

SORGHUM, THE CROP OF THE FUTURE UNDER CLIMATE CHANGE CONDITIONS

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Abstract

Sorghum, a herbaceous species of the Poaceae family is the fifth most cultivated plant in the world, being the main bread grain in Africa, Southern Europe, Central America and South Asia. Sorghum competes with corn, being an important fodder plant for biogas production of alcohol, growing with its inherent tolerance to drought, short cultivation times and relatively low operating costs of corn has determined the interest in cultivation. The aim of the paper is to identify the major sorghum-growing nations worldwide, in Europe, and domestically, examines their production levels, and analyzes their potential regarding yield, land utilization, and climate compatibility. Statistical data from FAOSTAT, EUROSTAT, and NIS Romania constituted the primary materials for this analysis. The methodological framework involved the calculation of the arithmetic mean, standard deviation, and coefficient of variation as key statistical indicators. These results are presented in both graphical and tabular forms. Main results and conclusions show that sorghum is recommended for drought-prone areas due to its resilience, low costs, profitability, and simple cultivation. Globally, top producers are the USA, Nigeria, Mexico, India, and Ethiopia, while highest yields per hectare are in Oman, Jordan, Israel, Austria, and Italy. Within the EU, France is the main cultivator, with Romanian cultivation showing significant variability (41.6% between 2013-2023). The current changing pedoclimatic conditions are increasing sorghum's importance in Europe, with France, Hungary, and Italy being major EU cultivators. Despite its drought resistance and nutritional value, Romanian sorghum production is declining annually.

Key words: sorghum crop, drought, productions, yields, EU, Romania

INTRODUCTION

Sorghum is one of the top five cereals cultivated in the world, along with the wheat, rice, maize, and barley, owning its popularity to its inherent drought tolerance, short growing season, and relatively low operating costs. The entire plant can be used by turning sorghum crop residues, such as stalks, leaves, peduncles, and panicles, into ethanol, presenting significant opportunities for sustainable biofuel production [12]. The beginnings of sorghum cultivation took place in sub-Saharan Africa, as suggested by the wild predecessors of sorghum that were discovered in Africa, south of the Sahara, in Yemen and Sudan. All over 30 different species of sorghum are rooted to tropical and subtropical climate regions of Equatorial Africa, characterized by adaptations to conditions of high temperature and limited water availability. Substantial sorghum production is also registered in China,

Southeast Asia, and America [22]. Following its introduction to Europe and the United States, sorghum's principal application remains in the composition of livestock nutrition [1, 25]. Ranking as the fifth most cultivated cereal globally and the second in Africa, sorghum is the most cultivated species in the Sahelian zone nutrition [2]. A species of sorghum called sorghum bicolor is an important crop cultivated worldwide, with a range of end uses, encompassing human consumption as a cereal grain and sorghum molasses, animal feed, and the production of both ethanol and other biofuels, with ethanol yields comparable to those of maize. In addition to the food benefits mentioned above, sorghum also has the ability to improve the soil's physical properties, such as structure and porosity, similar to the effect of the traditional tillage practices: thus in a well-structured soil the activity of microorganisms increases, stimulating the formation of humus, based on

the plant residues introduced into the soil [3]. From an agronomic perspective, farmers' preferences for including sorghum in their crop rotation plan are driven by the use of this plant as an alternative to corn in drought-prone areas, due to its resistance to high temperatures and high performance under water stress conditions. This makes the plant a viable option for cultivation, even though sorghum has a lower yield than corn. The sorghum plant can significantly reduce the transpiration process, restarting the vegetative cycle when humidity levels normalize [9]. Developing drought-adapted sorghum varieties is an important way to mitigate this agricultural constraint [24]. Sorghum cultivation is appreciated worldwide for its adaptation to diverse agro-pedological and environmental conditions, as well as for its multiple uses. In Romania, cultivated areas are quite small compared to the existing agro-climatic potential [14]. Its ability to withstand high temperatures makes sorghum cultivation suitable for coping with climate change [11]. The manifestation of the climate changes in the form of severe drought conditions presents a significant challenge, highlighting the need to improve the efficiency of sorghum breeding programs. The implementation of digital technologies in the form of "machine learning models" that can estimate the duration of drought resistance represents a critical step for the sorghum plant [19]. It is also necessary to improve production technologies to generate an enhanced capacity to adapt to future drought events [16]. Due to its widespread cultivation and the fact that it is a versatile crop, we can talk about sorghum cultivation as a multifunctional crop [12]. The utilization potential of sorghum cultivation is varied, from animal feed to biomass [17] and the improvement of antioxidant therapies [4]. In the context where emphasis is placed on agriculture's contribution to reducing greenhouse gas levels, sorghum is an optimal option, as one hectare cultivated with sorghum fixes about 50-55 tons of carbon dioxide, compared to wheat which does not fix more than 15 tons of CO₂/ha. Different residue management practices can affect carbon (C) allocation and, therefore, soil C and nitrogen

(N) rotation [23]. For human consumption, this ancient whole grain has a multitude of nutritional benefits. Being utilised as a flour substitute for wheat, it allows for the production of a range of food products, including porridges, flatbreads and cakes. Given its absence of gluten, it requires the addition of binding agents to replicate the function of gluten-containing flours. Intermediate ground sorghum flour has the lowest glycemic level [18]. The strong, characteristic flavor can be reduced by processing. The grains are also used to make edible oil, starch, dextrose, pasta and alcoholic beverages, as well as popped, making popcorn. Sorghum syrup retains all its natural sugars and other nutrients, being an important sweetener for many small communities until this century and, even today, is still important locally. Sweet sorghum has a high sugar content and is grown especially for the production of fodder, silage and syrup [20]. Before the introduction of daily vitamins, sorghum was prescribed as a daily supplement for people with nutrient deficiencies, as sorghum contains iron, calcium and potassium. Improvements in the nutritional value of sorghum can increase its use in the aquatic feed market as a new emerging substitute for fish meals [26]. In Romania, non-irrigated sorghum technology trials in the Amzacea Village, Constanta County, showing the necessity to adjust the planting period by about 25-30 days, compared to standard practices, to enhance soil moisture capture, the use of early hybrids to cope with the severe drought in June, and seed treatment before planting [10]. By 2030, global sorghum production and the marketing sector are expected to increase, on one hand due to the demographic expansion and on the other hand, due to the diversification of sorghum utilisation across multiple sectors [21]. In this context, the paper aims to identify the main sorghum-growing countries worldwide, in Europe and Romania, by analysing the areas and yields of sorghum cultivation, the purpose being to identify the technical, technological and economic potential regarding the cultivation, processing and consumption of this plant, considered a plant of the future, in the

context of increasingly evident climate changes.

MATERIALS AND METHODS

This paper is based on an extensive documentary basis, using the bibliographic method and highlights the quantities of pesticides and fertilizers used in the sorghum cultivation system in the main producing countries.

The statistical sites used were Faostat [7] and Eurostat [6] si NIS Romania [13].

The period covered by the study was 2013–2024, and the main indicators analyzed, which were processed based on the data taken from the sites mentioned above, are: areas cultivated with sorghum; total and average production for sorghum crop in the world, UE and Romania. The research results were presented in tabular and graphical form, using Microsoft Office.

The statistical indicators calculated for the areas cultivated with sorghum and for the total sorghum productions in the period 2013-2024 were the arithmetic mean of the variable X values denoted, the standard deviation S , the coefficient of variation $V = \frac{S}{X} \cdot 100$. The

closer the value of v is to zero, the weaker the variation, the more homogeneous the collective, the higher the degree of representativeness of the mean. The larger the value of v , the more intense the variation, the more heterogeneous the collective, and the lower the level of significance of the mean.

The linear regression equations $Y=a \cdot x+b$ determined using the least squares method, the correlograms and the graphical representation of the regression lines highlight the evolution of cultivated areas, total sorghum productions, as well as the relationship between production and cultivated area in the studied period. In the model $Y=a \cdot x + b$, the independent variable x represents time (year), or cultivated area, and the dependent variable Y represents sorghum production.

The Pearson linear correlation coefficient

$$r = \frac{\text{cov}(X, Y)}{S_x \cdot S_y}$$

measures the direction and intensity of the relationship between two

variables denoted X =cultivated area and Y =total production. Correlations are analyzed according to the interval in which r is found, as follows:

- r in the interval $(0; 0.2]$ results in a very weak, almost non-existent correlation;
- r in the interval $[0.2; 0.4]$ results in a weak positive correlation;
- r in the interval $[0.4; 0.6]$ results in a moderate positive correlation;
- r in the interval $[0.6; 0.8]$ results in a strong positive correlation.

The coefficient of determination R^2 establishes the share of the factorial variance in the total variance.

$$R^2 = 1 - \frac{\sum_{i=1}^n (y_i - \hat{y}_{regression})^2}{\sum_{i=1}^n (y_i - \bar{y})^2} \in [0, 1]$$

To validate the mathematical models, we applied the Fischer test.

RESULTS AND DISCUSSIONS

Main sorghum-growing countries worldwide

Worldwide, over 90% of the area cultivated with sorghum is found in developing countries (Figure 1), mainly in Africa and Asia, where it is grown on savannah lands, occupying approximately 40 million hectares. From the analysis of data provided by FAOSTAT (The world's most comprehensive statistical database on food, agriculture, fisheries, forestry, natural resources management and nutrition) [7], for 2023, in the top 10 sorghum-growing countries, by area, we find countries such as Sudan, Nigeria, Niger, India, USA, Burkina Faso, Mali, Ethiopia, Brazil, Mexico.

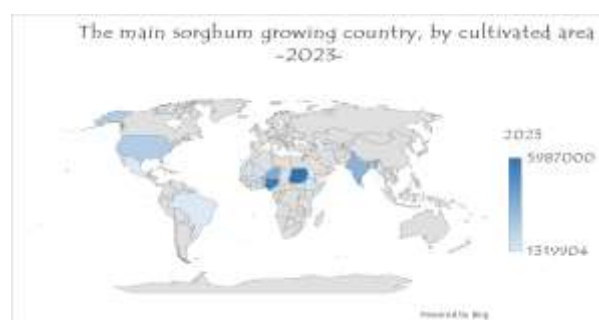


Fig. 1. Global distribution of the main sorghum-growing countries

Source: Own data processing based on the data from FAO [7].

Although sorghum is less known in the Western world, it is a widely cultivated cereal crop globally.

Farmers prefer the sorghum cultivation because of its heat and drought tolerance, and suitability for various soil types. It has multiple uses, primarily in animal feed and ethanol-based fuel production (North America), but also in human food, with research indicating an impressive nutritional profile for sorghum.

Among the sorghum-growing countries in Africa (Figure 2), Sudan stands out, being the world's largest sorghum cultivator in 2023. Cultivated areas in Sudan have fluctuated during the analyzed period (2013-2023), ranging from 5,197 million hectares (2015) to 9,157 million hectares (2016). Compared to 2013, Sudan cultivated an area smaller by 15.44% in 2023, representing 1,092 million hectares. Nigeria ranked second globally in 2023 in terms of sorghum cultivated areas, with 5,700 million hectares. This area remained relatively constant, with slight fluctuations during the analysis period (with a maximum of +/-7% from year to year).

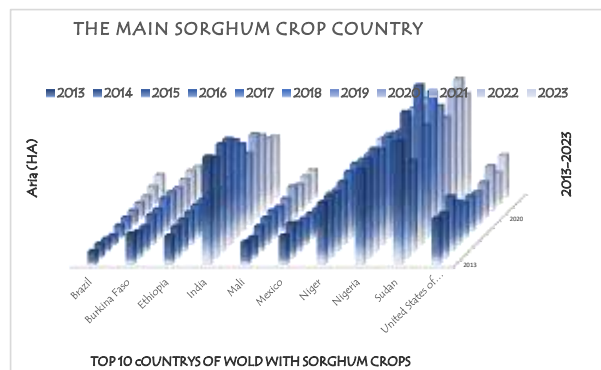


Fig. 2. Main sorghum-growing countries worldwide
Source: Own data processing based on the data from FAO [7].

Another African sorghum-growing country is Niger, ranking third among global producers in 2023 by cultivated area, with 3,700 million hectares.

Niger also shows a constant cultivation of sorghum, with small fluctuations of approximately +/-5% during the analysis period, similar to Nigeria.

India ranks fourth among sorghum-growing countries. In 2023, the cultivated area was

3,534 hectares, showing a downward trend in areas dedicated to this crop. The decrease in cultivated areas in 2023 compared to 2013 was 43.09%.

The United States of America occupies the fifth position in the mentioned ranking, with an area of 2,474 million hectares in 2023 (Table 1).

The trend is either to maintain or slightly decrease (7.14% lower in 2023 compared to 2013), except for 2015, when the area increased by 22.65% compared to the previous year.

The next sorghum-growing country in Africa is Burkina Faso, with a cultivation area of 1,793 million hectares in 2023.

Area fluctuations were observed during the analysis, recording years with increases compared to the previous period (20.02% in 2016 compared to 2015, 14.42% in 2018 compared to 2017, 5.34% in 2021 compared to 2020 and 7.20% in 2022 compared to 2021) but also years with decreases in area (14.29% in 2014 compared to 2013, 6.68% in 2015 compared to 2014 and 3.86% in 2017 compared to 2016, with insignificant differences in the other years).

Mali ranks seventh among sorghum-growing countries, with areas located at 1,632 million hectares in 2023, up 22.87% compared to the area cultivated with sorghum in 2013.

Ethiopia is the country ranked eight globally in sorghum cultivation, with 1,480 million hectares in 2023, an 11.78% reduction from 2013. Brazil's cultivation area reached 1,344 million hectares, marking a 69.57% increase over the same period.

Mexico ranks tenth among sorghum-growing countries, with 1,319 million hectares in 2023, down 11.85% compared to 2013.

Sorghum is mainly used in human food in climates that do not allow the production of other cereals, which justifies the predominance of cultivation in some African countries, where annual consumption is 100 kg of sorghum per person.

Analyzing the sorghum production achieved worldwide, the ranking of world countries changes.

Table 1. Evolution of areas cultivated with sorghum in the period 2013-2023

Country	2014/ 2013	2015/ 2014	2016/ 2015	2017/ 2016	2018/ 2017	2019/ 2018	2020/ 2019	2021/ 2020	2022/ 2021	2023/ 2022	The variation 2023/2013	
	-%-										Relative -%-	Absolute -ha-
Brazil	105.96	87.25	76.15	133.39	107.47	102.27	107.43	101.17	117.92	128.19	169.57	551,570
Burkina Faso	85.71	93.32	120.02	96.14	114.42	99.08	91.77	105.34	107.20	91.58	99.29	-12,746
Ethiopia	109.37	101.09	101.47	100.77	96.48	99.92	91.86	80.42	114.77	95.48	88.22	-197,486
India	93.24	106.39	98.70	92.51	89.33	81.46	117.86	90.76	86.82	93.00	56.91	-2,675,279
Mali	90.67	120.97	107.06	101.66	90.49	104.57	122.06	84.40	106.04	99.60	122.87	304,206
Mexico	119.24	82.36	91.22	94.37	91.09	101.87	109.73	89.26	104.08	97.73	78.15	-369,013
Niger	100.20	95.65	105.50	105.99	101.98	96.18	97.99	95.83	107.59	97.72	103.78	134,916
Nigeria	104.64	103.45	92.76	106.36	96.72	95.88	107.46	102.26	96.11	100.00	104.60	250,800
Sudan	118.33	62.04	176.21	70.73	124.23	84.86	84.86	119.39	104.71	82.66	84.56	-1,092,583
USA	97.21	122.65	78.50	81.84	100.34	92.37	108.98	127.38	70.42	133.81	92.86	-190,200

Source: Own data processing based on the data from FAO [7].

Taking into account the total production of sorghum in the main growing countries (Figure 3), we note the country that clearly leads this ranking, the USA (9,921 million tons), followed by Nigeria (6,697 million tons), Mexico (5,208 million tons), India (4,627 million tons), Ethiopia (4,487 million tons), Sudan (4,374 million tons), China (2,856 million tons), Brazil (2,506 million tons), Burkina Faso (1,738 million tons) and Australia (1,630 million tons).

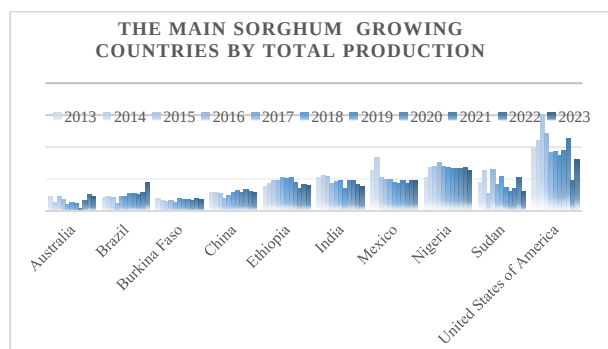


Fig. 3. Total production and its evolution in the main sorghum-producing countries

Source: Own data processing based on the data from FAO [7].

The yield of sorghum cultivation highlighted another ranking among sorghum-growing countries (Figure 4), with average yields per hectare, as follows: Oman (36,156.30 kg/ha), Jordan (22,113.01 kg/ha), Israel (20,202.30 kg/ha), Austria (8,006.56 kg/ha), Italy (7,211.92 kg/ha), Philippines (5,917.39 kg/ha), France (5,853.74 kg/ha), Egypt (5,641.43 kg/ha), Hungary (4,401.72 kg/ha), Romania (3,705.10 kg/ha), Uzbekistan (3,135.74 kg/ha).

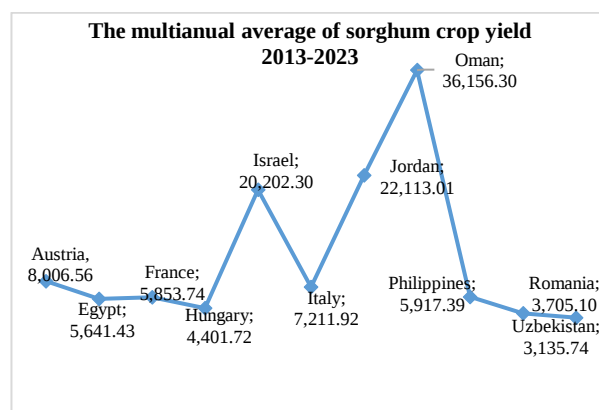


Fig. 4. Multi-annual average of sorghum yield in countries of the world

Source: Own data processing based on the data from FAO [7].

The recording of these significantly differentiated yields from one country to another indicates that some of the important factors involved are pedoclimatic conditions, sorghum production technology, genetics of cultivated plants (hybrid type), but also the professionalism of farmers (Table 2).

Considering that the global demand for sorghum is increasing, largely driven by China, which sources sorghum from the USA to supplement the deficit needed for animal feed, we can mention that sorghum ranks among the top countries with increasing demand among cereals.

The price of sorghum (Figure 5) has significant variations from one country to another, but also from one year to another in the period covered by the analysis, 2013-2023.

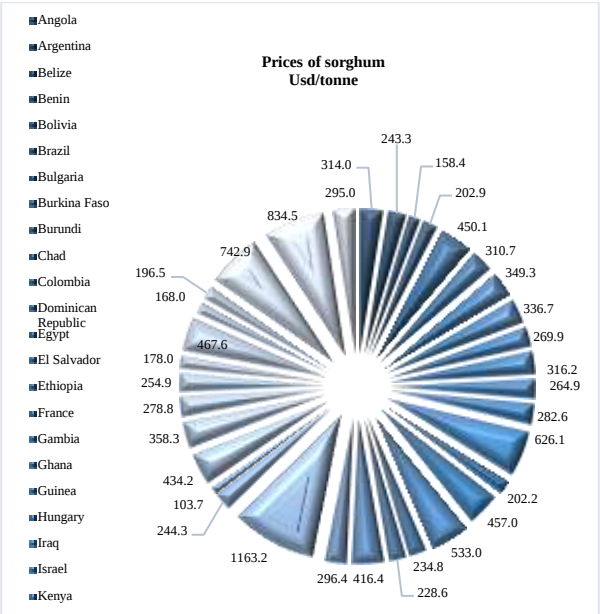


Fig. 5. Sorghum price, worldwide
Source: Own data processing based on the data from FAO [7].

The data provided by FAOSTAT are uneven; some countries have not reported sorghum prices at all or have reported them randomly. The price of sorghum is influenced primarily by the demand for consumption in the respective country but also on export markets. The most common frequency of sorghum prices is in the range of 103.7 USD/ton – 333.7 USD/ton but also in the range of 333.7 USD/ton-563.7 USD/ton [7].

Analyzing the data reported by world countries regarding sorghum producer prices, based on the Pareto diagram.

This diagram grouped sorghum prices in descending order in sorghum-growing and consuming countries, we note that in 2013, the highest prices were recorded in African countries, where there is a high demand for sorghum, given a significant consuming population [7].

Also in 2021, the price for sorghum producers remained high among African countries. We note the situation in the Republic of Moldova where the price of sorghum is much lower than the prices of other producers (103.7 USD/ton). The USA practices relatively low prices for sorghum, due to very high productions and which, through valorization and negotiation, lead to a reduction in the price of this cereal.

Table 2. Evolution of total production in the main producing countries, by production level

Country	Multiannual Average of production (to)	Variation 2023/2013	
		Relative (%)	Absolute (to)
United States of America	1,630,361.78	80.98	-1,894,580
Mexico	2,506,400.82	76.34	-1,492,215.09
India	1,738,569.91	72.23	-1,465,823.6
Ethiopia	2,856,897.99	104.73	181,130
Sudan	4,487,812.87	67.52	-1,469,000
Nigeria	4,627,754.22	120.78	1,101,730
China	5,208,476.37	102.55	74,033.56
Burkina Faso	6,697,557.73	94.23	-108,443.32
Brazil	4,374,330.14	211.56	2,372,120
Australia	9,921,546.36	104.33	96,557

Source: Multiannual average of production in the main sorghum-producing countries

Source: Own data processing based on the data from FAO [7].

• Main sorghum-growing countries in the EU

In Europe, the first sorghum hybrids were introduced in 1960. Grain sorghum is mainly used today for animal feed, although, as already mentioned, this plant, sorghum, is considered a cereal of the future, in the current changing pedoclimatic conditions, caused by global warming, which makes drought years increasingly frequent.



Fig. 6. Cultivated area with sorghum in the EU in 2024.
Source: Own data processing based on the data from Eurostat [6].

In 2024, in the EU, the total area cultivated with sorghum was 229,380 ha.

The use of sorghum in several areas (Figure 6), in addition to animal feed, having a significant percentage of vegetable protein and which is its main destination for EU farmers, has led them to consider sorghum for more diverse rotations, especially in areas with deficient rainfall in Southern and Central Europe.

In the European Union (Figure 7), the main sorghum-growing country is France, which in

2024 had a cultivated area of 101,980 ha and a production of 5,040 kg/ha, followed by Hungary with an area of 44,940 ha and an average production of 5,000 kg/ha, Italy, with an area of 40,590 ha and an average production of 6,210 kg/ha, and Romania, with an area of 16,000 ha, and an average production of 1,360 kg/ha.

Smaller areas (Table 3) were held in 2024 by Slovakia (8,160 ha), Bulgaria (6,000 ha), Austria (5,500 ha), Spain (4,020 ha), Greece (2,060 ha) [6].

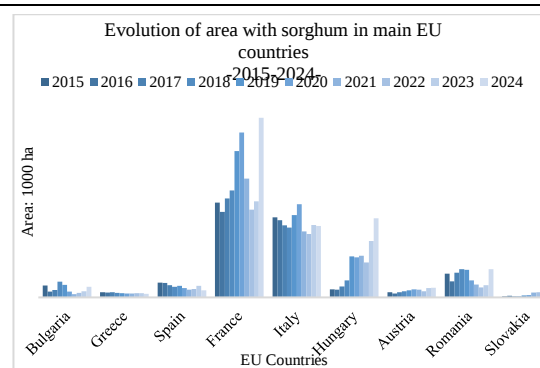


Fig. 7. EU sorghum cultivation area: 2015-2024 trends
Source: Own data processing based on the data from Eurostat [6].

Table 3. Structure of areas cultivated with sorghum in EU countries, in the period 2015-2024

COUNTRY S UE	2015		2016		2017		2018		2019		2020		2021		2022		2023		2024	
	1000 ha	%	1000 ha	%	1000 ha	%	1000 ha	%	1000 ha	%	1000 ha	%	1000 ha	%	1000 ha	%	1000 ha	%	1000 ha	%
Bulgaria	6.82	4.91	3.29	2.66	4.24	3.13	8.86	6.00	7.04	3.70	3.26	1.67	1.86	1.23	2.51	1.97	3.54	2.26	6.00	2.62
Greece	2.86	2.06	2.74	2.22	3.01	2.22	2.62	1.78	2.36	1.24	2.24	1.14	2.21	1.46	2.35	1.84	2.42	1.55	2.06	0.90
Spain	8.38	6.03	8.12	6.57	6.96	5.14	5.97	4.05	6.56	3.45	5.25	2.68	4.33	2.85	4.71	3.69	6.51	4.16	4.02	1.75
France	53.7 9	38.7 0	48.4 6	39.2 4	56.2 4	41.5 1	60.7 7	41.1 8	83.0 9	43.7 2	93.5 8	47.8 1	67.4 8	44.4 8	49.8 6	39.1 0	54.6 1	34.9 2	101.9 8	44.4 6
Croatia	0.03	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Italy	45.4 1	32.6 7	43.8 4	35.5 0	40.9 0	30.1 9	39.6 0	26.8 3	46.8 0	24.6 3	52.9 1	27.0 3	37.5 4	24.7 4	36.0 5	28.2 7	41.0 9	26.2 8	40.59	17.7 0
Hungary	4.58	3.29	4.45	3.60	6.25	4.61	9.62	6.52	23.3 2	12.2 7	22.8 2	11.6 6	23.7 1	15.6 3	19.7 7	15.5 0	32.0 0	20.4 6	44.94	19.5 9
Austria	2.92	2.10	2.26	1.83	2.99	2.21	3.53	2.39	3.94	2.07	4.64	2.37	4.39	2.89	3.55	2.78	5.22	3.34	5.50	2.40
Romania	13.4 9	9.71	9.16	7.42	13.9 9	10.3 3	15.9 3	10.7 9	15.7 1	8.27	9.59	4.90	7.35	4.84	5.70	4.47	6.86	4.39	16.07	7.01
Slovenia	0.09	0.06	0.11	0.09	0.14	0.10	0.08	0.05	0.13	0.07	0.09	0.05	0.17	0.11	0.05	0.04	0.02	0.01	0.06	0.03
Slovakia	0.62	0.45	0.97	0.79	0.64	0.47	0.57	0.39	1.07	0.56	1.36	0.69	2.66	1.75	2.94	2.31	4.00	2.56	8.16	3.56
Bosnia and Herzegovina	0.01	0.01	0.11	0.09	0.11	0.08	0.03	0.02	0.02	0.01	0.00	0.00	0.02	0.01	0.02	0.02	0.10	0.06	0.00	0.00
Total UE	###	###	###	###	###	###	###	###	###	###	###	###	151.7 2	###	127.5 1	###	156.3 7	100.0 0	###	###

Source: Own data processing based on the data from Eurostat [6].

In the European Union, the total sorghum production in 2024 was 1,112.29 thousand tons, but its needs are far from being covered. It is likely that sorghum production in each country will change (Table 4, Figure 8), as farmers who have been most affected by climate change, with all its arsenal regarding heat, soil drought, reduced rainfall, have been looking for crops to replace corn, with similar characteristics and uses, and sorghum is resistant to these changes, meeting the demands coming from farmers.

Unprecedented challenges in accelerating climate change make the future present major uncertainties for agriculture and implicitly for ensuring food for the planet's population, a context in which countries around the world

are looking for solutions, having the desire for *zero hunger*.

In this context, sorghum is suitable for cultivation in drought and even heat conditions, and the goal is to introduce and expand areas worldwide and European.

Sorghum demonstrates a significant capacity to for growth cycle modulation in response to fluctuating water potential. The wax that develops on the plant under water stress conditions helps the plant slow down its respiration and photosynthesis, protecting the stem and leaves from direct sunlight.

Grain sorghum offers an alternative in this context, as it is adaptable to different temperatures and soil conditions, being flexible and at the same time with high

robustness, in extreme heat and drought conditions for long period.

Table 4. Structure of total sorghum production in EU countries, in the period 2015-2024

Countries UE	2015		2016		2017		2018		2019		2020		2021		2022		2023		2024	
	1000 tone	%	1000 tone	%	1000 tone	%	1000 tone	%	1000 tone	%	1000 tone	%	1000 tone	%	1000 tone	%	1000 tone	%	1000 tone	%
Bulgaria	17.26	2.23	7.98	1.15	12.47	1.72	37.01	4.40	23.22	2.27	11.34	1.09	5.34	0.65	6.02	1.13	8.82	1.06	14.65	1.32
Greece	10.72	1.39	7.20	1.04	8.64	1.19	7.64	0.91	7.44	0.73	7.39	0.71	6.92	0.85	8.13	1.52	7.57	0.91	7.18	0.65
Spain	51.51	6.66	37.21	5.36	30.84	4.26	26.18	3.11	25.73	2.52	21.56	2.08	16.49	2.02	14.97	2.80	31.38	3.76	17.65	1.59
France	275.23	35.59	###	37.46	322.00	44.48	316.64	37.67	422.90	41.37	431.70	41.62	382.28	46.73	210.94	39.44	303.99	36.41	514.13	46.22
Italy	###	45.12	###	46.35	248.75	34.36	303.71	36.13	322.85	31.58	373.81	36.04	230.95	28.23	197.56	36.94	247.18	29.61	252.19	22.67
Hungary	15.53	2.01	16.11	2.32	24.55	3.39	43.47	5.17	126.29	12.36	108.73	10.48	95.02	11.62	47.55	8.89	160.03	19.17	224.69	20.20
Austria	20.56	2.66	16.52	2.38	20.21	2.79	27.43	3.26	29.74	2.91	40.32	3.89	36.93	4.51	26.17	4.89	37.47	4.49	36.44	3.28
Romania	31.73	4.10	24.41	3.52	54.28	7.50	76.31	9.08	60.01	5.87	35.70	3.44	33.75	4.13	14.83	2.77	20.78	2.49	21.79	1.96
Slovenia	0.52	0.07	0.57	0.08	0.41	0.06	0.38	0.05	0.51	0.05	0.23	0.02	0.53	0.06	0.08	0.01	0.08	0.01	0.23	0.02
Slovakia	1.22	0.16	2.11	0.30	1.62	0.22	1.73	0.21	3.43	0.34	6.35	0.61	9.87	1.21	8.42	1.57	16.90	2.02	23.34	2.10
Bosnia and Herzegovina	0.11	0.01	0.26	0.04	0.09	0.01	0.07	0.01	0.05	0.00	0.00	0.00	0.00	0.00	0.16	0.03	0.63	0.08	0.00	0.00
Total UE	773.35	###	###	100.00	723.86	100.00	840.57	###	1022.17	100.00	1037.13	100.00	818.08	100.00	534.83	100.00	834.83	100.00	1112.29	100.00

Source: Own data processing based on the data from Eurostat [6].

This crop also has the advantage that the need for nitrogen, pesticides, and water is lower compared to other crops, making it suitable for cultivation using the "No-till" conservation technology.

Sorghum is a competitive crop, especially when sown in narrow rows and performs well against weeds, releasing a chemical compound through the root which inhibits weed growth, acting like a natural herbicide.

These mentions recommend sorghum to be included in various crop rotations, being a crop with low operating costs, due to minimal phytosanitary treatments, resistance to disease and pest attacks, as well as weed infestation, low requirements regarding nutrient needs, due to its well-developed root system, which acts as a pump in extracting nitrogen and other nutrients it needs.

In this sense, there are countries that have started to increase cultivated areas rapidly, and examples of these countries are Hungary and Slovakia (Table 5).

The both figures show an upward trend.

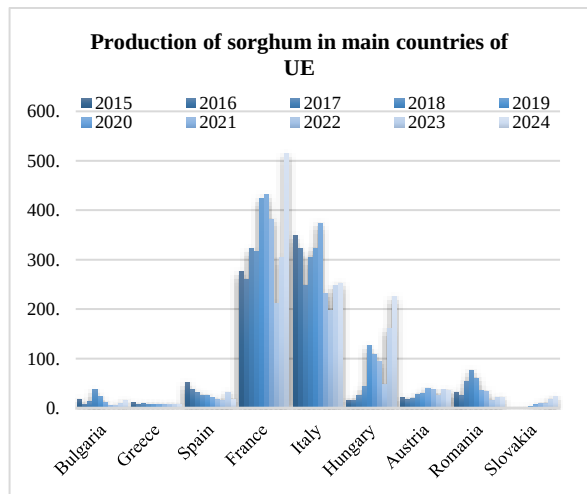


Fig. 8. Total sorghum production in EU countries, in the period 2015-2024

Source: Own data processing based on the data from FAO [7].

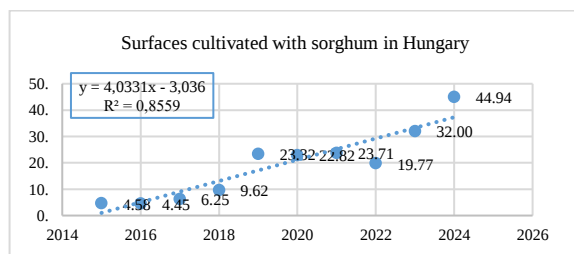


Fig. 9. Sorghum area in Hungary in the period 2015-2024

Source: Own data processing based on the data from Eurostat [6].

Table 5. Main statistical indicators regarding the area cultivated with sorghum in EU countries, for the period 2015-2024

Country UE	Mean	Standard deviation	Coefficient of variation (%)	Minimum area	Maximum area	Range Max-Min
Spain	6.08	1.51	24.83	4.02	8.38	4.36
France	66.99	19.18	28.63	48.46	101.98	53.52
Italy	42.47	4.94	11.64	36.05	52.91	16.86
Hungary	19.15	13.20	68.94	4.45	44.94	40.49
Austria	3.89	1.05	26.84	2.26	5.5	3.24
Romania	11.39	4.08	35.83	5.7	16.07	10.37
Slovakia	2.30	2.37	103.04	0.57	8.16	7.59

Source: Own data processing based on the data from Eurostat [6].

Table 6. Main statistical indicators regarding total sorghum production in EU countries, for the period 2015-2024

Country	Mean	Standard deviation	Coefficient of variation (%)	Minimum production	Maximum production	Range Max-Min
Spain	27.35	11.12	40.64	14.97	51.51	36.54
France	343.99	92.27	26.82	210.94	514.13	303.19
Italy	284.78	57.26	20.11	197.56	373.81	176.25
Hungary	86.20	69.80	80.98	15.53	224.69	209.16
Austria	29.18	8.39	28.74	16.52	40.32	23.80
Romania	37.36	19.88	53.21	14.83	76.31	61.48
Slovakia	7.50	7.45	99.39	1.22	23.34	22.12

Source: Own data processing based on the data from Eurostat [6].

Thus, the statistical models are expressed in the following regression equations:

$y = 19,042x - 18,535$, which shows an increase in the average production by 19,042 thousand tons each year (Fig. 9).

$y = 4,0331x - 3,036$, which reflects the average increase in cultivated areas by 4,0332 thousand ha/year (Fig. 10).

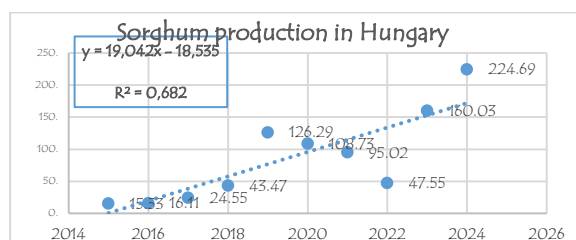


Fig. 10. Total sorghum production in Hungary, 2015-2024

Source: Own data processing based on the data from Eurostat [6].

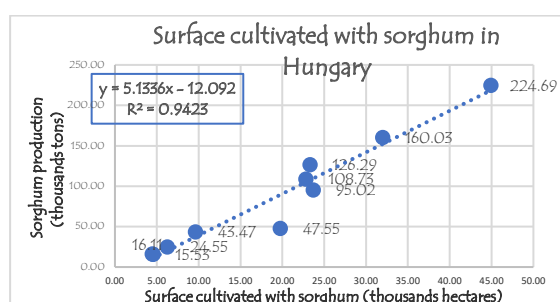


Fig. 11. Sorghum area-production in Hungary, 2015-2024

Source: Own data processing based on the data from Eurostat [6].

In Hungary, the correlation between total sorghum production and the area cultivated (Figure 11) with sorghum is strong, $R^2 = 0.9423$, a value that indicates that 94.23% of the production increase is due to the increase in cultivated area (Table 6).

Also, for Hungary, the Pearson linear correlation coefficient is 0.97, a value very close to 1, denoting a very strong correlation. Taking into account that, from an agronomic point of view, in the long term, sorghum can deplete the soil of nutrients, this aspect does not constitute a benefit for the soil, we mention that the economic advantage of the crop itself is undeniable.

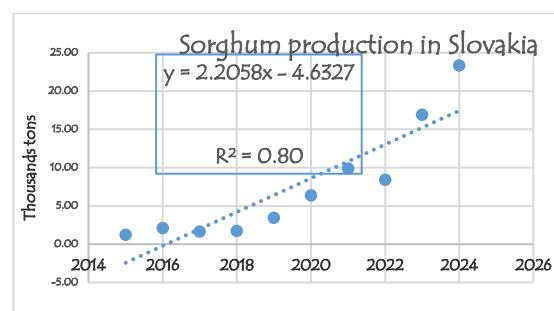


Fig. 12. Sorghum production in Slovakia, 2015-2024

Source: Own data processing based on the data from Eurostat [6].

In the case of Slovakia (Figure 12), a pronounced increase in sorghum production was also evident in the period 2015-2024, on average by 2.2058 thousand tons per year,

according to the linear model $y = 2.2058x - 4.6327$, so sorghum production tends to increase by 2.7766 thousand tons annually.

In Spain, a pronounced decrease in sorghum production (Figure 13) was evident in the period 2015-2024, on average by 2.7766 thousand tons per year, according to the linear model $y = -2.7766x + 42.623$, and sorghum production tends to decrease by 2.7766 thousand tons annually.

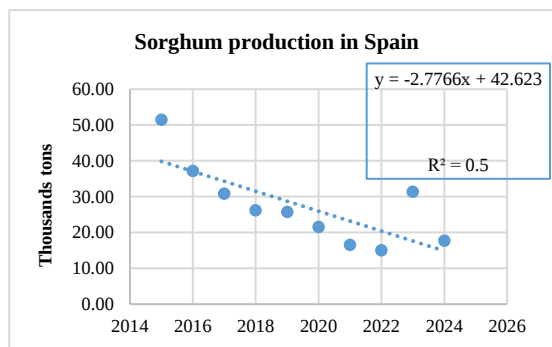


Fig. 13. Sorghum production in Spain

Source: Own data processing based on the data from Eurostat [6].

All these technological aspects, from an economic point of view, translate into lower crop maintenance costs, and due to the fact that sorghum has high yields, it can lead to significant revenues for farmers, compared to other crops more sensitive to drought, diseases and pests, in the mentioned context, of a conglomerate of specific negative phenomena frequently encountered in agronomic practice

such as heat, soil drought, disease attack, pests and weeds.

Sorghum cultivation in Romania

Romania is among the countries where recurrent drought has been a real challenge for spring crops, and where sorghum is an opportune alternative in farmers' rotations.

Known as a raw material for brooms, sorghum has come to the attention of Romanian farmers in southern Romania, who have steadily increased the areas introduced into crop rotation with this plant. Also, studies in Romania conducted on small and medium-sized farms have shown that the use of alternative fodder, such as sorghum, in conditions of reduced water regime, represents, from an economic point of view, a solution to reduce the vulnerability of farmers' incomes [5].

Grain sorghum cultivation does not have a technology much different from corn cultivation, using the corn seeder at a depth of 2-5 cm and at a population between 50,000 and 300,000 seeds per hectare, depending on the distance between rows and soil fertility.

Analysis of Romanian sorghum cultivation from 2013 to 2023 (Figure 14) reveals a high degree of variability, as evidenced by a coefficient of variation of 41.6%.

The mean cultivated acreage (Table 7) was 12,572.82 hectares, with a standard deviation of 5,231.05 hectares.

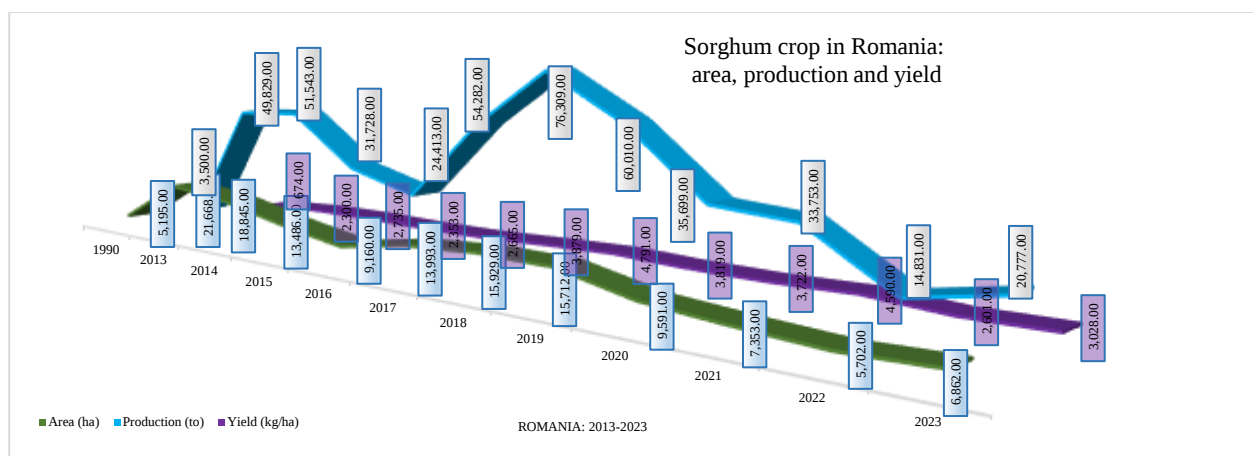


Fig. 14. Sorghum cultivation in Romania in the period 2013-2023: areas, total production and yield

Source: Own data processing based on the data from NIS Tempo online [13].

But, in the current changing pedoclimatic conditions, as a result of global warming which

has led to a higher frequency of drought years in Romania as well, sorghum has become a

choice for more diverse rotations in southern and eastern areas with deficient rainfall.

Table 7. Area (ha) cultivated with sorghum in Romania

Indicator	Value	Indicator	Value
Mean	12,572.82	Standard Deviation	5,231.05
Minimum	5,702	Range	15,966
Maximum	21,668	Coefficient of variation	41.60%
Sum	138,301	Count	11

Source: Own data processing based on the data from NIS Tempo online [13].

Table 8. Total production (tons) of sorghum cultivation in Romania, 2015-2024

Indicator	Value	Indicator	Value
Indicator	Value	Indicator	Value
Mean	4,1197.64	Standard Deviation	18,731.52
Minimum	5,702	Coefficient of variation	45.47%
Maximum	21,668	Range	61,478
Sum	138,301	Count	11

Source: Own data processing based on the data from NIS Tempo online [13].

Romanian farmers who wish to introduce this plant into their own crop rotations must take into account that this heat-loving plant requires an average temperature of at least 25°C to maximize its yield, developing without difficulty at temperatures of 30°C, conditions in which other similar crops would face adaptation difficulties.

In Romania, in the period 2013-2023, total production (Table 8) recorded an average value of 41,197.64 tons, with a standard deviation of 18,731.52 tons. And in the case of total production, the data have a fairly large variability, the coefficient of variation being at the level of 45.46% (>35%).

Romanian sorghum production and cultivated area (Figure 15, Figure 16) exhibited a simultaneous annual decline of 2,343 tons and 1,294.7 ha, respectively, as determined by statistical modeling.

The comparative analysis of the areas cultivated in Romania, in 2023 compared to 1990, showed that it increased by 32.09% (1,667 ha) which led to an increase in total production by 17,277 tons and also in the crop yield by 2,354 kg/ha. The "stay-green" characteristic of sorghum can naturally

increase yield by up to 20% in drought conditions.

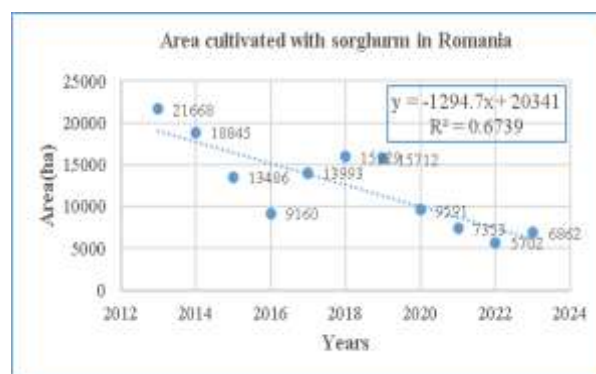


Fig 15. Sorghum cultivation in Romania in the period 2015-2024: areas

Source: Own data processing based on the data from NIS Tempo online [13].

This characteristic makes sorghum extremely flexible.

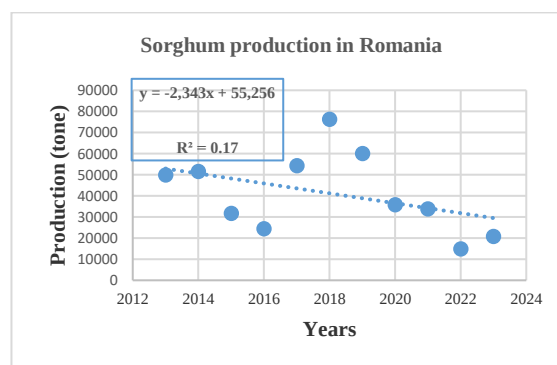


Fig. 16. Sorghum cultivation in Romania in the period 2015-2024: total production

Source: Own data processing based on the data from NIS Tempo online [13].

A 68.33% decrease in sorghum cultivation (Table 9) area was observed between 2013 and 2023 (-14,806 ha), this aspect leading to a decrease in production by 58.30% (-29,052 ha), but what is remarkable is the increase in yield by 31.65% (+728 kg/ha). This yield increase can be attributed to the choice of the right hybrid and an appropriate technology, sorghum also being able to be used as a second crop.

But this plant with increased temperature tolerance has the disadvantage that night time temperatures below 13°C for several days can have a negative impact on its potential yield, which must be taken into account when limiting the location and sowing dates.

According to the simple linear regression model $y = 2.7063x + 7,172.2$ and the coefficient of determination $R^2 = 0.5712$, sorghum production in Romania increased by 57.12% due to the increase in cultivated areas, the remaining 42.88% being caused by unexplained by the model, but explained by the hybrids used, the cultivation technology and

the agrometeorological conditions of each year, with heatwave temperatures, caused by climate change and which makes it possible for Europe and implicitly Romania, to meet the conditions required by sorghum cultivation, adapted to hot and dry climates, namely the climate of tropical and subtropical regions.

Table 9. Sorghum cultivation in Romania: areas, production, yield, 2015-2024

Romania	Specification	Variation in 2023 compared with 1990		Variation in 2023 compared with 2013	
		(%)	(ha)	(%)	(ha)
Sorghum	Area (ha)	132.09	1,667.00	31.67	-14,806
	Production (to)	593.63	17,277.00	41.70	-29,052
	Yield (kg/ha)	449.26	2,354.00	131.65	728

Source: Own data processing based on the data from NIS Tempo online [13].

The determined Pearson correlation coefficient (Figure 17), $r=0.755765$, indicated an important direct correlation between the areas cultivated with sorghum and production in the period 2013-2023.

Applying the Fisher test to validate the mathematical model, it was found that the model is valid because the calculated value of the test, $F_{calc}=11.98 > F_{table}=F(0.05; 1; 9) = 5.12$, and also by calculating the Significance F value $=0.00713435 < 0.05$.

Promoting this plant among farmers to be cultivated on as large areas as possible will be directly correlated with the increase in production.

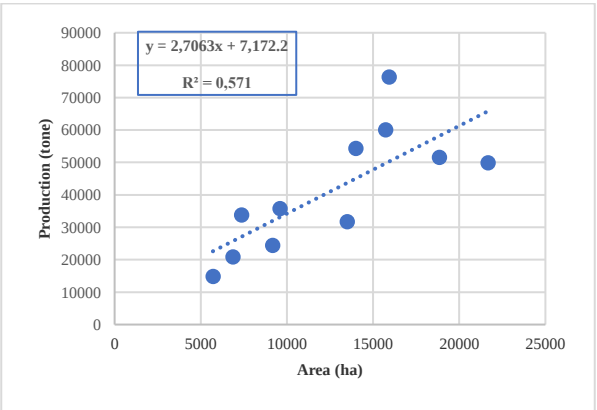


Fig.17. Linear correlation between total production and area cultivated with sorghum in Romania, 2015-2024
Source: Own data processing based on the data from NIS Tempo online [13].

This is due to the fact that sorghum has a significantly higher percentage of vegetable protein than corn, it will generate the

expansion of activities in the zootechnical field, sorghum being recommended for animal rations, by including it in fodder.

Also, increased production will generate income for farmers by capitalizing on it as biomass for biogas, in the production of alcohol or even for human food. All these arguments are in the sense of determining Romanian farmers to show an increased interest in sorghum cultivation by knowing the benefits of this crop, both technically, technologically and economically.

CONCLUSIONS

Sorghum sends a signal to the entire world, as a plant suitable for drought-prone areas, which recommends it in the present, in the context in which humanity is facing challenges related to ensuring food security, with the desideratum for the future of "zero hunger". Sorghum could be a choice for Southern and Central Europe, which is facing the drastic effects of climate change, a context in which Romania is directly targeted, considering the last four extremely dry years (2020-2024). Why do we recommend sorghum for expanded cultivation? The main arguments in favor of sorghum cultivation are the low water requirements, profitability, diversification and easy production technology. Sorghum's agronomic advantages include its hardiness, ability to interrupt pest and weed cycles, and reduced need for specialized machinery. Regarding the soil

structure, sorghum improves it, not having a long production cycle, while allowing the use of land with lower productive potential, etc. Adopting sorghum is an easy decision for farmers if they take these arguments into account.

The research carried out on sorghum cultivation, as a crop of the future, in the context of climate change and counteracting future food shortages, with the desideratum of zero hunger, also highlighted the following:

Globally, in 2023, among the top 10 sorghum-growing countries by cultivated area, we find countries such as Sudan (5,987 thousand ha), Nigeria (5,700 thousand ha), Niger (3,700 thousand ha), India (3,534.72 thousand ha), USA (2,474.68 ha), Burkina Faso (1,793.78 ha), Mali (1,632.82 ha), Ethiopia (1,480 thousand ha), Brazil (1,344.40 thousand ha), Mexico (1,319.90 ha).

Globally, for the multi-year total sorghum production in the 2013-2023 interval, we note the country that leads this ranking by far, the USA (9,921 million tons), followed by Nigeria (6,697 million tons), Mexico (5,208 million tons), India (4,627 million tons), Ethiopia (4,487 million tons), Sudan (4,374 million tons), China (2,856 million tons), Brazil (2,506 million tons), Burkina Faso (1,738 million tons) and Australia (1,630 million tons).

Globally, average sorghum production/ha is significantly differentiated from one country to another, indicating that pedoclimatic conditions, sorghum production technology, genetics of cultivated plants (hybrid type), are essential, as follows: Oman

Oman (36,156.30 kg/ha), Jordan (22,113.01 kg/ha), Israel (20,202.30 kg/ha), Austria (8,006.56 kg/ha), Italy (7,211.92 kg/ha), Philippines (5,917.39 kg/ha), France (5,853.74 kg/ha), Egypt (5,641.43 kg/ha), Hungary (4,401.72 kg/ha), Romania (3,705.10 kg/ha), Uzbekistan (3,135.74 kg/ha).

Globally, the most frequently encountered sorghum price range is between 103.7 USD/ton and 333.7 USD/ton, as well as between 333.7 USD/ton and 563.7 USD/ton.

At the EU level, in 2024, the total area cultivated with sorghum was 229,380 ha, with

France being the main sorghum-growing country, having a cultivated area of 101,980 ha and a production of 5,040 kg/ha in 2024, followed by Hungary with an area of 44,940 ha and an average production of 5,000 kg/ha, Italy, with an area of 40,590 ha and an average production of 6210 kg/ha, and Romania, with an area of 16,000 ha, and an average production of 1360 kg/ha. Smaller areas were held in 2024 by Slovakia (8,160 ha), Bulgaria (6,000 ha), Austria (5,500 ha), Spain (4,020 ha), Greece (2,060 ha).

Within the EU, certain nations demonstrated temporal stability in sorghum cultivation area during the study period, including France and Italy, countries that reduced the cultivated area, such as Romania and Spain, and countries that discovered in sorghum an alternative for high-yielding cereal crops, and showed a significant upward trend in cultivated areas, such as Slovakia and Hungary, were noted. According to statistical models, it was shown that total productions evolved similarly to cultivated areas.

In the European Union, the total sorghum production in 2024 was 1,112.29 thousand tons, of which, France 514.13 thousand tons, Italy 252.19 thousand tons, Hungary 224.69 thousand tons, Austria 36.44 thousand tons, Slovakia 23.34 thousand tons, Romania 21.79 thousand tons, Spain 17.65 thousand tons and Bulgaria 14.65 thousand tons.

Romanian sorghum cultivation from 2013-2023 demonstrated significant variability, the coefficient of variation being 41.6%, with a mean cultivated area of 12,572.82 ha and a standard deviation of 5,231.05 ha.

In Romania, the total production recorded an average value of 41,197.64 tons, with a standard deviation of 18,731.52 tons. And in the case of total production, the data have a fairly large variability, the coefficient of variation being at the level of 45.46% (>35%). Statistical modeling revealed a 2,343ton annual decline in Romanian sorghum production, concurrent with a 1,294.7 ha reduction in cultivated area during the study period. For Romania, it was concluded that sorghum production in Romania increased by 57.12% due to the increase in cultivated areas, the remaining 42.88% being caused

unexplained by the model, but explained by the hybrids used, the cultivation technology and the agrometeorological conditions of each year, with heatwave temperatures, caused by climate change and which makes it possible for Europe and implicitly Romania, to meet the conditions required by sorghum cultivation, adapted to hot and dry climates, similar to the climate of tropical and subtropical regions.

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