harvest remains of sunflower will amount to about 13.0 t/ha[19]. The yield of dry heads is 56-60% of sunflower seeds and 19-20% of the mass of the aboveground part of the plant[20]. In Turkey, the ratio of sunflower stalks yield to seeds is taken as 1.29 and that of heads to seeds is taken as 1.17[21].

[19] Kokhan A.V., Gangur V.V., Koretskyi O.Ye., Len O.I., Manko L.A. sunflower in the crop rotations of the Left-Bank Forest-Steppe of Ukraine / Bulletin of the Center for Scientific Support of Agricultural Production of Kharkiv Region 2015, №18. https://agromage.com/stat_id.php?id=1060
[20] Nikitchyn D.I. Sunflower. – К.: Urozhai, 1993. – 192 p. – (in Russian).
[21] http://www.fao.org/3/a-i6480e.pdf

According to other estimates, in addition to seeds, 3-7 tons of dry biomass, of which 10% are heads, can be obtained from a hectare of sunflower[22]. On average, the residues factor of sunflower by-products yield to seeds is taken as 1.9[23,24]. Approximate flows of biomass during the growing and processing of sunflower are shown in **Fig. 1.6**.

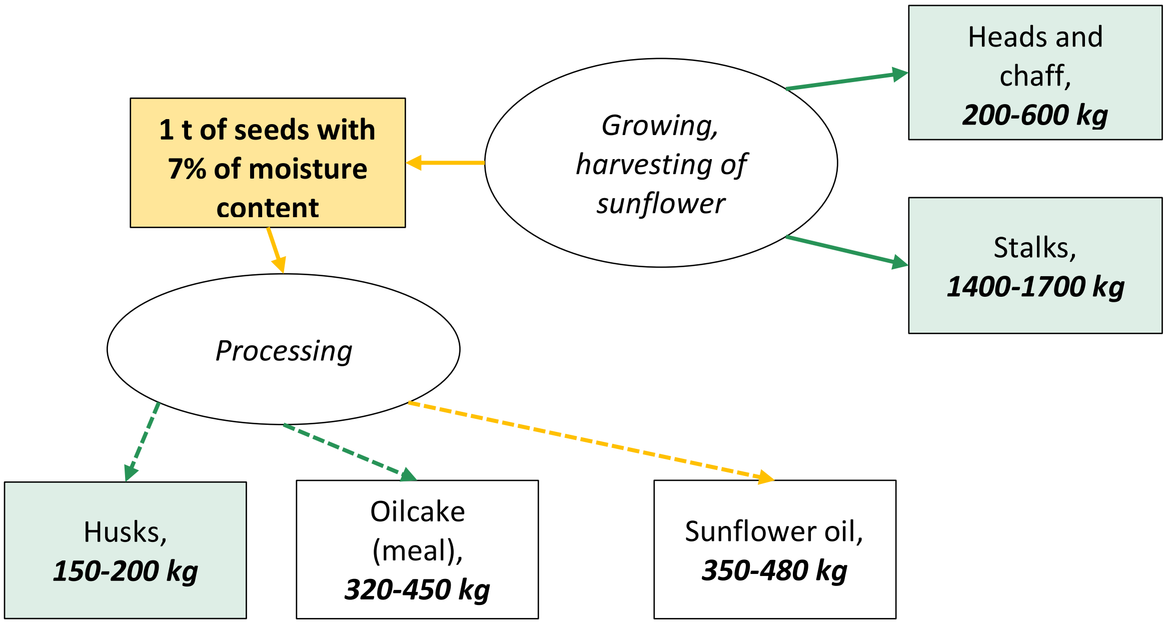

Fig. 1.6. Mass of sunflower aboveground parts and their processing products per 1 ton of seeds

The sunflower harvest can be fully used for bioenergy. **Fig. 1.7** shows the results of estimating the amount of energy that can be obtained from the use of by-products generated from growing sunflower on the area of 1 hectare and processing its seeds into biodiesel. To assess the growing, the yield of sunflower seeds was taken as 2.86 t/ha (2.6 t d.m./ha), and the yield of by-products was taken as 6.33 t/ha (5.66 t d.m./ha). To calculate the processing of this amount of sunflower seeds, the yield of biodiesel was taken as 0.96 t/ha, oilcake 0.91 t d.m./ha, husk 0.64 t d.m./ha, and glycerine 0.11 d.m./ha.

[22] V. Marechal, L. Rigal Characterization of by-products of sunflower culture – commercial applications for stalks and heads / Industrial Crops and Products 10 (1999) 185–200.
[23] Methods of generalized assessment of technical energy potential of biomass / V.O. Dubrovin, G.A. Golub, C.V. Drahniev, G.G. Geletukha, T.A. Zheliezna, P.P. Kucheruk, Yu.B. Matveev, S.O. Kudria, G.M. Zabarnyi, Z.V. Masliukova. – K. : «Violprin» Ltd, 2013. – 25 p.
[24] Ye.N. Bogatyreva, T.M. Seraya, O.M. Biriukova, T.M. Kirdun, Yu.A. Beliavskaya, M.M. Torchilo. Conversion factors for recalculation of grain and seeds into by-products, and the content of basic nutrients in by-products of agricultural crops in the Republic of Belarus / Soil science and agro-chemistry, № 2(57), 2016. – 78-89 c. http://aw.belal.by/russian/science/soilandagro_pdf/57/57-7.pdf

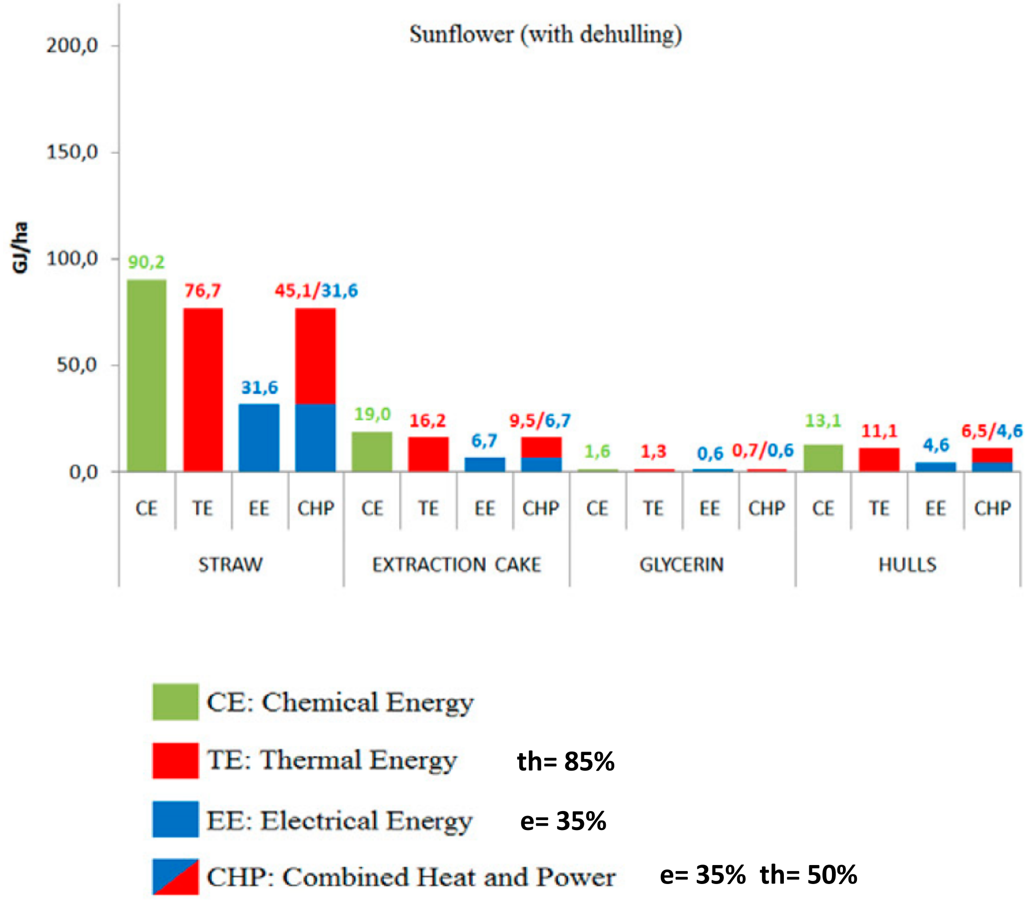

Fig. 1.7. Energy potential of by-products from growing sunflower on 1 ha and from processing sunflower seeds into biodiesel [25]

1.2.2. Energy potential of sunflower production by-products.

Assessment of energy potential of sunflower production by-products in Ukraine in 2019 was made taking into consideration methods developed by the Bioenergy Association of Ukraine[26]. The results are the following (**Table 1.3**):

- Theoretical potential (the whole amount of the generated by-products) is **28.9 Mt** or **4.2 Mtoe**;
- Economic potential (the amount **available for energy production**, which is **40%** of the theoretical potential) makes up **11.6 Mt** or **1.7 Mtoe**.

[25] D. Duca, G. Toscano, G. Riva, C. Mengarelli, G. Rossini, A. Pizzi, A. Del Gatto, E. Foppa Pedretti Quality of residues of the biodiesel chain in the energy field, Industrial Crops and Products Volume 75, Part A, 2015, 91-97.

[26] Geletukha G.G., Zheliezna T.A. Prospects for the use of agricultural residues for energy production in Ukraine. UABIO Position Paper N 7 – Bioenergy Association of Ukraine, 2014. – 33 p. https://uabio.org/wp-content/uploads/2020/04/position-paper-uabio-7-en.pdf

Table 1.3. Energy potential of sunflower residues in Ukraine (2019)

Regions (oblasts)	Theoretical potential		Potential available for energy (economic potential)	
	kt	ktoe	kt	ktoe
Vinnytsya	1607.5	230.4	643.0	92.1
Volyn	179.5	25.7	71.8	10.3
Dnipropetrovsk	**2752.3**	**394.4**	**1100.9**	**157.8**
Donetsk	1302.8	186.7	521.1	74.7
Zhytomyr	616.8	88.4	246.7	35.4
Zakarpattia	15.3	2.2	6.1	0.9
Zaporizhzhia	1939.0	277.9	775.6	111.2
Ivano-Frankivsk	116.1	16.6	46.5	6.7
Kyiv	965.2	138.3	386.1	55.3
Kirovohrad	**2926.5**	**419.4**	**1170.6**	**167.8**
Luhansk	1635.1	234.3	654.0	93.7
Lviv	138.0	19.8	55.2	7.9
Mykolaiiv	2020.5	289.6	808.2	115.8
Odesa	1317.4	188.8	527.0	75.5
Poltava	1860.7	266.6	744.3	106.7
Rivne	148.1	21.2	59.2	8.5
Sumy	1476.4	211.6	590.6	84.6
Ternopil	409.7	58.7	163.9	23.5
Kharkiv	**2813.1**	**403.1**	**1125.2**	**161.3**
Kherson	1218.2	174.6	487.3	69.8
Khmelnytskyi	975.4	139.8	390.2	55.9
Cherkasy	1280.0	183.4	512.0	73.4
Chernivtsi	65.2	9.3	26.1	3.7
Chernihiv	1204.0	172.5	481.6	69.0
UKRAINE	**28982.828**	**4153.46**	**11593.131**	**1661.38**

Distribution of the potential of sunflower by-products is not even over the territory of Ukraine. Regions with the highest concentration of this type of biomass are those with the largest production of sunflower. In 2019, the biggest potential of sunflower by-products was in Kirovohrad region (with the economic potential of 167.8 ktoe), Kharkiv region (161.3 ktoe), and Dnipropetrovsk region (157.8 ktoe) (**Fig. 1.8**).

According to the EU ECOFYS project[27], the technically sustainable potential of sunflower by-products in Ukraine, which takes into account technical and environmental constraints of agro-biomass harvesting, is 5.7 Mt/yr. There is an opportunity to increase this potential by 2-8% using specialized crop production strategies and by 10-15% using special strategies regarding crop residues. However, it should be noted that this study considered three ranges of sunflower yield: low that is < 1.5 t/ha, medium that is 1.5-2.2 t/ha, and high that is > 2.2 t/ha, and for Ukraine, the low yield was taken. In 2019, Ukraine achieved

[27] https://ec.europa.eu/energy/sites/ener/files/documents/Ecofys%20-%20Final_%20report_%20EC_max%20yield%20biomass%20residues%2020151214.pdf

an average sunflower yield of 2.56 t/ha; thus, we can assume that further growth of the energy potential of sunflower by-products can be achieved mainly by increasing the area under sunflower.

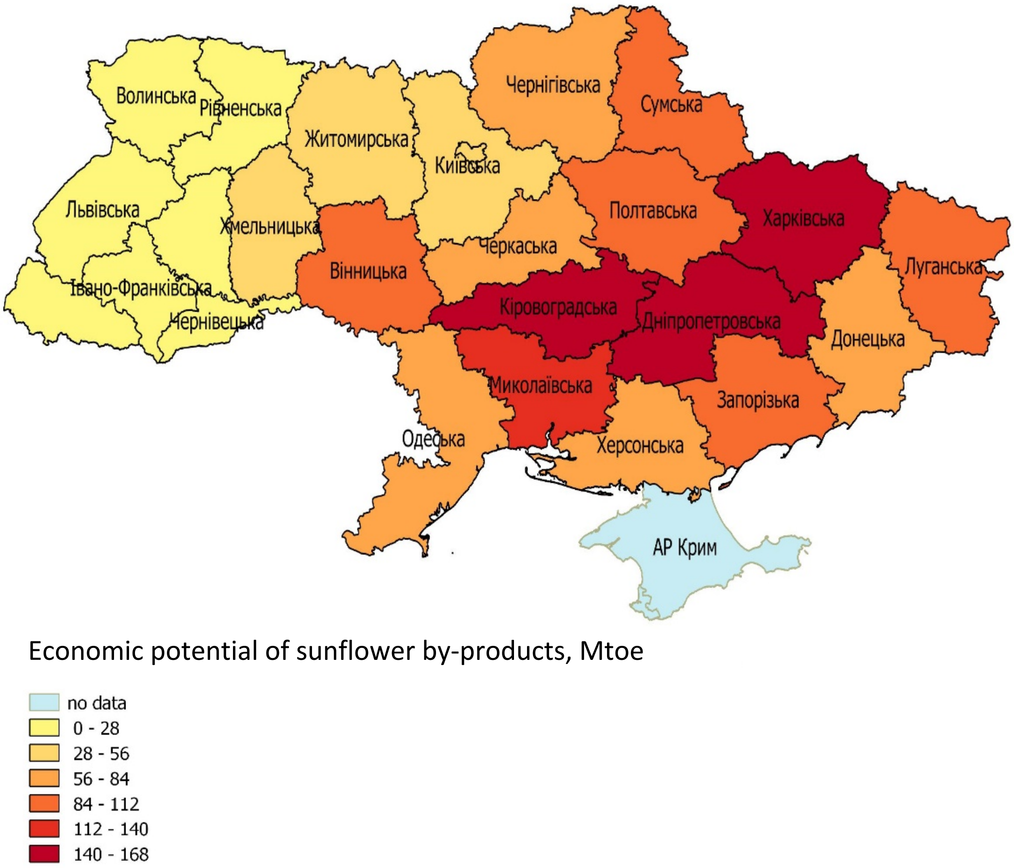

Fig. 1.8. Map of the economic potential of sunflower by-products in Ukraine's regions in 2019

1.3. Review of the characteristics of sunflower by-products

Stalk, sunflower heads (without seeds), and their mixture are fibrous materials with low protein content and very variable composition due to the difference in maturity and proportions of different fractions of residues[28]. The energy characteristics of stalks, heads, husk of sunflower, and oilcake are given in **Table 1.4**. The chemical composition and fuel characteristics of heads and stalks of sunflower are similar. In general, sunflower by-products can be considered as lignocellulosic raw material that can be processed into solid, liquid and gaseous biofuels, but also this biomass can be used for feed production and as a raw material for various industries.

[28] https://www.feedipedia.org/node/143

Table 1.4. Energy characteristics of various components of sunflower by-products and products of sunflower processing[25]

Material	Heating Value		Moisture, %	Ash content, %	Cl, %	S, %	C, %	H, %	N, %	Ash melting temperature, °C	
	(NHV), MJ/kg a.r.	(LHV), MJ/kg d.m.								ST	DT
Stalks	14.252	16.190	10.4	8.3	0.13	0.06	44.6	7.2	0.8	920	1100
Heads	13.824	15.980	11.7	12.5	0.3	0.16	44.3	7.3	1.4	960	1130
Husk	19.153	20.704	6.7	3.6	0.05	0.14	54.4	7.3	1.6	897	1002
Dehulled oilcake	19.360	21.026	7.1	6.6	0.12	0.27	51.2	7.6	5.4	925	1155

Notes:
a.r.: means as received by the analyst, value expressed on wet basis.
d.m.: means dry matter, value expressed on dry basis.
ST – shrink temperature; DT – deformation temperature.

Threshed heads of sunflower contain fat (3.5-4%), protein (5-8%), cellulose (14-17%), ash elements (phosphorus, potassium, calcium, magnesium – 13-15%, nitrogen-free extractives – up to 60%) on the absolute dry weight. Heads contain a lot of pectin matters, the amount of which reaches 22-27%. Sunflower heads are good fodder for animals. Green heads are stored in a silo with the addition of green mass (corn, beet tops). Heads with a moisture content of 20-25% are staked, adding layers of dry straw. Under such conditions, the heads can be stored for a long time[29]. Dry heads are processed into flour that is not less nutritious than medium quality hay. In addition, heads are used to produce pectin that is used in the confectionery industry[20].

Sunflower stalk is straight round or ribbed, covered with rough hairs, filled inside with spongy tissue[30]. The stalk is covered with bark outside. The volume of the stalk is 90% of the volume of the sunflower [31]. The density of the bark is 350 kg/m^3, spongy tissue – 29 $kg\ m^3$.

During seed ripening, the stalk dries out, as do the leaves attached to it. The content of cellulose in the stalks is 34-42%, hemicellulose – 19-33%, lignin – 12-30%[32]. Sunflower stalks can be used for energy, fodder purposes, and as fertilizer (**Table 1.5**). The ash content of the stalks is in the range from 3 to 13.2%.

[29] Vasiliev D. Sunflower. – M.: Agropromizdat, 1990. – 174 p. (Rus.)
[30] Kutsenko O., Kocherga A., Filonenko C. Industrial crops. Tutorial. – Poltava. – 2003. – 180 p. (Ukr.)
[31] Mathias et al. Upcycling Sunflower Stems as Natural Fibers for Biocomposite Applications, BioResources 10(4), 8076-8088 (2015)
[32] Đ. Kovačić, D. Kralik, S. Rupčić, D. Jovičić, R. Spajić, and M. Tišma Soybean Straw, Corn Stover and Sunflower Stalk as Possible Substrates for Biogas Production in Croatia: A Review, Chem. Biochem. Eng. Q., 31 (3) 187–198 (2017)

Table 1.5. The main physical and chemical characteristics of sunflower stalks [33]

Physicochemical properties	Average	Standard deviation	Min.	Max.	Number of samples
Fuel characteristics					
Higher Heating Value (HHV), MJ/kg	18.7	3.34	15.9	26.0	9
Lower Heating Value (LHV), MJ/kg	17.7	3.29	15.2	24.4	8
Fixed Carbon, (%wt)^{db}	8.7	6.59	1.2	14.4	4
Volatile Matter, (%wt)^{db}	81.0	6.03	72.7	85.9	4
Ash, (%wt)^{db}	7.9	3.6	3.0	13.2	18
Moisture, (%wt)^{am}	9.1	5.82	2.3	18.0	5
Carbon, (%wt)^{db}	46.0	7.07	35.1	60.3	10
Oxygen, (%wt)^{db}	37.6	5.39	26.8	47.5	10
Hydrogen, (%wt)^{db}	5.4	0.74	4.8	7.1	10
Nitrogen, (%wt)^{db}	1.2	0.69	0.3	2.6	11
Sulfur, (%wt)^{db}	0.1	0.07	0.0	0.2	8
Fodder characteristics					
Dry matter, (%wt)^{am}	88.9	5.08	82.0	94.0	4
Crude protein, (%wt)^{db}	7.3	4.49	1.5	16.3	12
Crude fiber, (%wt)^{db}	48.8	n.a.	48.8	48.8	1
Neutral Detergent Fiber (NDF), (%wt)^{db}	71.7	16.82	43.2	89.5	6
Acid Detergent Fiber (ADF), (%wt)^{db}	37.2	10.17	22.1	51.0	6
Lignin, (%wt)^{db}	16.1	5.85	7.3	26.5	7
Ether extract, (%wt)^{db}	1.0	0.79	0.5	2.0	3
Ash, (%wt)^{db}	7.9	3.64	3.0	13.2	18
Gross energy, MJ/kg	18.8	3.57	15.9	26.0	8
Characteristics as fertilizer					
Nitrogen, (g/kg)^{db}	11.1	5.53	3.1	20.0	10
Phosphorus, (g/kg)^{db}	0.9	0.73	0.1	2.3	7
Potassium, (g/kg)^{db}	27.5	22.50	8.0	67.8	7
Calcium, (g/kg)^{db}	8.1	4.80	1.6	13.7	7
Magnesium, (g/kg)^{db}	1.1	0.27	0.9	1.5	6
Sulfur, (g/kg)^{db}	1.2	0.79	0.1	2.5	8
am: as measured; db: dry base					

The comparison of fuel characteristics of sunflower stalks with straw, corn stalks, and wood chips is given in **Table 1.6**. It should be noted that during the harvesting of seeds, the water content of the stalks is in the range of 60-70%, so if it is planned to burn them, this biomass must be dried. The ash melting temperature of sunflower stalks is close to straw one and lower than that of corn stalks and wood chips, which should be taken into account when choosing heating equipment. Sunflower stalks have a high chlorine content of 0.7-0.8%, which also complicates their combustion, as chlorine compounds cause corrosion of steel elements of power equipment.

[33] Characterisation of Agricultural Waste Co- and By-Products. Report of AgroCycle project. http://www.agrocycle.eu/files/2017/10/D1.2_AgroCycle.pdf

***Table 1.6. Chemical composition and some properties of different types of biomass*[34]**

Parameter	Yellow straw	Grey straw	Corn stalks*	Sunflower stalks*	Wood chips
Water content, %	10-20	10-20	45-60 (after harvesting) 15-18 (air dried)	60-70 (after harvesting) ~20 (air dried)	40
Lower Heating Value, MJ/kg	14.4	15	16.7 (db) 5-8 (W 45-60%) 15-17 (W 15-18%)	16 (W<16%)	10.4
Volatile Matter, %	>70	>70	67	73	>70
Ash content, %	4	3	6-9	10-12	0.6-1.5
Ultimate analysis, %:					
carbon	42	43	45.5	44.1	50
hydrogen	5	5.2	5.5	5.0	6
oxygen	37	38	41.5	39.4	43
chlorine	0.75	0.2	0.2	0.7-0.8	0.02
potassium (alkali metal)	1.18	0.22	corn cobs: 6.1 mg/kg d.m.	5.0	0.13-0.35
nitrogen	0.35	0.41	0.69; 0.3	0.7	0.3
sulfur	0.16	0.13	0.04	0.1	0.05
Ash melting temperature, °C	800-1000	950-1100	1050-1200	800-1270	1000-1400

d.m. – dry matter; W – moisture content.

** Data for volatile matter, ash content, and ultimate analysis are based on dry matter.*

The elemental composition of sunflower stalks is almost the same as for straw and corn stalks, so they have nearly equal calorific value. The moisture content has the most significant effect on the calorific value of sunflower residues. As with other types of crop by-products, the characteristics of the matter of stalks and heads depend on the place of cultivation, harvesting time and weather, soil, and fertilizers. Also, the quality characteristics of the harvested sunflower by-products are significantly influenced by the technology of harvesting and storage.

[34] G. Geletukha, S. Drahniev, T. Zheliezna, A. Bashtovyi Analysis of pellets and briquettes production from corn residues. UABio Position paper 23 – Bioenergy Association of Ukraine, 2020. – 42 p. https://uabio.org/wp-content/uploads/2020/04/position-paper-uabio-23-en.pdf

2. Analysis of the supply chain of sunflower by-products

Harvesting is the initial operation of the supply chain of crop by-products. Two streams of sunflower by-products can be separated: biomass that has passed through a combine and stalk biomass that was remained in a field. In this case, the stalk biomass under favorable weather conditions can dry out that will improve its fuel characteristics.

In the past, farms used to have a practice of dividing the sunflower fields into smaller areas so that locals could cultivate them. They cut sunflower heads with seeds by hand and gave them to the farm. Locals also cut by hand and collected in bundles stalks, which was then used as biomass for heating. There is a lack of information on modern examples of sunflower by-products harvesting.

A diagram with the main technologies of mechanized harvesting of stalk biomass is shown in **Fig. 2.1**. For sunflower, stalks can be cut and chopped with a forage harvester, followed by the use of dry biomass as a solid biofuel, and wet as a raw material for biogas plants. The biomass that has passed through the combine can be collected in the trailer in chopped form, but if the raw material is wet (moisture content >25%), there is a need for its drying. An alternative option is to use the technology of harvesting corn for grain by-products, which includes chopping and forming windrows of post-harvest sunflower residues in the field, their further baling or picking up in the chopped form.

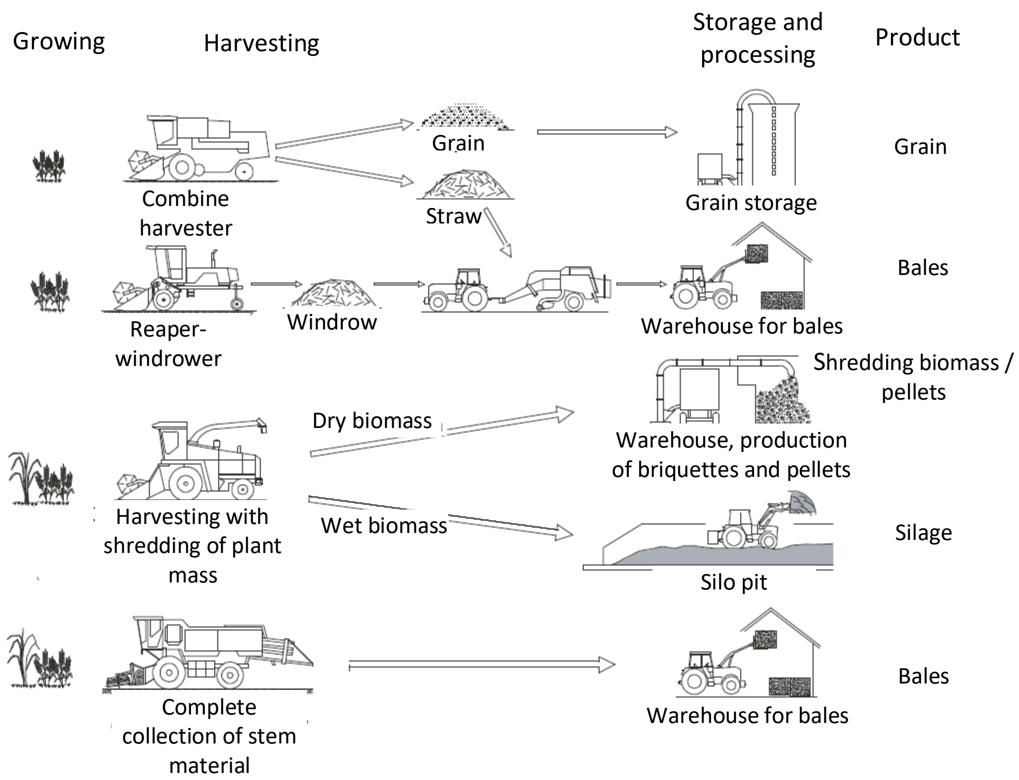

Fig. 2.1. Harvesting options for stalk biomass[35]

[35] Brochure «Supply of solid biofuels for middle-scale boiler plants». / Project «Bioenergy for Business» (B4B), 2016. – 23 p.

Calculations of harvesting technologies will be carried out for yields from 15 to 50 m.c./ha. The dependence of the yield of various components of by-products (heads and stalks) is shown in **Fig. 2.2**. Some amount of this biomass can be harvested for energy needs.

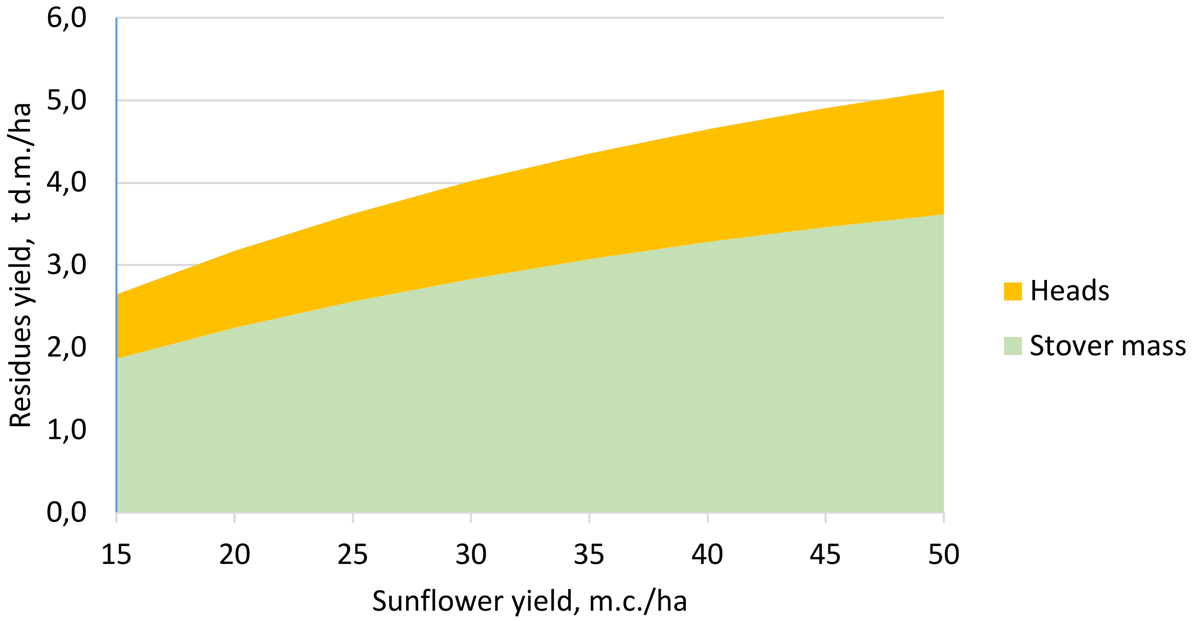

Fig. 2.2. Dependence of sunflower by-products on sunflower yield

We will perform a feasibility study of sunflower stalks harvesting with a self-propelled forage harvester, which is equipped with a reaper for harvesting coarse-stemmed crops (**Fig. 2.3**). The chopped biomass is fed to a trailer that moves next to the combine. Many tractors with trailers must be used to transport biomass simultaneously with the harvest due to the low density of chopped sunflower by-products and the high productivity of the combine. For this chain, the transport distance is up to 10 km.

Fig. 2.3. Forage harvester Claas Jaguar 940

Due to the lack of the described practical examples of sunflower by-products harvesting by forage harvesters, the calculations are based on the experience of corn stalks harvesting, taking into account the peculiar properties of sunflower. Initial conditions: the duration of harvesting is 30 days, the duration of work is 8 hours/day, deductions for maintenance and repair is 5%, amortization is 10 years, the salary of the operator is 20.6 euros/day, the yield of sunflower: min. 1.5 t/ha, av. 2.5 t/ha, max. 5 t/ha; the volume of stalks for harvesting from 1 ha of a field: min. 1.6 t d.m./ha, av. 2.1 t d.m./ha, max. 3.0 t d.m./ha.

The approximate cost of the equipment is given in **Table. 2.1**. The conditional cost is the part of the actual cost of the machinery that depends on the duration of their direct use for the harvest of the target biomass during a year.

Table 2.1. Capital cost of the machinery required for the harvesting of sunflower by-products with a forage harvester

Process/ machinery	Unit price, 1000 EUR	Use of equipment, % of the annual usage	Min 1.6 t d.m./ha		Average 2.1 t d.m./ha		Max 3.0 t d.m./ha	
			Quantity	Conditional cost, 1000 EUR	Quantity	Conditional cost, 1000 EUR	Quantity	Conditional cost, 1000 EUR
1. Collection	**240**		**1**	**120**	**1**	**120**	**1**	**120**
Forage harvester Claas Jaguar 850	240	50	1	120	1	120	1	120
2. Transportation to storage facility	**177**		**4**	**200**	**5**	**250**	**6**	**300**
Tractor Claas Axion 850	125	20	4	100	5	125	6	150
Trailer Kobzarenko TZP-39	51,9	50	4	100	5	125	6	150
Total				**320**		**370**		**420**

The results of the estimation of the net cost of the harvesting of by-products for the three volumes of biomass collection per unit area are shown in **Fig. 2.4**. Amortization is the main component of costs.

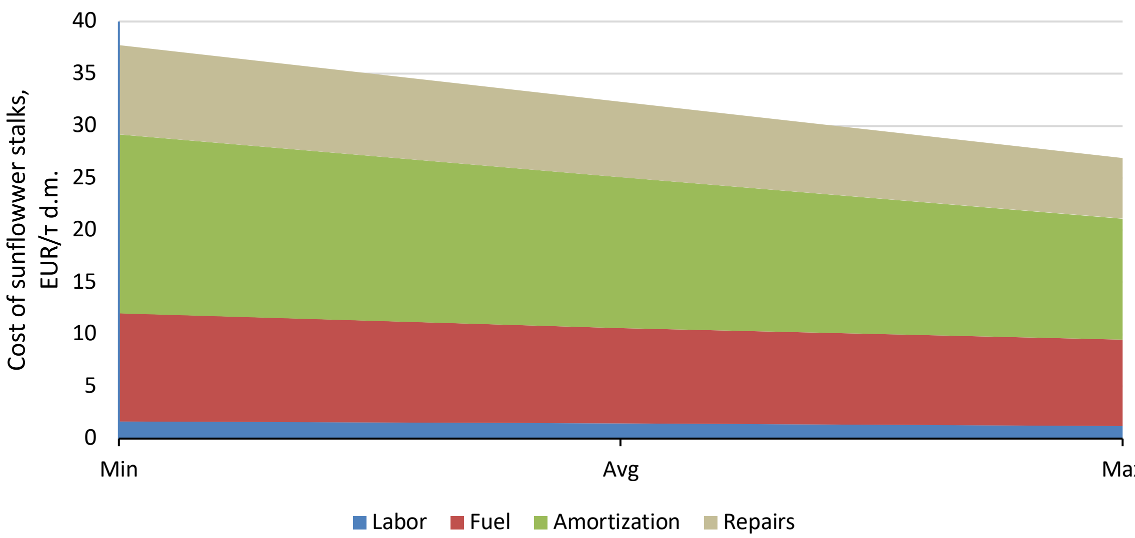

Fig. 2.4. Cost of sunflower stalks harvesting with a forage harvester

The results of the feasibility study of the chain on the basis of a self-propelled forage harvester are given in **Table. 2.2**. The payback period of crop by-products harvesting significantly depends on the volume of biomass harvested per hectare, which also affects the loading of equipment. Thus, when harvesting sunflower by-products in the amount of 3 t d.m./ha, the simple payback period of the harvesting unit is 4.8 years. In the scenario of harvesting average biomass volumes of 2.1 t d.m., which can be achieved with a sunflower yield of 25 m.c./ha, the simple payback period of such a harvesting unit is 6.4 years. At the yield of sunflower by-products of 1.6 t d.m./ha, the simple payback period of the harvesting is 8.2 years.

Table 2.2. Techno-economic assessment of harvesting sunflower by-products with a forage harvester

Indicators	Sunflower by-products yield		
	1.6 t d.m./ha	*2.1 t d.m./ha*	*3.0 t d.m./ha*
Productivity of biomass harvesting, t d.m./yr	1867	2559	3616
Capital costs, thous. EUR	320	370	420
Operating costs, thous. EUR/yr	38.5	45.7	55.3
Loan (the share of capital costs), %	60		
Loan rate, %	7		
Net cost of biomass bales*, EUR/t d.m.	37.7	32.3	26.9
Sale price of biomass**, EUR/t d.m. with VAT	45		
Simple payback period, yr	8.2	6.4	4.8
Discounted payback period (under discount rate of 7%), yr	>10	8.6	5.7
IRR, %	5.0	12.2	22.9

** The cost includes direct costs for harvesting biomass and deductions for equipment amortization.*
*** The price is equal to the sale price of sunflower by-products (W25%) of 33.8 EUR/t without VAT.*

We will also assess the effectiveness of the technology of harvesting of sunflower chaff in a trailer behind a combine harvester SK-5 Niva[18] with a shredder PSP-1.5, which were used in Ukraine at the end of the last century. Initial data: duration of harvesting is 30 days, duration of work is 8 hours/day, deductions for maintenance and repair is 5%, amortization is 10 years, the salary of a machine operator is 20.6 euros/day, the volume of chaff per unit area of a field is 0.5 t d.m./ha, annual volume of biomass harvesting is 181 t d.m./season. The net cost of sunflower chaff harvesting per unit area will be 15.9 euros/t d.m., or 11.1 euros/t d.m. without amortization of the equipment. The simple payback period for the introduction of such harvesting activity with used trailers 2PTS-4-887A, the shredder PSP-1.5, and a new tractor MTZ-82 will be 2.3 years with the sale of harvested biomass at a price of 35 euros/t d.m. without VAT and 1.7 years at a price of 45 euros/t d.m. without VAT.

At present, modern commercial combine harvesters provide scattering of crop by-products over a field surface or windrowing. Only a few individual models can be equipped with a rick-maker, while a trailer unit for the harvesting of chaff and sunflower baskets is not used. The Kherson Machine-Building Plant used to produce combines and reapers, which allowed to harvest by-products of agricultural crops in trailers at the same time as harvesting grain and seeds. Therefore, in the event of a demand for such equipment from agricultural producers, machine-building plants can establish the production of appropriate equipment in a short time.

The technology of windrowing of sunflower by-products with subsequent baling or harvesting in chopped form requires field tests.

Biomass can be transported by different types of transport, but due to the low density of shredded stalk mass and baskets, it is necessary to use vehicles with maximum volumes of trailers and bodies. In general, both existing tractors with trailers and agricultural trucks, in particular, grain trucks, and specialized vehicles can be used to transport chips with a volume of 82 to 120 m^3.

When organizing the storage of sunflower by-products, it is possible to use approaches similar to the storage of corn for grain by-products, which provide conditions to prevent excessive wetting of biomass under the influence of precipitation and from the ground, avoiding rot and providing the necessary fire protection[34]. Dry biomass is stored under cover or in indoor storages, and moisture biomass is ensiled or preserved under anaerobic conditions.

Given the insufficiently covered practice of harvesting sunflower by-products and the prospects of its implementation in Ukraine, it is necessary to conduct field tests of technologies at least on the basis of existing agricultural machinery, in particular, a forage harvester and a mulcher-windrower with a baler.

3. Use of sunflower by-products for energy

3.1. Solid biofuels

In contrast to the significant use of sunflower husk for heat and electricity and the production of fuel briquettes and pellets from them, the number of examples of sunflower by-products processing into solid biofuels in Ukraine and other countries is still quite small. Sunflower by-products are mainly used in small quantities to supply the heat energy needs of agricultural producers and rural households. Sunflower cultivation is not widespread in many countries of the world, while in Ukraine this crop has significant potential for the use in bioenergy.

Technologies for processing sunflower residues into solid biofuels have already been developed. Fuel briquettes from a mixture of sunflower parts are included in the register of alternative fuels of the State Agency on Energy Efficiency and Energy Saving of Ukraine in 2018[36].

Fuel characteristics of the by-products determine the use of specialized heating equipment. Therefore, it is important that the equipment manufacturer confirms the possibility of burning such biomass and biofuels produced from it. In Ukraine, projects for the production of energy from sunflower stalks are carried out by Kotloturboprom LLC of the MAST-IPRA Corporation[37]. Also, heat generators and burners for grain dryers, which burn the stalks and other sunflower by-products, are offered on the market [38].

The results of the experiment[39] on sunflower stalks burning to obtain thermal energy on different grates are given in **Tables 3.1-3.2**. Three forms of stalks were used:

1) harvested from the field without chopping and compression;
2) chopped without compression;
3) chopped and compressed in plastic bags.

[36] http://saee.gov.ua/uk/business/reestry
[37] https://vse.energy/docs/OEW-anokhin.pdf
[38] http://www.brig-zerno.com.ua/stati/23-sushit-zerno-gazom-ili-solomoj
[39] Halil Unal and Kamil Alibas Determining of the Suitable Burning Method for Wheat Straw and Sunflower Stalks. Journal of Applied Sciences, 6 (2006): 435-444.

Three different types of holes in grates were used in a boiler: circular, oblong, and mixed (circular with oblong). The air supply was provided by front natural draft, lower natural draft, and a lower blow fan.

Table 3.1. Averaged results of the experiment on the burning of sunflower stalks on three different grates

Circle holed grate						
Parameters	1F	1F	2F	2F	2F	3F
	FB	BB	FB	BB	*BB	*BB
Bulk density of fuel, kg/m^3	66.0	68.0	90.0	87.0	95.0	125.0
Moisture content of fuel, %	14.6	14.5	10.4	10.3	14.7	11.8
Total fuel consumption, kg	21.8	21.5	14.5	28.0	36.5	21.0
Ash, %	13.3	12.1	11.7	14.2	17.5	13.3
Fuel feeding rate, kg/h	13.3	10.5	6.2	5.2	8.8	7.0

Oblong holed grate							
Parameters	1F	1F	2F	2F	2F	3F	3F
	FB	BB	FB	BB	*BB	BB	*BB
Bulk density of fuel, kg/m^3	69.7	72.0	110.0	90.5	105.0	121.0	115.0
Moisture content of fuel, %	15.4	16.2	9.7	16.4	12.5	11.4	10.2
Total fuel consumption, kg	28.2	35.3	18.0	45.0	24.5	24.0	38.0
Ash, %	14.5	14.5	-	18.6	-	13.8	-
Fuel feeding rate, kg/h	13.9	11.1	10.0	11.4	12.7	10.5	13.2

Mixed (circle + oblong) holed grate					
Parameters	1F	2F	2F	3F	3F
	FB	BB	*BB	BB	*BB
Bulk density of fuel, kg/m^3	65.5	92.0	89.5	105.0	117.0
Moisture content of fuel, %	13.5	13.4	11.0	11.8	9.8
Total fuel consumption, kg	26.5	19.0	37.3	24.0	27.6
Ash, %	16.0	15.4	13.1	13.3	-
Fuel feeding rate, kg/h	15.5	10.1	14.0	12.0	12.7

***Notes**: 1F – sunflower stalks as it was harvested from the field, 2F – chopped stalks without compression, 3F – chopped and compressed stalks in polyethylene bags; FB – front burning, BB – natural draft burning, *BB – fan blowing burning.*

Table 3.2. Averaged results related to the flue gas measurement during sunflower stalks burning on three different grates

Circle holed grate						
Parameters	1F	1F	2F	2F	2F	3F
	FB	BB	FB	BB	*BB	*BB
T_{CG} (°C)	148.0	77.2	72.8	89.8	96.4	94.4
V_{CG} (m/s)	3.4	1.7	2.6	1.5	2.0	1.9
$Q_{N\ CG}$ (nm^3/h)	555.6	327.4	512.3	290.8	366.2	362.1
O_2 (%)	16.7	13.6	18.0	11.8	12.1	11.7

CO_2 (%)	3.8	6.6	2.7	8.1	7.8	8.1
λ (13% O_2)	1.84	1.08	2.64	0.87	0.90	0.86
CO_N (mg/nm^3)	5060.8	9119.0	12738.7	10572.1	7575.8	5525.2
$SO_{2\ N}$ (mg/nm^3)	0	21.5	119.8	0	0	0
$NO_{x\ N}$ (mg/nm^3)	442.8	213.6	313.6	167.1	110.3	137.9

Oblong holed grate

Parameters	1F	1F	2F	2F	2F	3F	3F
	FB	BB	FB	BB	*BB	BB	*BB
T_{CG} (°C)	133.9	152.2	88.5	135.9	176.8	149.7	142.8
V_{CG} (m/s)	3.9	3.5	2.4	2.8	3.1	3.2	3.7
$Q_{N\ CG}$ (nm^3/h)	650.9	558.2	460.5	471.1	474.2	520.9	612.2
O_2 (%)	16.5	13.7	18.3	13.0	14.1	13.8	13.9
CO_2 (%)	3.9	6.4	2.4	7.1	6.0	6.4	6.2
λ (13% O_2)	1.76	1.10	2.99	0.99	1.16	1.11	1.13
CO_N (mg/nm^3)	4570.2	2953.9	10808.8	1765.5	1626.3	2851.7	3414.7
$SO_{2\ N}$ (mg/nm^3)	0	15.6	0	23.5	0	0	0
$NO_{x\ N}$ (mg/nm^3)	346.2	271.5	197.6	193.8	403.9	276.0	333.8

Mixed (circle + oblong) holed grate

Parameters	1F	2F	2F	3F	3F
	FB	BB	*BB	BB	*BB
T_{CG} (°C)	149.1	116.0	121.8	130.2	167.5
V_{CG} (m/s)	3.2	2.8	3.1	2.9	3.2
$Q_{N\ CG}$ (nm^3/h)	521.6	486.4	531.5	486.3	499.8
O_2 (%)	13.0	13.1	14.3	13.9	14.4
CO_2 (%)	7.0	7.0	5.9	6.3	5.9
λ (13% O_2)	1.0	1.01	1.19	1.12	1.20
CO_N (mg/nm^3)	2834.8	2181.5	2920.0	1706.3	4223.8
$SO_{2\ N}$ (mg/nm^3)	0	0	18.6	3.4	0
$NO_{x\ N}$ (mg/nm^3)	190.0	117.2	172.3	246.8	305.2

***Notes** are the same as in Table 3.1.*

Air supply under grate allows to reduce emissions of pollutants from the burning of sunflower stalks. High CO emissions are related to the specific conditions of the experiment. The organization of combustion and regulation of air supply in industrial boilers provide CO emissions within the permissible limit. According to Ukrainian regulations[40], the maximum permitted emissions from the combustion of solid fuels in stationary sources are 250 mg/m^3 for CO, 500 mg/m^3 for NO_x, and 500 mg/m^3 for SO_2. Boilers can be equipped with filters to meet the requirements for the maximum permitted emissions from the combustion of biofuels, produced from sunflower by-products. Thus, the necessary conditions for the processing of sunflower by-products into solid biofuels and its following combustion for energy production are already available.

[40] Norms for the permissible emission of pollutants from stationary sources. Ministry of Environmental Protection of Ukraine, Order No. 309 of 27.06.2006. Ministry of Justice of Ukraine, 1 July 2006 No. № 912/12786. URL: https://zakon.rada.gov.ua/laws/show/ru/z0912-06

3.2. Biogas

During harvesting, sunflower by-products can have a high moisture content, making it difficult to store and process them into solid biofuels. At the same time, such wet biomass can be used for biogas production. However, due to the high content of lignocellulosic chemical compounds in sunflower by-products, it must be pretreated for mechanical, physical, or chemical destruction before the fermentation.

Methane yield from sunflower heads and stalks is shown in **Fig. 3.1**. The biochemical potential of methane of untreated heads was 210 ± 1.97 ml of CH_4/g volatile solids (VS), and 127.98 ± 5.19 ml CH_4/g VS for untreated stalks.

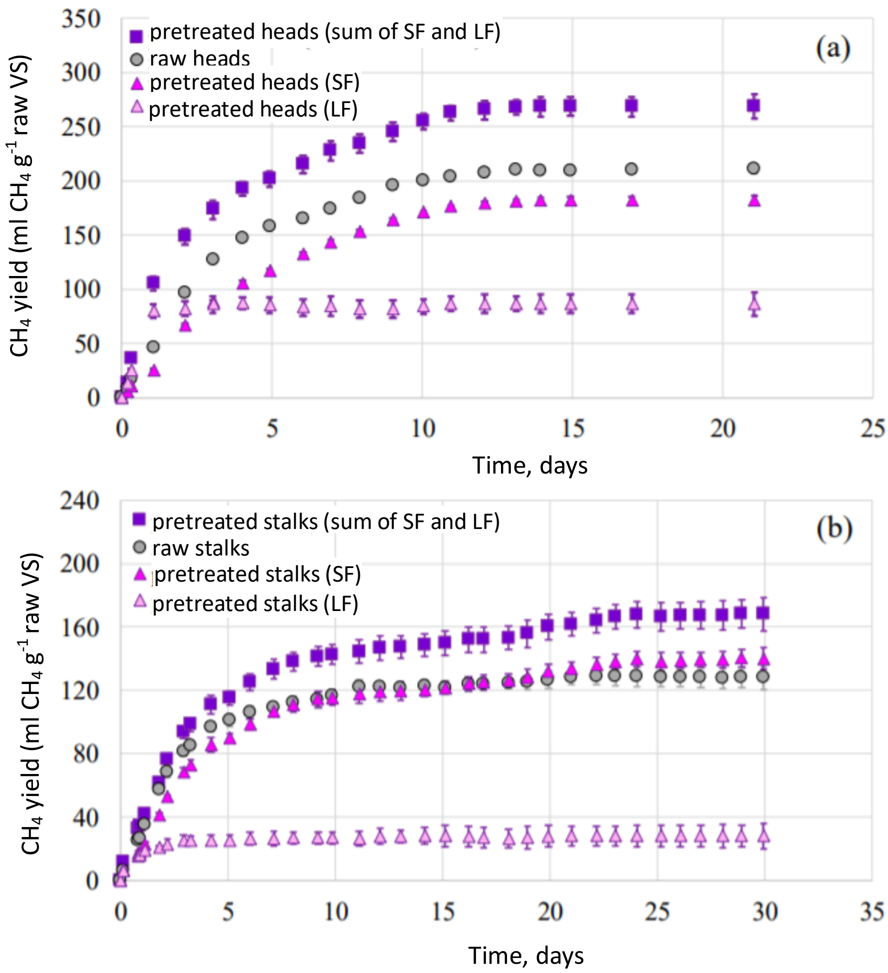

Fig. 3.1. Biochemical methane potential (BMP) profiles of pretreated and untreated sunflower (a) heads and (b) stalks[41]

Notes: *Values correspond to three times repeatability of independent values ± standard deviations (error bars). SF: solid fraction, LF: liquid fraction.*

Heads are considered to be better raw material for biogas production in comparison with sunflower stalks. After alkali pre-treatment, the yield of methane from the head residues was 268.35 ± 0.11 ml of CH_4/g VS, while the yield of methane from the treated sunflower stalks was 168.17 ± 6.87 ml

[41] Marinela Zhurka, Apostolos Spyridonidis, Ioanna A. Vasiliadou and Katerina Stamatelatou Biogas Production from Sunflower Head and Stalk Residues: Effect of Alkaline Pretreatment / Molecules 2020 Jan; 25(1): 164.

of CH_4/g VS. According to the experimental data, the content of VS was 79.9 ± 0.5% of dry weight in heads and 87.7 ± 0.1% of dry weight in sunflower stalks. Thus, up to 214 m^3 of methane can be obtained from 1 t d.m. of heads and up to 154 m^3 from 1 t d.m. of sunflower stalks.

Some farmers grow sunflower for green fodder and silage. For comparison: the yield of methane from sunflower silage is 298 nm^3/t[42]. The yield of methane from various plant substrates is presented in **Table 3.3**.

Table 3.3. Methane yield from some plants and plant parts [43]

Crop	Methane yield, m^3/VS
Maize (whole crop)	205-450
Grass	298-467
Clover grass	290-390
Sunflower	154-400
Oilseed rape	240-340
Potatoes	275-400
Sugar beet	236-381
Fodder beet	420-500
Straw	242-324
Leaves	417-453

The analysis of different options for the pre-treatment of sunflower stalks before the anaerobic fermentation was performed in the studies[44,45]. The highest yield of methane (259 ± 6 ml CH_4/g VS) was achieved after alkali pre-treatment of stalks with 4% NaOH at a temperature of 55 °C for 24 hours. Thus, alkali pre-treatment of sunflower by-products before the anaerobic fermentation, as well as alkali pre-treatment of other lignocellulosic substrates, increases methane yield, but to ensure the high process efficiency, more concentrated substrates (over 35 g d.m./l) and heat recovery systems must be used.

3.3. Bioethanol

The use of sunflower biomass as a raw material for bioethanol production requires its pre-treatment to destroy the lignocellulosic structure, which makes the access of enzymes to the cellulose chains easier or directs the use of their lignocellulosic fractions[46]. The pre-treatment by steam and simultaneous saccharification and fermentation makes it possible to obtain 1 l of ethanol from 3.8 kg of pretreated sunflower stalks. In terms of the equivalent amount of raw material, it can be produced

[42] Guide to biogas. From production to us, FNR, 2012. https://mediathek.fnr.de/media/downloadable/files/samples/g/u/guide_biogas_engl_2012.pdf

[43] The biogas handbook. Science, production and applications. Edited by Arthur Wellinger, Jerry Murphy and David Baxter. Woodhead Publishing Series in Energy (Book 52), 2013. – 512 p.

[44] F. Monlau, A. Barakat, J.P. Steyer, H. Carrere Comparison of seven types of thermo-chemical pretreatments on the structural features and anaerobic digestion of sunflower stalks, Bioresource Technology 120 (2012) 241–247.

[45] F. Monlau, P. Kaparaju, E. Trably, J.P. Steyer, H. Carrere Alkaline pretreatment to enhance one-stage CH_4 and two-stage H_2/CH_4 production from sunflower stalks: Mass, energy and economical balances, Chemical Engineering Journal 260 (2015) 377–385.

[46] Osiris Ashton Vital Brazil et al. Integral use of lignocellulosic residues from different sunflower accessions: Analysis of the production potential for biofuels. Journal of Cleaner Production 221 (2019) 430-438.

101.4 liters of bioethanol from 1 ton of sunflower stalks[47]. Prehydrolysis at the temperature of 180-230 °C with simultaneous saccharification and fermentation makes it possible to obtain 12 g of bioethanol/100 g of sunflower stalks (150 l/t), which is equivalent to 72.2% of the theoretical yield[48]. A typical scheme of bioethanol production from lignocellulosic raw material is shown in **Fig. 3.2.** The data on the theoretical yield of bioethanol from different types of biomass is provided in **Table 3.4**.

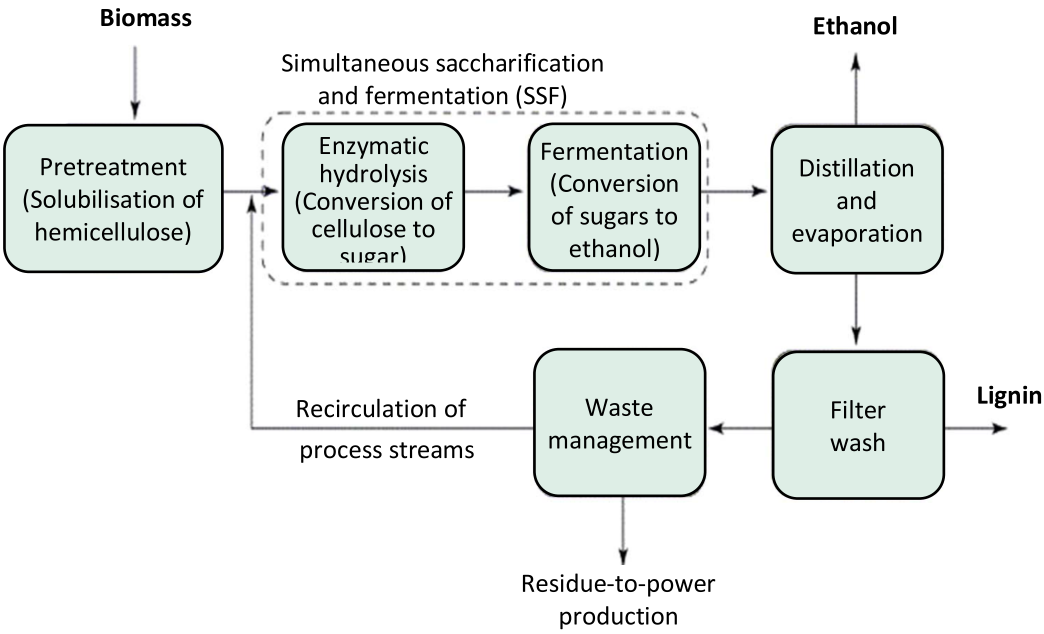

Fig. 3.2. Bioethanol production process from lignocellulosic biomass [49]

Table 3.4. Bioethanol yield from different feedstocks [49]

Feedstock	Potential ethanol yield, (litre per dry tonne of feedstock)
Corn grain	470
Corn stover	428
Rice straw	416
Forest thinnings	309
Hardwood sawdust	382

In a study of growing four varieties of sunflower in the semi-arid region of north-eastern Brazil with further processing into liquid biofuels[46] (seeds for biodiesel, and stalks and heads for bioethanol), from one hectare it was received 2537 kg d.m. of by-products and 1635 kg d.m. of seeds, respectively, 663 kg/ha of oil and 1115 kg/ha of sugars (871 kg/ha of cellulose and 244 kg/ha of hemicellulose). It was possible to obtain 293 l of bioethanol/ha from these amount of sunflower by-products.

[47] Ruiz, E., Cara, C., Ballesteros, M., Manzanares, P., Ballesteros, I., & Castro, E. (2006). Ethanol Production From Pretreated Olive Tree Wood and Sunflower Stalks by an SSF Process. Applied Biochemistry and Biotechnology, 130(1-3), 631–643.
[48] Evelin Raquel Ruiz et al. Strategies for bioethanol production from sunflower stalks Afinidad –Barcelona – 68 (556): 417-423. – November, 2011.
[49] M. N. A. M. Yusoff, N. W. M. Zulkifli, B. M. Masum and H. H. Masjuki Feasibility of bioethanol and biobutanol as transportation fuel in spark-ignition engine: a review. RSC Adv., 2015, 5, 100184–100211.

4. Sustainable development of value-added chains of sunflower by-products

In Ukraine, in 2019, sunflower crops covered almost 6 million hectares, which was about 21% of the total sown area of annual and biennial crops. According to the methodological recommendations on the optimal ratio of crops in crop rotations of different soil and climatic zones of Ukraine[50], approved by the Order of the Ministry of Agrarian Policy No. 440/71 of 18.07.2008, the rotation period of sunflower in the Forest-Steppe should be 7-8 years and 7-9 years for the Steppe. According to the recommendations of the State Institute of Grain Crops of NAAS of Ukraine[51], it is better to have no more than 20% of sunflower in the structure of the sown area, returning to the previous place in 5-6 years. But in real practice, the sunflower area significantly exceeds the recommendations, and sometimes reaches 35-40%. The analysis of the agricultural platform EOS Crop Monitoring[52] shows that a significant percentage of agricultural land in Ukraine is cultivated against the principles of the crop rotation. In some areas, almost 70% of sunflower fields are sown two or more times in a row.

Exceeding the recommended norms increases the probability of deterioration of water balance, phytosanitary condition of crops and soil and intensifies the degradation processes, in particular leads to the humus loss. For the formation of 1 ton of seeds, sunflower takes from the soil, on average, 40-42 kg of nitrogen, 8-10 kg of phosphorus, and 60-62 kg of potassium[53].

In recent years, the main source of organic matter in the soil is the vegetative remains of crops and their roots. Often more nutrients enter the soil with plant residues than with fertilizers. The remains of the root system with root secretions are particularly important because they are biologically more valuable than stalks, which is why crops with a well-developed root system, such as sunflower with a root mass of 2.5-5.8 t/ha[54], are beneficial. To decompose the post-harvest residues of sunflower it is needed to apply at least 5 kg of active material of nitrogen/t[55]. The use of mineral and organic fertilizers will replace the nutrients that are taken from the fields with the crop by-products. Characteristics of sunflower stalks for their use as fertilizer are given in **Table 1.4**.

An example of sunflower growing on an area of 30 hectares in Italy with the processing of sunflower seeds into biodiesel and by-products for energy, bioethanol, biogas, and biomaterials is shown in **Fig. 4.1**. Such a package solution allowed to obtain market products for 3815 euros/ha.

[50] https://zakononline.com.ua/documents/show/54725___54725
[51] Agrotechnological and organizational strategy of a spring field (Special aspects of growing crops in the Steppe of Ukraine in 2019) / State Institute of Grain Crops of NAAS of Ukraine, 2019. – 82 p. http://www.institut-zerna.com/library/sci_recomendation2019.pdf
[52] https://superagronom.com/news/9866-bilshist-sonyashniku-v-ukrayini-viroschuyetsya-z-porushennyam-sivozmini
[53] Innovative agro-strategy 2020 (Special aspects of growing agricultural crops in the Steppe of Ukraine in 2020) / State Institute of Grain Crops of NAAS of Ukraine, 2020. – 96 p.
[54] https://propozitsiya.com/ua/yaki-kulturi-visnazhuyut-grunt-bilshe
[55] https://agro.dn.gov.ua/najchastishe-girshe-sonyashnik-i-rodyuchist-gruntu/

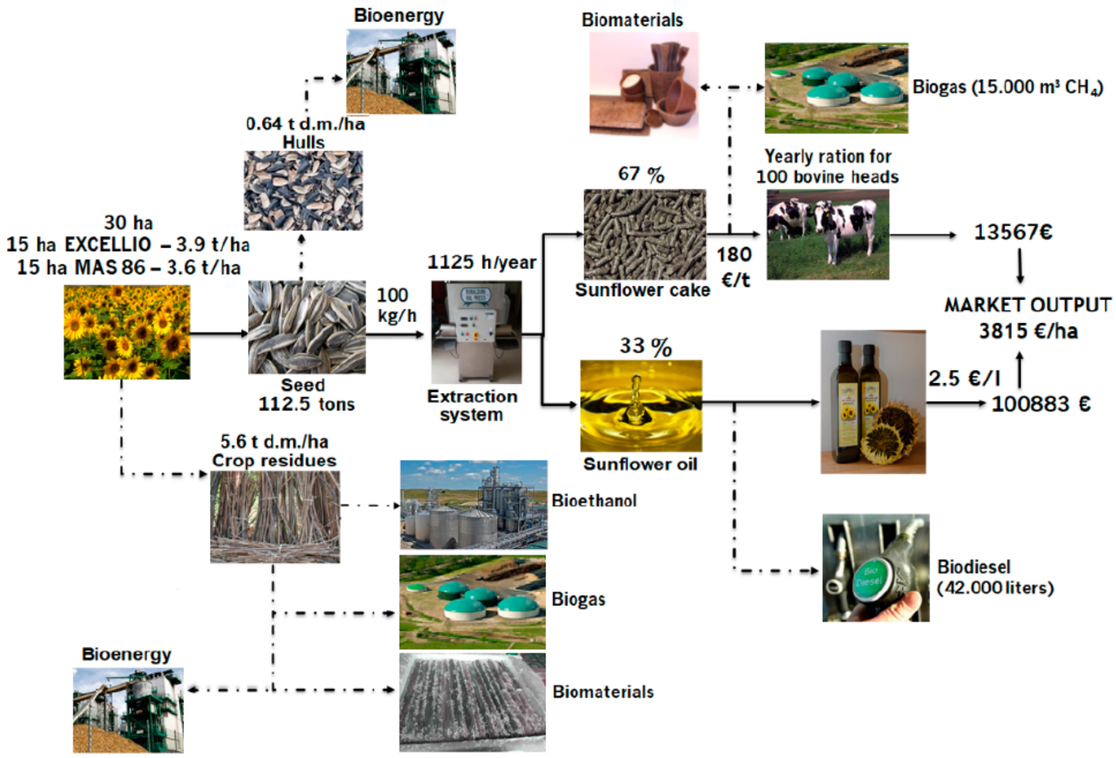

Fig. 4.1. Mass balance and market output of a small local system of sunflower cold-pressed oil production [56]

Notes: *Possible alternative ways of obtaining added value from residues and by-products are shown by a dotted line.*

The scheme of the environmental analysis of the use of sunflower stalks for the production of biomaterials is shown in **Fig. 4.2**. When growing sunflower the most significant negative impact on human health (over 40%) and ecosystems (about 60%) is associated with the use of fertilizers and pesticides, and these substances account for almost 50% of the cost of resources. Various factors of the impact of sunflower during the life cycle on the environment were compared with the impact of corn growing. Growing sunflower has less impact on the environment in terms of moisture, fertilizer, and pesticide needs than standard crop production practices such as corn for grain. Moreover, the use of available sunflower by-products allows obtaining environmental benefits in comparison with other natural fibers, which require additional agricultural land that increases the environmental impact.

[56] Foppa Pedretti, E.; Del Gatto, A.; Pieri, S.; Mangoni, L.; Ilari, A.; Mancini, M.; Feliciangeli, G.; Leoni, E.; Toscano, G.; Duca, D. Experimental Study to Support Local Sunflower Oil Chains: Production of Cold Pressed Oil in Central Italy. *Agriculture* **2019**, *9*, 231; https://doi.org/10.3390/agriculture9110231

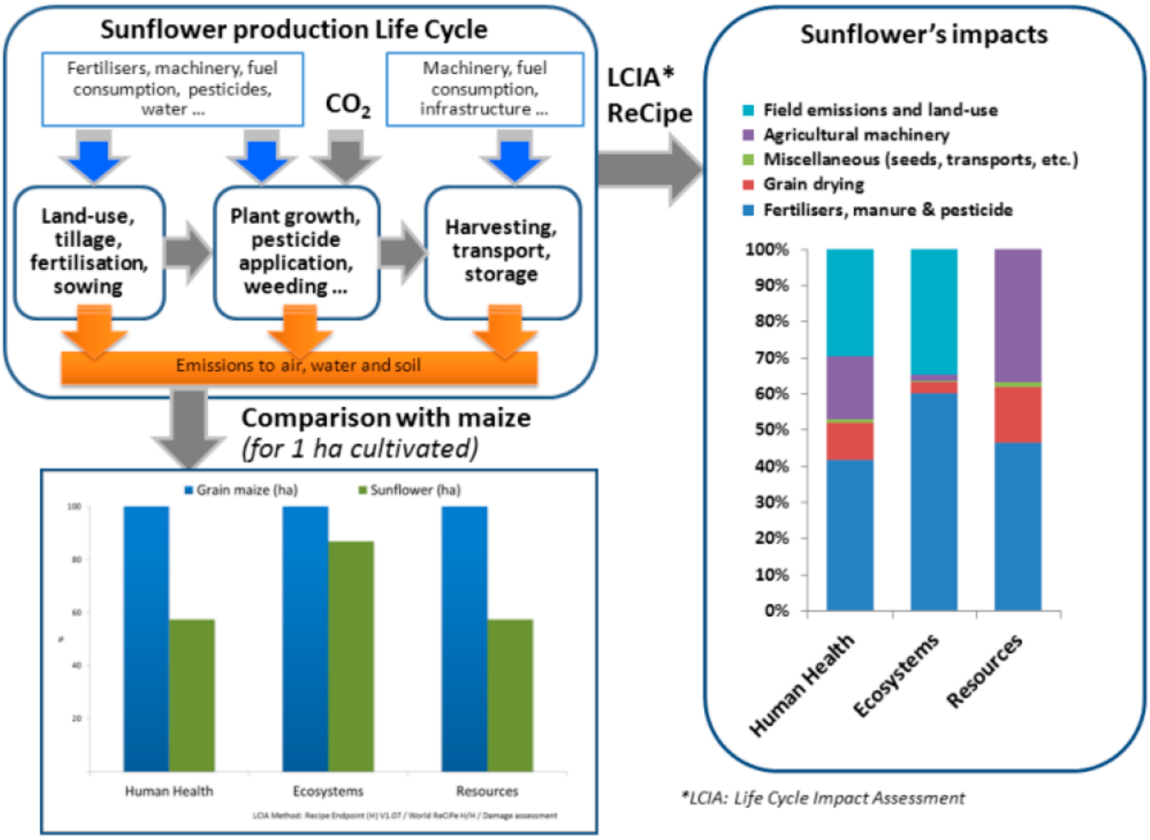

Fig. 4.2. Environmental analysis of sunflower production [31]

Thus, when introducing value-added chains of sunflower by-products, it is important to ensure a humus balance in the soil and keep within the agrochemical law of nutrient return, according to which nutrients taken from the soil with the cultivated crops must be returned to the soil and such consequences as erosion and deterioration of soil characteristics must be avoided. Partially, nutrients can be returned with ash, bioethanol production waste and fermented substrate.

Conclusion

1. Ukraine is a world leader in sunflower production. In 2019, the gross harvest of sunflower in Ukraine amounted to **16.5 million tons**, which is almost 30% of the world production, with an average yield of 2.58 t/ha. In addition to the grain part, a very large amount of by-products (stalks, heads, leaves, etc.) are formed, which can be processed into solid, liquid, and gaseous biofuels.
2. The economic energy potential of sunflower potential in Ukraine made up 11.6 Mt or **1.7 Mtoe**. Among the regions, **Kirovohrad (167.8 Mtoe)**, Kharkiv (161.3 Mtoe), and Dnipropetrovsk (157.8 Mtoe) regions were the leaders.
3. **Sunflower by-products can be considered as lignocellulosic biomass.** Sunflower heads and stalks generally have similar fuel characteristics and have almost the same calorific value as for corn stalks. The ash melting point of sunflower stalks is 800-1270 °C, which is close to straw, and lower than for the corn stalks and wood chips, which should be considered when choosing heating equipment. Sunflower stalks have a high chlorine content of 0.7-0.8%, which also complicates their combustion, as chlorine compounds cause corrosion of steel elements of power equipment. For the biogas and bioethanol production, sunflower stalks and heads must be pretreated to destroy the lignocellulosic structure. After that, up to 214 m^3 of methane can be obtained from 1 t d.m. of sunflower heads, and up to 154 m^3 of methane or 101.4 l of bioethanol from 1 t d.m. of sunflower stalks.
4. The feasibility study of two chains of sunflower by-products harvesting was conducted: stalks with the use of a modern forage harvester and sunflower chaff in a trailer behind a grain harvester SK-5 Niva with a shredder PSP-1.5, using the technology used in Ukraine at the end of the last century. **The cost of harvesting of sunflower chaff per unit area is 11.1 EUR/t d.m. without equipment amortization. Harvesting of stalks was considered for three values of by-products output from the field: 1.6, 2.1, and 3.0 t d.m./ha, for which the total cost of harvesting is respectively: 37.7, 32.3 and 26.9 EUR/t d.m.** The simple payback period for the harvesting of 3.0 t d.m./ha is 4.8 years on conditions that the sale price of biomass is 45 EUR/t d.m. without VAT. Given the insufficiently covered practice of harvesting sunflower by-products and the prospects of its implementation in Ukraine, it is necessary to conduct field tests of technologies based on the existing agricultural machinery, in particular, a forage harvester and a mulcher-windrower with a baler.

Abbreviations

d.m. – dry matter
ha – hectare
ktoe – thousand tons of oil equivalent
m.c. – metric centners
Mt – million tones
Mtoe – million tons of oil equivalent
MY – marketing year
NAAS – National Academy of Agrarian Sciences
VS – volatile solids

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