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Source / Izvornik: **Agriculture, 2023, 13**

Journal article, Published version
Rad u časopisu, Objavljena verzija rada (izdavačev PDF)

https://doi.org/10.3390/agriculture13071447 agriculture

Review

Agrivoltaics and Aquavoltaics: Potential of Solar Energy Use in Agriculture and Freshwater Aquaculture in Croatia

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Abstract: Agrivoltaics and aquavoltaics combine renewable energy production with agriculture and aquaculture. Agrivoltaics involves placing solar panels on farmland, while aquavoltaics integrates photovoltaic systems with water bodies and aquaculture. This paper examines the benefits and challenges of agrivoltaics and aquavoltaics, focusing on their potential for Croatian agriculture and freshwater aquaculture. Benefits include dual land use, which allows farmers to produce clean energy while maintaining agricultural practices. They diversify renewable energy sources and reduce dependence on fossil fuels and greenhouse gas emissions. Solar panels in agrivoltaics provide shade, protect crops, reduce water needs, and increase yields. Challenges include high initial costs and limited accessibility, especially for small farmers. Integration with existing systems requires careful planning, considering irrigation, soil moisture, and crop or fish production. Maintenance and cleaning present additional challenges due to dust, debris, and algae. Policy and regulatory frameworks must support implementation, including incentives, grid integration, land use regulations, and conservation. The location, resources, and crops grown in Croatia present an opportunity for agrivoltaics and aquavoltaics, considering cultivation methods, species, and regulatory requirements.

Keywords: agrivoltaics; aquavoltaics; Croatia; water evaporation; dual land use

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Citation: Matulić, D.; Andabaka, Ž.; Radman, S.; Fruk, G.; Leto, J.; Rošin, J.; Rastija, M.; Varga, I.; Tomljanović, T.; Čeprnja, H.; et al. Agrivoltaics and Aquavoltaics: Potential of Solar Energy Use in Agriculture and Freshwater Aquaculture in Croatia. *Agriculture* **2023**, *13*, 1447. https://doi.org/10.3390/agriculture13071447

Academic Editor: Igor V. Yudaev

Received: 27 June 2023
Revised: 18 July 2023
Accepted: 19 July 2023
Published: 22 July 2023

1. Introduction

1.1. Agricultural Production and Climate Changes

Climate change poses a growing threat in the 21st century. It is a challenge to all humanity, affecting all aspects of the environment and the economy while threatening the sustainable development of society. Climate change affects the frequency and intensity of extreme weather events (extreme rainfall, floods and flash floods, erosion, storms, droughts, heat waves, and fires) and causes gradual climate change (increase in air, soil, and water surface temperatures, sea level rise, ocean acidification, and expansion of drylands) [1].

The agricultural sector is especially vulnerable to the profound impacts of climate change because of its dependence on weather [2]. Expected impacts on the agricultural sector include: (i) changes in growing seasons of arable crops, with a focus on crops and oilseeds (e.g., corn, sugar beets, soybeans, etc.); (ii) lower yields of all types of crops; and (iii) greater dependence on water. Extreme weather events such as droughts and hail led to average losses of 76 million euros per year in Croatia between 2000 and 2007, equivalent to 0.6% of national GDP [3]. Climate changes affect the duration/length of the vegetative period of agricultural crops and lead to lower yields. Frequent droughts will lead to a higher demand for irrigation water. A longer growing season will also allow for the cultivation of some new crops and varieties. On the other hand, more frequent flooding and stagnation of surface water will reduce or eliminate yields.

Agriculture faces the challenge of producing sufficient food, feed, and fiber to meet increasing demand under conditions of a changing climate and the depletion of natural resources [4]. A rise in temperature beyond the optimum becomes a major concern since most agricultural crops are directly dependent on climatic conditions. Shifts in acreage, length of growing season, winter hardiness potential, frost and hail events, lower yields, and food quality are some of the most obvious consequences of global warming trends [5]. Observations show an increase in the frequency and duration of warm weather extremes [6]. Warming tends to result in lower yields as plants accelerate their annual development and yield less. In general, both winter and summer crops exhibit advanced growth, anthesis, and maturity stages in response to higher temperatures, and the duration of the crop growth cycle is predicted to decrease [7].

Agricultural intensification also suggests that agriculture will have higher energy demands. As part of the global energy transition, fossil fuels are being replaced by renewable energy. The installed capacity of PV power plants around the world and the amount of energy they generate continue to grow almost exponentially, and the cost of electricity for new projects has already reached minimum levels in many countries compared to other generation methods [8,9].

Renewables are expected to overtake coal in electricity generation in the second half of the 2020s, and by 2050, renewables will account for 50% of global electricity generation. In agriculture, solar energy can dry hay, heat water, build more efficient greenhouses, provide energy for buildings and equipment that are away from residential power lines, etc. Mandatory use of energy supply measures in all sectors will increase the role of RES [10,11].

Croatia is located in a sensitive area of Europe, as a transition zone between Central Europe and the Mediterranean, where the trend of increasing average annual air temperature is present throughout Croatia. In Croatia, extreme weather events such as droughts and hail have resulted in average losses of EUR 76 million per year from 2000 to 2007, or 0.6% of national GDP [3]. In the field of low-carbon development in the Republic of Croatia, major changes are planned in the near future. Power plants that run on fossil fuels will be replaced by renewable energy sources, and the development will move towards decentralization of electricity generation. Consumers (households and institutions) will also be energy producers, and energy exchange will take place at the local level. Energy producers and energy storage will be interconnected by advanced grids. In the Proposal for the Strategy of Low Carbon Development of the Republic of Croatia until 2030 with a view to 2050 [12], the Government of the Republic of Croatia has emphasized the need to build facilities that use renewable energy sources for electricity and/or heat production, such as solar power plants. The aim of the strategy is to initiate changes in Croatian society that will contribute to the reduction of greenhouse gas emissions and enable the decoupling of economic growth from greenhouse gas emissions.

The intensive use of solar energy (photovoltaics) in agriculture and freshwater aquaculture could make a significant contribution to avoiding or reducing potential damage from climate change. The combination of photovoltaics and agriculture or aquaculture, i.e., agrivoltaics (AgriPV) and aquavoltaics (AquaPV), creates a novel link between energy and food (land or water) that potentially benefits both parties. Agrivoltaics and aquavoltaics are emerging approaches that aim to combine agriculture/aquaculture and solar energy production in the same location on the land [13,14]. According to published statistics, the annual GHG emissions of all aquaculture operations worldwide (260 million t CO_2-eq/year) are rather small compared to those of cattle (3000 million t) or pig (800 million t) farming [15]. To meet the growing demand for aquatic food for a world population of 10 billion in 2050 [16], energy consumption and greenhouse gas emissions from the aquaculture industry are likely to increase significantly in the coming decades. In this regard, PV-integrated aquaculture systems with simultaneous production of food and electricity would be an important contribution to sustainable land use and climate change mitigation. By promoting intensive synergies between solar energy projects and the agriculture and aquaculture sectors, multiplier effects such as physical protection of certain crops (e.g., vineyards, olive groves, and pastures) from certain extreme weather events (heat waves, extreme rainfall) can be achieved, which would have a positive impact on yield levels and product quality. In addition to the impact on crop and fish production, the implementation of AgriPV and AquaPV increases the profitability of agriculture and aquaculture by generating additional revenue through energy production [14,17].

1.2. Use of Solar Energy in the Agricultural Sector

Climate changes in turn triggered the development of projects based on renewable energy sources (RES), with particular interest in photovoltaic systems, including the use of photovoltaic systems in the agriculture sector (agrivoltaics) [18]. To reduce its greenhouse gas emissions, the EU has decreed that 40% of energy consumption must come from renewable resources by 2030. Photovoltaics are expected to reach 16% of global electricity generation in 2050, but given climate change, it should be 30 to 100 TW before 2050 [19]. There is no internationally unified definition of agrivoltaics as such. The term "agrivoltaic" was firstly proposed in 1982, which combines electricity generation and crop planting on the same farmland. The word agrivoltaics is a neologism based on "agri" for agriculture and "voltaics" for photovoltaics [20]. "Agricultural photovoltaics (agrivoltaics) is the combined use of one and the same area of land for agricultural production as the primary use, and for electricity production by means of a PV system as a secondary use. The dual use of the land not only leads to increased ecological and economic land use efficiency, but in practice can also lead to positive synergy effects between agricultural production and the agrivoltaic system" [20]. Agrivoltaics is also known as agrophotovoltaics, solar sharing, farming photovoltaics (PV), AgriPV, or solar farming.

Numerous studies have shown that it is possible to combine photovoltaics (PV) with agricultural production, enabling PV development on a larger scale while protecting agricultural crops and maintaining yield [21–24]. The first advantage of AgriPV is the area productivity in winter, when agricultural production is not possible in the fields. This land productivity refers to the generation of electricity. Many studies indicate that it is possible to increase crop yields under PV systems [25,26].

This is possible because agrivoltaics create a modified microclimate beneath modules by altering air temperature, relative humidity, wind speed, wind direction, and soil moisture [27]. Agrivoltaics protects crops from both excess solar energy and stormy weather, such as hail [1]. Agrivoltaics also offers more efficient use of water, which may help reduce water consumption [22] and stabilize yield in dry years [28]. This is of particular interest in drylands where unfavorable growing conditions such as excessive sunlight, high temperatures, and severe droughts (water shortages) are predominant.

When trying to describe the challenges associated with AgriPV, the term solar sharing is probably the most descriptive. Sharing solar resources to produce food and energy simultaneously means that the design of the PV system cannot always follow a standard approach of orienting panels to optimize energy production, and that system design may conflict with optimized food production [26,29]. Therefore, the system must be adapted to the local climate, crop type, or land shape [30].

AgriPV, as a concept or approach, includes a variety of different technologies defined by a specific way of combining agriculture and PV [20]. A closer look at the diversity of AgriPV solutions can be made using the framework recently proposed by some authors [31]. The first line of distinction is defined by whether the modules are installed in the open field or on the roof. Totally opaque roofs may be associated with agricultural buildings, even indoor agriculture, but there is no direct interaction between PV systems (other than electricity use) and agricultural activity. Aquaculture and horticulture can also be combined with ground-mounted PV or greenhouse systems. Open-space systems can be further differentiated by growing crops between rows of the modules (inter-space PV) or under modules that have a greater vertical distance (overhead PV). These systems can be fixed tilt, single-axis tracking, or dual-axis tracking. Since compatibility with agricultural machinery is a key planning criterion for AgriPV, interspatial photovoltaics are expected to focus primarily on grassland farming, fodder production, and grazing, while ground-mounted systems can accommodate a wider variety of stable food crops on arable land as well as horticulture, including perennial crops, permanent crops, and specialty crops [20].

2. Agricultural Potentials of Croatia for Application of AgriPV

The Republic of Croatia is divided into the Adriatic region and Continental Croatia. The territory of Continental Croatia includes central Croatia, Slavonia, and Baranja. Central Croatia is a slightly hilly region covered with vineyards, meadows, and forests and crossed by river courses. Slavonia is located in the far east of Croatia and is characterized by vast plains and large amounts of arable crops, the so-called green treasury. In the Adriatic region, permanent grasslands prevail, and plant production includes mostly viticulture and olive growing as the most important branches of this area, but also the production of Mediterranean fruits and vegetables. The Republic of Croatia covers a surface of 56,594 km^2, which is divided into: forests and bushes cover about 35%, agricultural land about 27%, urban areas 9%, inland waters 1%, and others 29% (Figure 1). According to the Croatian Bureau of Statistics [32], total agricultural land used in the period from 2010 to 2019 on average was around 1,477,000 ha, and main field crops—cereals, industrial plants, and fodder crops—were sown on about 675,000 ha (46%).

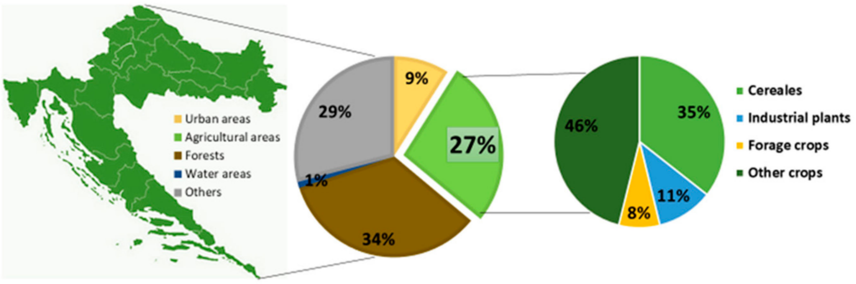

Figure 1. Land use in the Republic of Croatia Reproduced with permission from [32].

The agricultural farms of the Republic of Croatia are characterized by a large number of different production and economic entities. According to [32], the largest number of agricultural farms are small farms. Of the total number of farms, 14.1% have no agricultural land in use, while 59.7% use up to 3 ha of agricultural land. Of the total number of agricultural holdings, only 6% of holdings use more than 20 ha of agricultural land [33]. According to [34], of the total number of agricultural holdings (143,927), most of them (39%) have less than 2 ha, 30% have from 2 to 4.9 ha, and 15% have from 5 to 9.9 ha. The lowest number of agricultural holdings have over 100 ha (1%) (Figure 2).

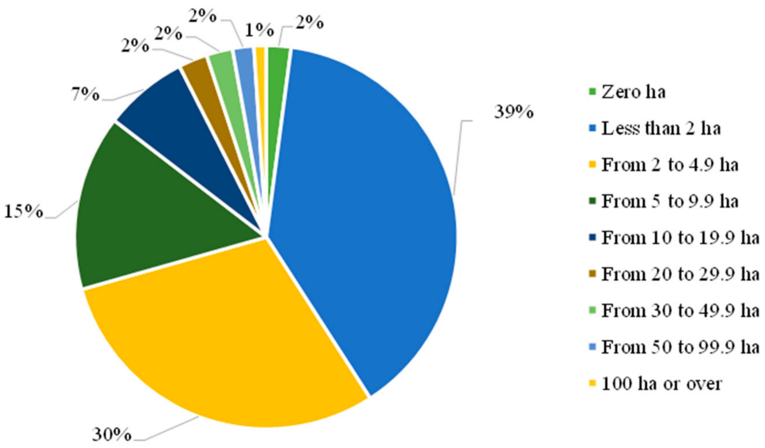

Figure 2. Agricultural land of family farms in Croatia in 2020 Reproduced with permission from [34].

This indicates that fragmentation of farms is still great in Croatia, where the average of commercial farms is about 8.5 ha and the average of all farms is only 2.9 ha, which can be a limiting factor in the wider application of AgriPV projects. About 55–60% of used agricultural land belongs to the category of arable land and gardens, which occupies more than 850,000 ha (Figure 3), followed by perennial grass areas (about 540,000 ha). Other crops—vegetables, orchards, olive groves, and vineyards—occupy about 6% of agricultural land (about 80,000 ha) [32].

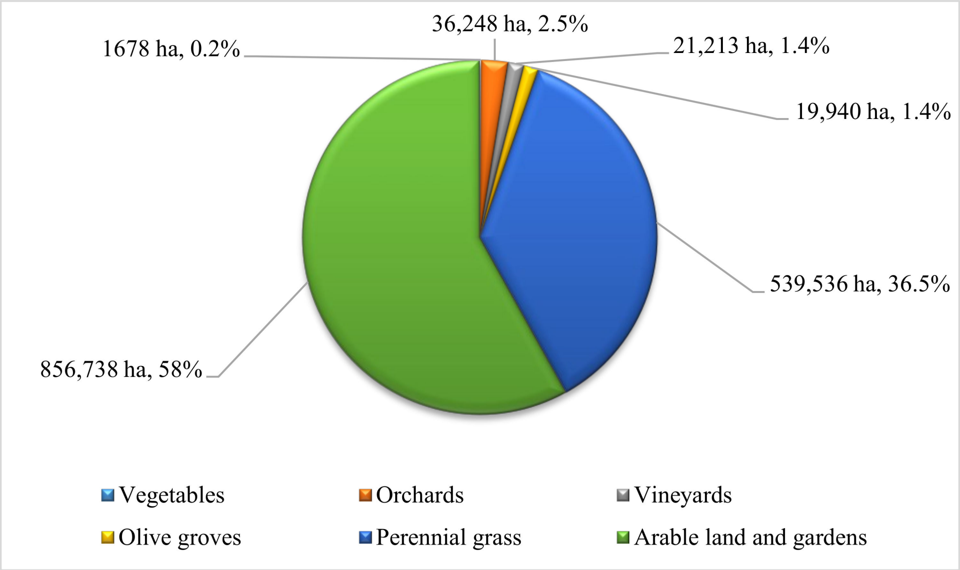

Figure 3. Area (ha) and share (%) of agricultural land by category in 2021, reproduced with permission from [32].

In the last decade, of the total agricultural area used, about 70% was located in the continental and about 30% in the Adriatic parts of Croatia (Figure 4).

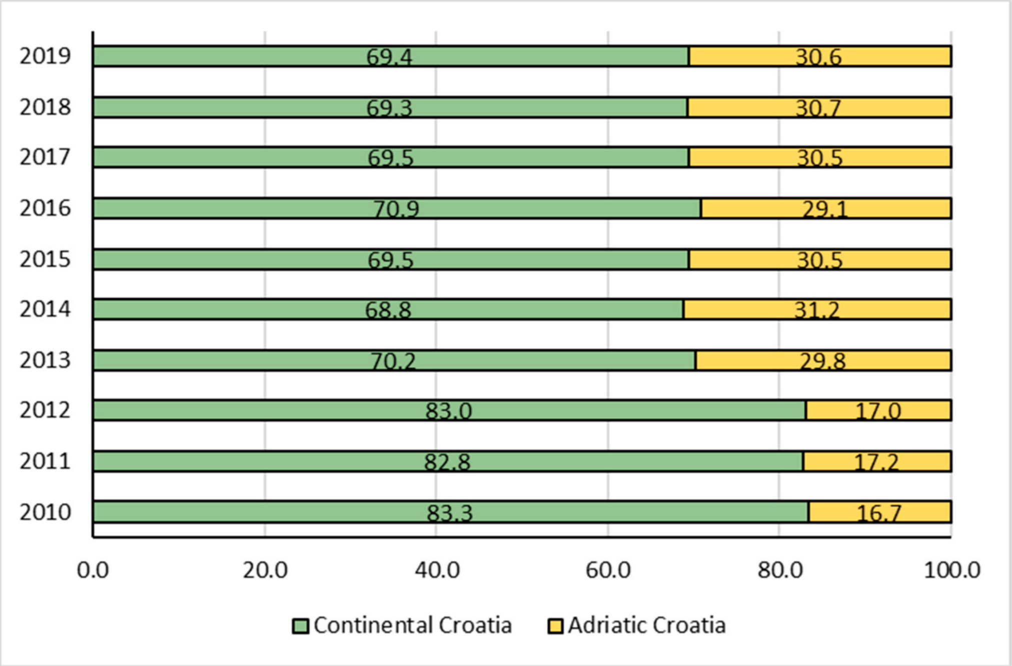

Figure 4. Share of used agricultural area for Continental and Adriatic Croatia from 2010 to 2019, reproduced with permission from [32].

The analysis of the advantages and limitations for the application of AgriPV projects for certain types of cultivated species considering different researches, the applicable case studies and examples of similar corresponding projects, and the conclusion about the applicability of AgriPV projects for certain types of crops in Croatia are given.

Unfortunately, there is still no legislation on AgriPV in Croatia. But, there is some slight movement in this area, as the Croatian government issued two legal documents on 28 June 2023: the Regulation on the Promotion of Electricity Production from Renewable Energy Sources and High-Efficiency Combined Heat and Power (OG 70/2023) and the Regulation on the Criteria for Conducting a Public Tender for the Granting of an Energy Permit and the Conditions for Granting an Energy Permit (OG 70/2023). In these documents, AgriPV (the term Agrosolar is used in the documents) is defined as a solar power plant located on an area designated as agricultural land by the land use plan of any level and on which the establishment of permanent agricultural plantations is registered in the Agricultural Land Use Records (ARKOD) or on which, in addition to the existing area, farms, greenhouses, or greenhouses with the installation of an agrosolar power plant achieve the objectives of the development of agricultural activity while maintaining the purpose of agricultural land, except in the National Park and Natural Park. These two documents are the only official legal documents that mention or define AgriPV in Croatia. Croatia has considerable solar energy potential due to its geographical location and climate. The country receives a considerable amount of sunlight throughout the year, which makes it suitable for solar energy production. The southern regions, especially Dalmatia, have the highest solar potential as they experience more direct sunlight. The use of photovoltaics is steadily increasing in Croatia. The government has also introduced various incentives and support programs to encourage the use of solar energy. However, the overall solar energy capacity in Croatia is still relatively modest compared to other European countries.

2.1. Viticulture

Vineyards could generally be considered for agrivoltaic farms. Firstly, one of the main reasons is the fact that grapevines are an agricultural crop of high economic value. Vineyards are usually established in areas with moderate temperatures and a significant sunlight duration. Grapevines are normally considered full-sun plants, but even in the absence of full sunlight all day, it is still possible to grow grapes in mostly shade [35]. Possible solutions should find the balance between energy production and tolerable shade that will not have a negative effect on grapevine growth and development. The main research questions still remain regarding the co-existence of crop vegetation and agrivoltaics, especially regarding soil characteristics, microclimate modifications, as well as agrivoltaics installation and maintenance costs and performance. Vineyards are generally planted in a row-based layout. The usual method to fully utilize the sunlight is to use fixed support systems with solar panels elevated above the crops. This allows vineyard machinery undisturbed access to the vines. Refs. [36,37] proposed PV panels in the interspace between vineyard rows. On the other hand, a vertical integration of photovoltaic surfaces over the vines is proposed using the same trellis structure, therefore minimizing cost and land building [30]. The authors have tried to avoid the negative impact of shading on grapevine yield and quality. They have established optimal trellis heights and distances between rows to minimize shading. The proposed symbiotic integration of photovoltaic modules into a vineyard trellis structure was termed Enovoltaics. APV modules placed above the vineyard can act not only as a sunlight barrier but also as protection against hail and/or intense rain showers. Vineyards with optimal surfaces for APV installations are usually larger than 1 hectare. In such large vineyards, grapevines are usually managed with mechanized equipment. Thus, APV architecture must adhere not only to regional climatic conditions and grapevine varieties, but also to canopy management in the vineyard. The elevation of APV modules, distance between modules, density, and sloping angle of solar panels are still the subject of much research [38]. The studies dealing with Agri PV systems have generally focused on very few crops, with almost no information for grapevine. Only in recent years have some investigations into fruit trees such as grapevine [39] been started, but the data are very limited.

Structure of Vineyard Areas in Croatia

Climate is one of the main regionalization factors, along with soil and variety. The Republic of Croatia has a specific geographical position as it is a meeting point of two climate types: continental (eastern and central parts of the country) and Mediterranean (southern and coastal parts). According to the climate, temperature is one of the limiting factors for the cultivation of the grapevine. For grapevines, a mean daily temperature of 10 °C represents a biological zero, while all temperatures above that are regarded as active. As a rule, active temperatures last from April until the end of October (vegetative season). If biological zero is deducted from the active temperature, the result is the effective temperature. The Republic of Croatia is divided into four wine regions (OG 81/2022): the Croatian Uplands, Istria and Kvarner, Slavonia and Podunavlje, and Dalmatia. These regions are divided into 12 subregions: Hrvatsko Podunavlje, Slavonia, Moslavina, Prigorje-Bilogora, Zagorje-Međimurje, Plešivica, Pokuplje, Hrvatska Istra, Hrvatsko Primorje, Northern Dalmatia, Dalmatinska Zagora, and Central and Southern Dalmatia. According to the data in the viticulture database (OG 81/2022) from November 2022, the total winegrowing area in the Republic of Croatia was 17,715.31 ha [40].

The structure of vineyard areas in Croatia is characterized by small production plots and a small number of large viticulture producers (Table 1). In Table 1, it can be seen that 92.44% of producers have viticulture plots smaller than 1 ha, but, at the same time, their viticulture plots have a share of 32.12% in the total viticulture area in the Republic of Croatia. The chosen discriminating criterion for the construction of agrivoltaics was a plot size larger than 1 ha, which transpires to 67.88%, meaning that 12,026.17 ha of the total vineyard area is suitable for APV application. The average slope of vineyards is 6.38%, which does not represent an obstacle during the construction of agrivoltaics.

Table 1. Structure of vineyard plots in the Republic of Croatia.

Viticulture Plots (ha)	Area/No of Producers	Total	Share in Total Area (%)
<0.1	Area (ha) No. of producers	837.50 13,075.00	4.73 39.09
0.1–1	Area (ha) No. of producers	4851.63 17,848.00	27.39 53.35
1–5	Area (ha) No. of producers	4257.83 2191.00	24.03 6.55
5–10	Area (ha) No. of producers	1351.11 197.00	7.63 0.59
10–50	Area (ha) No. of producers	2143.14 117.00	12.10 0.35
50–100	Area (ha) No. of producers	700.68 11.00	3.96 0.03
100–200	Area (ha) No. of producers	973.91 7.00	5.50 0.02
>200	Area (ha) No. of producers	2599.50 6.00	14.67 0.02
Total Republic of Croatia	Area (ha) No. of producers	17,715.31 33,452.00	100 100
Avg. slope of the vineyard [%]		6.38	

Subregions with the most vineyards with an area larger than 1 ha are Croatian Danube, Slavonia, Croatian Istria (the regions with the most grid capacities available), Central and

South Dalmatia, and Dalmatian Interior. The fewest such vineyards are found in Pokuplje, Hrvatsko Primorje, Prigorje-Bilogora, and Norther Dalmatia subregions.

2.2. Fruit Growing

Agrivoltaics in orchards are an interesting but complex addition to farm production. Solar panels on top of the orchard will interfere with plant growth and fruit yielding, for sure. Whether this will have a positive or negative effect depends on various factors (fruit species, fruit varieties, location, weather conditions, etc.). In light of climate change, numerous problems are appearing in traditional combinations of fruit growing and location. That means either changing fruit species that are grown in certain locations, changing fruit growing region schemes, or adapting fruit growing technologies. Using agrivoltaics as part of fruit-growing technology seems to be a good idea. Photovoltaic panels on top of plants will definitely reduce sunlight that reaches the plant and thus reduce plant growth or fruit yield. That is important, as photosynthesis in plants produces nutrition for plant growth. But, on the other hand, vegetative and generative growth are in constant competition. If PV panels on top of the orchard reduce vegetative growth (at some certain level), there is a possibility that this will affect fruit production. This is confirmed by agrivoltaics in raspberry production (Babberich, The Netherlands, Figure 5), where the density of installed PV panels (60% coverage) reduces yield by only 5% in comparison to conventional technology (personal communication). Also, shading that is caused by installed PV in orchards has a positive effect on reducing some physiological disorders in plants and fruits, such as sunburn, heat stress, fruit overcoloration, etc. Installation of PV panels in orchards has its potential and benefits for fruit growing, but it needs to be carefully adjusted and applied. Considering the possibility of using agrivoltaics in plantations of Mediterranean fruit species, several aspects should be taken into consideration. First, it is about the influence of the system itself on cultivated crops. It is evident from the available foreign data that this influence can go in several directions. The ideal situation is when the use of an agrivoltaics system achieves a synergistic effect with fruit culture, i.e., agricultural production is improved qualitatively and/or quantitatively with the optimal effect of the agrivoltaics system. A situation is also possible when the impact on agricultural production is neutral or even slightly negative, but the overall effect of both sectors is positive. Of course, there is also the possibility of an extremely unfavorable impact of agrivoltaics on cultivated plants, in which case their connection to the same plots should be avoided.

Figure 5. Agrivoltaics in a raspberry orchard (Photo: Fruk, G.).

Structure of Fruit Growing in Croatia

Croatian fruit production is organized on an area of approximately 55,000 ha [32]. In Table 2, data on the total production area for different fruit crops are presented, while in Table 3, data about the number of orchards by county and by size are shown.

Table 2. Area of fruit production in Croatia in 2021.

Crop	**Area Harvested (ha)**
Apples	4390
Pears	750
Plums and sloes	3490
Sour cherries	2200
Cherries	1000
Peaches and nectarines	800
Apricots	310
Strawberries	270
Blueberries	380
Other berries and fruits of the genus vaccinium n.e.c.	1160
Raspberries	130
Tangerines, mandarins, clementines	2040
Oranges	40
Lemons and limes	60
Walnuts (in shell)	8420
Hazelnuts (in shell)	6710
Almonds (in shell)	810
Chestnuts (in shell)	280
Olives	19,940
Figs	570

Source: [41].

Table 3. Number of orchards by county by size (on 31 December 2022).

County	**Orchard Size (ha)**					
	0–1	**1–5**	**5–20**	**20–100**	**>100**	**TOTAL**
Continental part						
Bjelovarsko-bilogorska	3906	926	61	1	0	4894
Brodsko-posavska	5850	656	53	13	0	6572
Grad Zagreb	1612	30	0	0	0	1642
Karlovačka	4314	547	33	3	0	4897
Koprivničko-križevačka	3859	294	13	3	0	4169
Krapinsko-zagorska	8261	56	0	0	0	8317
Međimurska	1628	255	21	0	0	1904
Osječko-baranjska	4042	1381	136	20	0	5579
Požeško-slavonska	4415	607	26	5	0	5053
Sisačko-moslavačka	4572	589	52	6	0	5219
Varaždinska	4694	137	5	0	0	4836
Virovitičko-podravska	2608	479	29	9	1	3126
Vukovarsko-srijemska	1981	465	50	12	0	2508
Zagrebačka	5995	326	42	4	0	6367
	57,737	**6748**	**521**	**76**	**1**	**65,083**
*Highlands/Coastal part **						
Ličko-senjska	4670	42	0	0	0	4712
Primorsko-goranska	805	15	1	0	0	821
Šibensko-kninska	1281	22	9	1	0	1313
	6756	**79**	**10**	**1**	**0**	**6846**
Coastal part						
Dubrovačko-neretvanska	7929	360	3	0	0	8292
Istarska	1931	68	5	1	0	2005
Splitsko-dalmatinska	3900	28	9	1	0	3938
Zadarska	4807	167	29	5	0	5008
	18,567	623	46	7	0	19,243
TOTAL	**83,060**	**7450**	**577**	**84**	**1**	**91,172**

* Three counties in this group are situated in both areas (highlands and coastal parts); Source: [42].

The main characteristic of all Mediterranean fruit crops, as can be seen from Table 4, is the small average land area (0.84 ha). Out of a total of 22,142 farms, only 292 (1.31%) have areas larger than 1 ha, while only 31 farms (0.14%) have slightly larger areas (>10 ha).

Table 4. Cultivation of Mediterranean fruit species in the Adriatic agricultural subregion (2021).

	Total Area (ha)	Agricultural Activity	Average Area (ha)	Agricultural Activity >1 ha	Agricultural Activity >10 ha
Olive	14,225.35	14,187	1.00	180	15
Mandarin	1589.87	1335	1.19	13	1
Lemon	31.92	201	0.16	1	0
Orange	14.96	92	0.16	0	0
Kumquat	0.60	10	0.06	0	0
Grapefruit	0.10	3	0.03	0	0
Almond	738.34	1041	0.71	33	5
Marasca sour cherry	347.09	236	1.47	8	4
Fig	303.96	813	0.37	31	1
Pomegranate	55.18	172	0.32	5	0
Carob	50.61	14	3.62	1	1
Kiwifruit	15.95	14	1.14	1	1
Jujube	3.01	12	0.25	0	0
Mixed fruit Cultivation	1273.31	3994	0.32	16	3
Fruit nurseries	17.28	18	0.96	3	0
TOTAL	**18,667.53**	**22,142**	**0.84**	**292**	**31**

Source: [43].

The most represented fruit among Mediterranean fruit species is the olive. The entire olive growing area in Croatia can be divided into six growing sub-regions with their own specificities based on various factors (Istria, Kvarner Islands, North Dalmatia, Central Dalmatia, South Dalmatia, and the hinterland of Dalmatia) (Table 5).

Table 5. Olive cultivation in the Adriatic agricultural subregion (2021).

	Total Area (ha)	Agricultural Activity	Average Area (ha)	Agricultural Activity >1 ha	Agricultural Activity >10 ha
Istria County	3171.84	2492	1.27	68	6
Primorje-Gorski Kotar County	562.05	495	1.14	19	0
Lika-Senj County	121.93	96	1.27	1	0
Zadar County	2625.96	3522	0.75	23	6
Šibenik-Knin County	2061.95	2082	0.99	28	0
Split-Dalmatia County	3511.11	2728	1.29	28	1
Dubrovnik-Neretva County	2170.51	2772	0.78	22	2
TOTAL	**14,225.34**	**14,187**	**1.00**	**180**	**15**

Source: [43].

2.3. Vegetable Growing

Conventional open fields face many challenges due to the pronounced effects of climate change, especially global warming, and the associated weather-related difficulties. The main concern is to produce adequate yields and high-quality, nutritious plant material. To protect vegetables from external influences, expensive protective structures such as hail nets or films are often used. In the agricultural sector, greenhouse technology, also known as closed agriculture, is strategic for increasing production and meeting global demand, as it provides plants with a suitable microclimate that enables optimal plant growth, extended production time, earlier harvest, and higher and better-quality yields [44]. Hydroponic systems in greenhouses are considered one of the most important technical approaches for sustainable food supply and reducing pressure on agricultural land by moving food production to urban environments [45]. The advantage of this method of cultivation is easier management and control of a number of factors during cultivation (air temperature and relative humidity, balanced and rational fertilization, etc.), which ensures better conditions for the growth and development of vegetables according to their needs [46]. Although these systems ensure food production with efficient water use, they are not an energy-efficient solution and may cause additional costs and waste problems. The enormous energy consumption of the hydroponic system leads not only to an increase in operating costs, but also to environmental impacts [47], which are not in accordance with European environmental policy and the Green Deal. More recently, most hydroponic systems are increasingly using the natural power of the sun. To meet the high energy demand and make greenhouse agriculture more sustainable, there is a great interest in integrating photovoltaics [44]. Photovoltaic panels on greenhouse roofs may be opaque, semi-transparent, or transparent, allowing less solar radiation to pass through, which may or may not intentionally affect plant development [48]. As for cultivation in the open field, the risk of using solar panels lies especially in crop rotation, since these are usually annual species that alternate in space and time, i.e., during one year preceding crops are cultivated (usually a species in early spring or winter such as spinach, lettuce, radish, peas, early potatoes, and spring onions), then follows the main crop with the longest growing season (tomatoes, peppers, cabbage, and onions), and on the end the succeeding crop grown after the main crop (lettuce, spinach, spring onions). Such cultivation makes it possible to maximize the use of a specific growing plot throughout the year, as different vegetable species have different biological characteristics (mesophilic and thermophilic species) and different durations of vegetation. Due to different temperature, light, and water requirements, the use of solar panels could be a potential challenge, as well as adjusting the agrotechnical measures according to the installed AgriPV system when growing the different species.

The height of the steel structures and the spacing between PV rows must be suitable for standard agricultural equipment that can pass between the rows for harvesting without interfering with the PV modules. Generally, the distance between two rows of PV arrays in conventional PV systems is 6–12 m. The reason for this distance is to avoid shadows of PV modules on the next row, and it must be suitable for harvesting. The following parameters are important for plant growth between rows of PV plants: height of plant, diameter of plant, and number of plants [49]. All types of crops are generally suitable for cultivation under an AgriPV system, but different effects on yield can be expected due to shading effects. Highly shade-tolerant crops such as leafy vegetables (lettuce, chard, and spinach), field forage (grass/clover mix), various types of pome and stone fruits, berries, soft fruits, and other crops (such as wild garlic, peppers, carrots, asparagus, and hops) appear to be particularly suitable [50]. There is some concern about the impact solar panels may have on crop yields and fruit quality, as there is a direct correlation between solar radiation received by plants and lower crop yields and smaller fruit [48]. According to Edouard et al. [19], plants can become accustomed to the shading caused by the panels by increasing their efficiency in absorbing radiation. It has even been shown that a shade-tolerant plant, such as lettuce, grown under PV panels adapts its morphology (e.g., by producing larger leaves). In particular, lettuce, peppers, tomatoes, aloe vera, maize, and pasture grasses are successfully grown using this method. In one of the studies, it is mentioned that this method increased the product efficiency by 60–70% [49].

Structure of Vegetable Growing in Croatia

The Republic of Croatia has significant advantages for vegetable production, and thanks to climatic, pedological, and hydrological possibilities, the production of vegetables in the open field is possible almost all year round [51]. Intensive production (for the market) of vegetables in Croatia in 2021 amounted to 168,624 tons and took place on 8398 ha, while a smaller part of production is extensive production on family farms (kitchen gardens), where 45,750 tons of vegetables were produced on 1678 ha (Table 6). The most represented vegetable is cabbage, whose share in the total vegetable production is about 15%. Cabbage is grown mainly in continental Croatia. It is followed by onions and garlic with 10%, peppers with 9%, watermelons with 8.5%, and green peas with 7%.

Table 6. Cultivation of vegetables in the Republic of Croatia (2021).

	Area (ha)	**Production (t)**	**Yield (t/ha)**
Total fresh vegetables (including kitchen gardens)	10,076	214,374	21.3
Total fresh vegetables	8398	168,624	20.1
Cauliflower and broccoli	195	3154	16.2
Cabbage (white and red)	1201	28,844	24
Other brassicas	146	2536	17.4
Leeks	97	1697	17.5
Lettuce	195	3586	18.4
Lettuce under glass	31	701	22.6
Other leafy or stalked vegetables	520	6419	12.3
Tomatoes	292	18,785	64.3
Tomatoes for fresh consumption	64	1316	20.6
Tomatoes under glass	88	11,902	135.3
Cucumbers and gherkins	98	8549	87.2
Cucumbers and gherkins under glass	43	7554	175.7
Melons	132	1852	14
Watermelons	720	21,476	29.8
Red peppers, capsicum	803	13,559	16.9
Red peppers and capsicum under glass	31	1778	57.4
Other vegetables cultivated for fruit	1327	17,938	13.5
Carrots	306	6403	20.9
Onions and garlic	914	19,044	20.8
Beetroot	126	3173	25.2
Other root and tuber vegetables	289	4107	14.2
Green peas	563	4600	8.2
Green beans	474	2902	6.1
Fresh vegetables (kitchen gardens)	1678	45,750	27.3

Source: [32].

Considering the areas under cultivation as well as the ecological conditions necessary for growth (thermophilic vegetable species), tomato, pepper, melon, watermelon, and cucumber could have been interesting in terms of AgriPV application. They are heat-loving vegetables with a long growing season, which makes them suitable and potentially profitable for an AgriPV system.

2.4. Aromatic and Medical Plants

It is estimated that 60,000 species are used worldwide for their medicinal, aromatic, and nutritional properties [41]. In the world, the need for medicinal plants is still mostly satisfied by collecting wild populations from nature, and a smaller part is cultivated. In Europe, around 20,000 to 30,000 tons of medicinal and aromatic plants are collected annually, and only 10% are from plantation cultivation. The Republic of Croatia has an extremely rich vascular flora and favorable conditions for the cultivation of medicinal and aromatic plants. The production of medicinal and aromatic plants in Croatia differs by region due to the diversity of climatic and agroecological conditions.

Structure of Medical Plant Production in Croatia

Chamomile is a mostly cultivated medicinal plant in Croatia. It is cultivated in continental Croatia, in the areas of Slavonia and Baranja. The second-largest production is of immortelle in Adriatic Croatia, as well as the third-largest of lavender. Fennel, milk thistle, mint, lemon balm, sage, wormwood, and common mallow also have more significant production.

Chamomile (Table 7) is the most cultivated medicinal plant in Croatia, covering a total area of over 6300 ha (more than 86% of all areas covered with medicinal and aromatic plants). It is grown in almost all counties, but mostly in Virovitica-Podravina County (about 65% of Croatian chamomile production) and Osijek-Baranja County (about 22% of Croatian chamomile production). Larger areas can still be found in the areas of Sisak-Moslavina County, Bjelovar-Bilogora County, and Koprivnica-Križevci County. The vast majority of chamomile is grown in plantations larger than 1 ha; there are 475 such plantations with a total production area of 6348 ha, while there are 178 plantations larger than 10 ha. Some plantations even reach a size of around 100 ha.

Table 7. Chamomile cultivation in Croatia (2021).

	Total Area (ha)	**Agricultural Activity**	**Average Area (ha)**	**Agricultural Activity >1 ha**	**Agricultural Activity >10 ha**
Zagreb County	41.64	13	3.20	8	1
Sisak-Moslavina County	346.37	17	20.37	14	7
Karlovac County	0.23	1	0.23	0	0
Koprivnica-Križevci County	115.30	18	6.41	17	2
Bjelovar-Bilogora County	219.61	10	21.97	10	7
Primorje-Gorski Kotar County	1.06	1	1.06	1	0
Virovitica-Podravina County	4137.89	361	11.46	351	123
Požega-Slavonia County	45.97	5	9.19	5	1
Brod-Posavina County	8.10	5	1.62	3	0
Osijek-Baranja County	1400.21	61	22.95	58	36
Vukovar-Syrmia County	22.38	3	7.46	3	1
Istria County	1.75	1	1.75	1	0
Dubrovnik-Neretva County	0.75	1	0.75	0	0
Međimurje County	2.02	2	1.01	1	0
City of Zagreb	16.54	4	4.14	3	0
TOTAL	**6359.92**	**503**	**12.64**	**475**	**178**

Source: [43].

2.5. Cereals, Industrial, and Fodder Plant Production

There is not much research dealing exclusively with the growing of most common field crops like cereals, industrial plants, and fodder plants in an agrivoltaics system. Cultivation under PV arrays is not identical to conventional farming on open fields. The main differences relate to methods of tilling, crop selection, and crop management. Regarding field management and arable crop growth, it is very important to adapt APV systems. It is essential to adjust the mounting structure of APV arrays to allow the passage of conventional agricultural machinery. For example, for cereal cultivation, a clearance of at least 4–5 m is necessary, especially because of large combine harvesters [14]. For Agri-PV systems combined with light-sensitive crops, alignment and spacing between the module rows must be designed to optimize light availability and homogeneity to avoid negative effects on plant growth [52,53]. Attention must be paid to ensure the PV system does not endanger workers or machinery [54]. In order to maintain crop yields in an agrivoltaic system and reduce the loss of quality arable land, mounting structures should be improved by adjusting the shading level of the system to the specific crops or growing shade-tolerant crops [55]. Generally, numerous studies have proved that agrivoltaics through combined crop and energy production can significantly increase land productivity [14,19], but also that crop performance and final yield are under great influence of weather conditions during the growing season, despite altered microclimatic conditions. Yield ranges of the crops cultivated under AV systems compared to the reference field were −19 to +3% for winter wheat, −20 to 11% for potato, and −8 to −5% for grass-clover in the common growing season, while in the hot and dry year, yields of wheat in AV were increased by 2.7% and of potato by 11% [56]. It is generally well known that the main effect of AgriPV systems is reduced solar radiation, which, especially for shade-intolerant crops (like maize or sunflower, for example), could lead to a considerable yield reduction. Information on the effects of shading on field crop yield and quality in real conditions is scarce. So far, the most research on shading impacts on maize growing under APV or in artificial shade confirms a negative effect on maize performance and yield [57–59]. In a meta-analysis on the effects of shade on the yield of 38 different crop species, i.e., nine crop types, the greatest yield loss due to a reduction in solar radiation was determined for maize and grain legumes [60]. Under an AgriPV system, the average grain yield and the number of pods per plant for soybean were reduced by 8% and 13% [11]. Wheat grown in a shade condition in a Paulownia-wheat intercropping system in China showed a yield reduction of about 50% [61]. In an agroforestry system in France, durum wheat yield was decreased in all shading intensities, and by almost 50% in the most intense shade conditions (31% of light reduction). The greatest impact of shading was the reduction in grain number per spike and grain weight [62]. It can be assumed that other small-grain cereals would similarly respond.

Structure of Cereals, Industrial, and Forage Plant Production in Croatia

From all arable land areas with field crops, the most common are cereals, with about 60%. After cereals, about 20% are industrial plants and 13% are fodder crops (Figure 6).

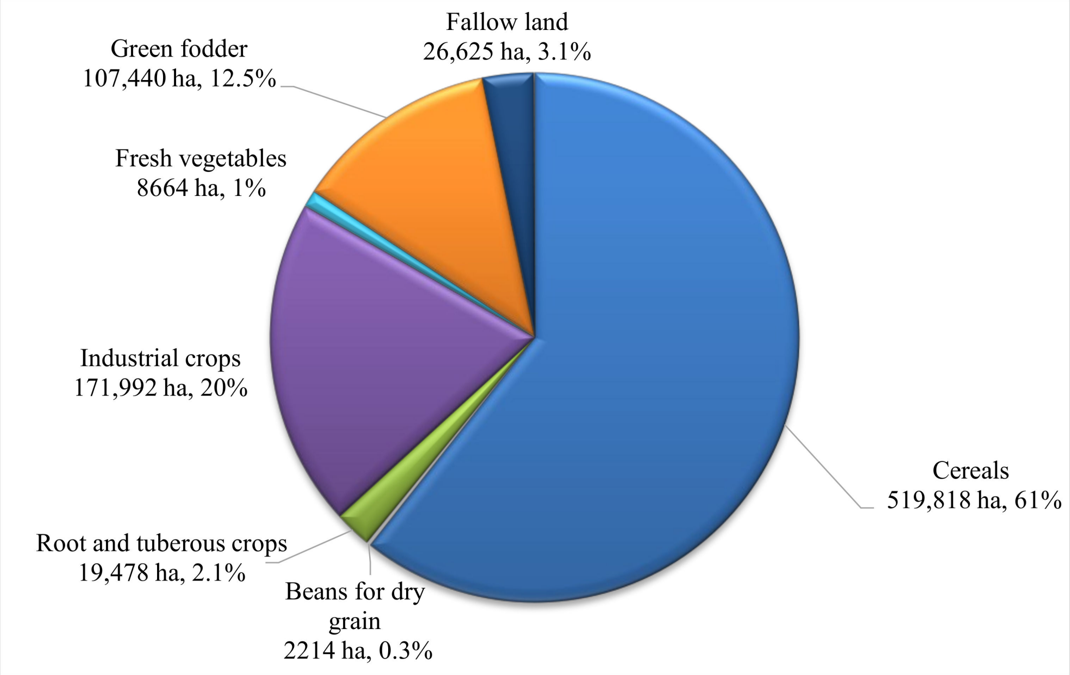

Figure 6. Area (ha) and share (%) of main field crops in 2021, reproduced with permission from [32].

In the Republic of Croatia, especially in the east, there are very favorable conditions for cereal production and also the tradition of growing them. Croatian agricultural production is dominated by cereal and oilseed production, and maize and wheat are the dominant crops in Croatia. Maize (for dry grain) occupies more than 30% of arable land, followed by winter wheat (spring and durum wheat are growing on a much smaller scale), then winter and spring barley, oats, triticale, rye, and other cereals like spelt, buckwheat, sorghum, etc.

The main industrial plants in Croatia are oilseeds (soybean, sunflower, and rapeseed, oilseed pumpkin), root crops (sugar beet and root chicory), potatoes, and tobacco, while fiber plants (industrial hemp and flax) are grown to a lesser extent. In the continental part of Croatia, the biggest share of total industrial plant production is located. Regarding fodder crops, alfalfa and green maize are the most represented (Table 8).

Table 8. Cultivation of some field crops in the Republic of Croatia (2021).

	Area (ha)	Production (t)	Yield (t/ha)
Cereals			
Grain maize	287,976	2,242,119	7.8
Wheat	143,535	961,940	6.7
Rye	511	2082	4.1
Barley	56,478	306,209	5.4
Oats	17,063	58,840	3.4
Triticale	9386	42,497	4.5
Other cereals	4869	15,463	3.2
Industrial plants			
Soybean	86,259	227,872	2.6
Sunflower seed	40,969	124,363	3.0
Rapeseed	30,281	73,423	2.4
Other oil seeds	4098	3548	0.9
Sugar beet	10,066	707,000	70.2
Potatoes	8786	127,826	14.5
Tobacco	3488	7384	2.1
Fodder crops			
Green maize	25,133	873,179	34.7
Other annual green fodder	5794	91,218	15.7
Alfalfa	28,128	179,680	6.4
Clover and mixtures	8425	46,986	5.6
Other leguminous plants harvested green	11,283	83,764	7.4
Fodder peas	792	2331	2.9

Source: [32].

2.6. Grassland and Animal Husbandry

The experiences of other countries [63,64] have shown that the use of AV systems on grasslands, in combination with animal husbandry (mostly sheep), can have different positive effects. By using sheep, it is ensured that grass and other plants at their photovoltaic arrays do not interfere with the functioning of the solar panels. This best practice also means less damage to the solar panels and lower operating costs. By keeping vegetation under control, the solar plant becomes a natural firebreak, helping prevent the spread of a fire should one break out in a neighboring area. It also leads to the saving of fuel that would be needed for mechanical cutting and avoids the use of chemical herbicides that can pollute both the soil and water resources [65]. Ref. [66] investigated the effect of grazing under solar panels on lamb live weight gains, pasture production, and land productivity. In solar pastures, the distance between solar panels was 6 m, giving a 3-m fully shaded and 3-m partially shaded sites. While the DM yield from open and partially shaded areas was similar, pastures under fully shaded sites were significantly lower. On average, pasture production was 9–33% less in agrivoltaic systems than open pastures. Live weight production of the lambs was similar as both open and solar pastures were grazed at the same stocking rates. Increased temperatures decrease the amount of time cattle are in zones of thermal comfort, and heat stress typically occurs above 25 °C for cows [67]. Heat stress has been estimated to cost the dairy industry in the United States more than $900 million annually due to production losses [68]. Ref. [69] investigated the effects on grazing cattle under shade from a solar photovoltaic system. They found no differences in fly prevalence, milk production, fat and protein production, or drinking bouts between cattle in shade and those not in shade. The authors concluded that agrivoltaics incorporated into pasture dairy systems may reduce the intensity of heat stress in dairy cows and increase their well-being and the efficiency of land use.

The Structure of Grasslands and Animal Husbandry in Croatia

According to [32], utilized agricultural area by categories, the total area of permanent grassland (meadows and pastures) in 2017 was 607,555 ha. According to data from the

ARKOD database [70], the total meadow area in the Republic of Croatia was 101,633 ha, the total area of pastures was 25,313 ha, and the total area of karst pastures was 91.499 ha (Table 9). Therefore, the total number of grasslands registered in the ARKOD system is 218,444.6 ha.

Table 9. Type of agricultural land use.

Meadow		Pasture		Karst Pasture	
Total Surface (ha)	**Number of Parcels**	**Total Surface (ha)**	**Number of Parcels**	**Total Surface (ha)**	**Number of Parcels**
101,632.95	242,376	25,313.13	16,479	91,498.52	56,051

Source: [70]

In the AGRONET system from 2022, there are a total of 24,602.68 ha of pastures (continental grasslands-pastures), karst pastures of 91,933.64 ha, and meadows of 93,825.45 ha (Table 10). The total area of grasslands in 2022 was 210,361.77 ha. The majority of grasslands of all types were reported by family farms (82% of continental grasslands and pastures, 85% of karst pastures, and 81% of meadows).

Table 10. Pastures by type of agricultural holding.

Type of Agricultural Holding	Continental Pasture (ha)	Karst Pasture (ha)	Meadows (ha)
Family farm	20,244.76	78,388.62	76,266.18
Craft	863.71	913.10	2259.69
Other legal entities (church, army, educational institutions)	134.01	272.47	244.13
Self-sufficient agricultural holding	401.6	1581.86	12,100.29
Company	2656.62	7447.78	2698.5
Cooperative	301.98	3329.81	256.66
TOTAL	**24,602.68**	**91,933.64**	**93,825.45**

Source: [40].

3. Aquavoltaics

Considering the title of the review article, this subsection provides a somewhat more detailed overview of the definition of aquavoltaics, its uses, benefits, and challenges, with an addition on the structure of freshwater aquaculture (cyprinids) in Croatia.

Aquavoltaics, or AquaPV, is a concept combining electricity production with aquaculture. The goal of AquaPV is the efficient use of water for both food and energy generation. While solar panels above the water or on its surface provide electrical energy, the aquatic organisms living within the water below provide a sustainable food source. AquaPVs floating on the water body can lessen water losses by preventing evaporation by up to 70–85% due to covering the water [71]. Aquavoltaics technology enables electricity to be generated and aquaculture to be carried out in the same area, significantly improving overall productivity per unit area compared to conventional land use [17]. These systems withstand fluctuating water levels; however, they are not commonly designed to operate while resting on the bottom if the body of water is drained [72]. The AquaPV approach aims to maintain parameters such as water and air temperature, light availability, water pH, dissolved oxygen (DO), feeding system, and predator pressure and improve the system by exploiting synergies between the aquaculture and PV systems. Cultured species have different requirements, confirming the need for variation in essential parameters as a function of species type and farming systems. The integration of photovoltaic technology with aquaculture creates synergies as aquatic farming can benefit from module shading effects when temperatures are high, while modules' efficiency values are enhanced at the same time due to the proximity to cool water environments [73]. Aquaculture systems are characterized by a very high energy input, mainly due to their need for an artificial oxygen supply.

Electric power generation using floating, elevated, or other forms of PV module integration offers the possibility to substitute fossil-based energy sources without the occupation of additional land. To maximize the productivity of aquavoltaic systems, the coverage of PV modules and the mounting of the whole system require careful consideration [73]. Common benefits from these installations were a reduction in water evaporation from the reservoir/pond [74,75] and decreased algal growth (due to the reduction in sunlight penetration within the water body) [76]. Also, electrical yields were slightly improved in most reported cases, probably because of the cooling benefit offered by the underlying water surface, as illustrated in some papers [77] while testing a PV panel that was in direct contact with water (Figure 7). According to [67], the high humidity conditions under aquavoltaics operation can reduce the lifespan of photovoltaic modules. Additionally, advancements in photovoltaic technology, such as longer lifespans and higher power output rates, can improve the economic and environmental efficiency of the system.

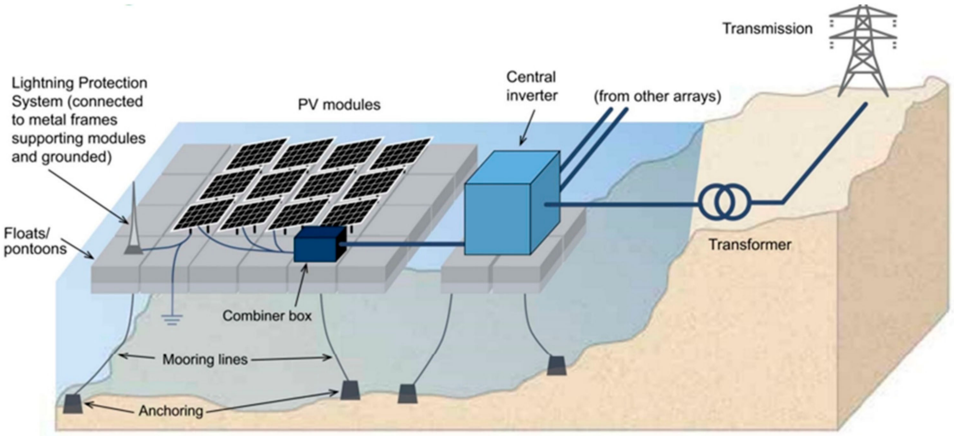

Figure 7. Schematic representation of a typical large-scale FPV (Reproduced with permission from source: Solar Energy Research Institute of Singapore (SERIS) at the National University of Singapore).

Several projects and studies are carried out to verify positive and negative aspects in terms of ecosystems and the technical and economic feasibility of dual use in aquavoltaics:

Cooling

Regardless of the system design, several aspects must be considered when integrating PV modules into aquaculture systems. It is well known that the efficiency of PV modules decreases with increasing temperatures. In the AquaPV approach, a positive cooling effect can be achieved by both water and increased wind speeds. Thanks to the cooling effect, increases of ~10–15% in PV output can be achieved compared to fixed ground-mounted solar systems [78]. The cooling effect of water on solar cells, which favors higher energy conversion efficiency, is considered one of the main advantages of FPVs [79]. The magnitude of this effect depends on the orientation and the amount of contact of the module with the water. The greatest improvement was found for floating, tracking, cooling, and concentrating (FTCC) systems [17].

Light

In waters exposed to the sun, photosynthesis allows the growth of organic matter, including algae. These algae are generally not desirable in water reservoirs because they can obstruct pumping and filtration systems and require costly chemical treatment to control the problem. Installing FPVs shades the water and reduces photosynthesis. This reduces the formation of algal blooms and reduces chemical and operational costs. Aquavoltaic systems provide shade on the water surface of the pond, and the blocked light is absorbed by solar cells and converted into usable energy. If uncontrolled, an increase in shading decreases, and general plant life and microbial density are reduced, affecting the entire food chain down to the fish intended for breeding [80]. Typically, fish are either more active in light and less active in darkness or vice versa [81], and this can be altered by daily changes in factors such as temperature or oxygen [82]. The growth of aquatic organisms is linked to light, but it is not unique because species vary in their growth conditions. Fish and larvae, for example, must be reared in specific light ranges depending on the species and stage of development [81]. Light-emitting diodes (LEDs) can be installed on the underside of the pontoon structures in the aquavoltaic system, powered by the PV portion of the system, to affect the photoperiod of aquatic life. This design provides the "aquaculturist" with a powerful tool to increase and further optimize production for specific aquatic species [17]. This needs to be tested further, and the effects of energy conversion need to be considered. Another alternative is to rotate or move the plant around the water body in which it is located. This action would limit the amount of natural light shading that a given water area experiences [80]. A change to the pontoon structure itself could increase the distance between the modules that make up a facility. This change would allow a controlled amount of light to penetrate the water below. This approach does reduce the efficiency per unit area of the array because the density of the solar modules is lower, but if the area is not a constraint, this is an insignificant drawback [83].

Land use and evaporation

PV systems floating on water do not occupy habitable land and can be deployed in degraded environments and reduce land-use conflicts [84–86], as can dual-use infrastructure, such as reservoirs, where evaporation can also be reduced [87,88]. One of the most important synergistic effects resulting from coupling PV systems with aquaculture is saving water. In aquaculture systems where high water flow rates are observed, the prevention of water loss is a great benefit from both economic and ecological points of view. FPVs save water by reducing evaporation and improving water security in arid areas while being flexible for use in various water bodies such as fishponds, drinking water reservoirs, etc. Because the system acts like a protective blanket over the water, FPVs can reduce water evaporation by up to 33% for natural lakes and ponds and up to 50% for man-made facilities [89]. Some authors noted that water loss from reservoirs could be reduced by as much as 70–85% with FPV [17,71]. Especially in the context of climate change, where dry periods are becoming more frequent, reducing evaporation is a major achievement [75].

Maintenance

Another advantage related to proximity to water emerges when considering pollution effects. First, particles are washed off the module surface more regularly. Soiling of the surface of PV modules can also occur from other sources, such as bird droppings or biofouling [17]. Biofouling describes the colonization of organisms such as algae on PV surfaces, which can affect not only the modules but also mounting systems and cables. According to some of the authors [17], one of the biggest unknowns is the interaction of FPVs with aquatic organisms and the potential for biofouling to occur. Mechanical stress would also be high due to increased wind speeds and waves, especially during stormy conditions [73]. Stable anchoring is essential to compensate for lateral forces [74], while flexible mounting of PV modules offers the advantage of floating with the waves and protecting the system from external forces. Depending on the location, maintenance of the system may be more difficult, as work must be performed from boats or from the movable pontoons. However, because accessibility is difficult, vandalism and theft can be expected to decrease [3]. On the other hand, floating systems do not require thousands of metal frames to be attached to the ground, which means that a panel array can be constructed more quickly. In addition, decommissioning a floating system is much easier and less expensive.

Material availability

Material requirements for PV are likely to increase substantially to limit warming to well below 2 °C, but PV materials are widely available, have possible substitutes, and can be recycled [18,90]. The main materials for PV are silicon, copper, glass, aluminum, and silver, with silicon being the most expensive and glass the most important by mass at 70%.

None of these materials are considered critical or potentially in short supply [91]. FPVs are compatible with the existing hydropower and electric infrastructure, which supports diversifying the energy supply and its resilience. The lack of supporting policies and development roadmaps by governments could hinder FPVs' sustainable growth [85]. There is scarce research on the socio-environmental impacts of FPV farms. [92] reflected on three key socio-environmental impacts of FPVs: job creation, non-occupation of habitable land, and improving water security in water-scarce regions. The addition of floating modules will most likely increase the difficulty of tending the aquaculture system, and the aquatic life may slow or disrupt the maintenance of the PV modules. After a typical useful life of 30 years, PV modules can be recycled to prevent environmental pollution from the toxic materials they contain, reuse valuable materials, and avoid the accumulation of waste (Figure 8).

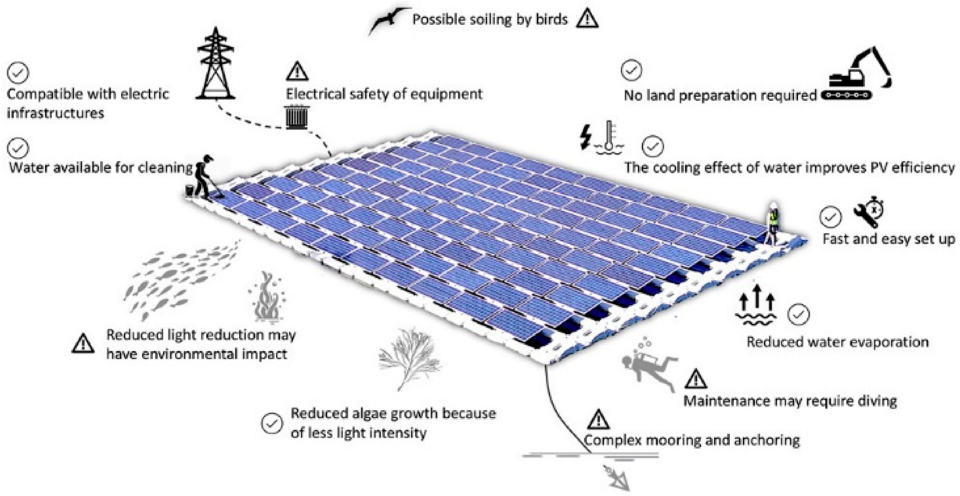

Figure 8. Benefits and challenges of floating solar panels Reproduced with permission from [85].

Structure of Freshwater (Cyprinid) Aquaculture in Croatia

In Croatia, cyprinid species are traditionally farmed in carp ponds, which usually cover several hundred hectares, with five carp ponds having an area of over 1000 ha. The total area of carp ponds in Croatia is currently 14,081.49 ha, while the production area in 2021 was 12,539 ha [93], preliminary data) (Table 11).

Table 11. Register of aquaculture permits for inland waters (warmwater species only).

County	Area (ha)
Bjelovar-Bilogora	3267.04
City of Zagreb *	1273.69
Požega-Slavonia/Bjelovar-Bilogora	1274.659
Osijek-Baranja	2920.31
Karlovac	391.78
Virovitica-Podravina	981.22
Sisak-Moslavina	742.15
Brod-Posavina	3069.95
Zagreb/Bjelovar-Bilogora	117.99
Varaždin	4.72
Međimurje	5.75
Požega-Slavonia	0.44

Source: [92]; * permit for cold and warmwater aquaculture.

Most carp ponds are located along larger river basins in the lowlands and the continental area of the Republic of Croatia, where the continental climate prevails. Continental Croatia has a temperate continental climate, and throughout the whole year it is in a circulation zone of mid-latitudes, where the atmospheric conditions are very variable. They are characterized by a diversity of weather situations with frequent and intense exchanges during the year. These are caused by moving systems of low or high air pressure, often resembling vortices hundreds and thousands of kilometers in diameter. The climate of continental Croatia is modified by the maritime influence of the Mediterranean, which is stronger in the area south of the Sava River than in the north and weakens towards the east. Cultivation of cyprinids in Croatia mostly involves controlled rearing of common carp (*Cyprinus carpio*) in monoculture or polyculture with other species, the most common of which are Grass carp (*Ctenopharyngodon idella*), bighead carp (*Hypophthalmichthys nobilis*), silver carp (*Hypophthalmichthys molitrix*), catfish (*Silurus glanis*), perch (*Sander lucioperca*), pike (*Esox lucius*), and tench (*Tinca tinca*). The production is mostly semi-intensive, where, in addition to the natural food produced in the pond by biological processes and whose production is stimulated by agrotechnical measures (fertilization, etc.), the fish are also fed additional feed, usually cereals (corn, wheat, rye, and barley). The production cycle in carp farming usually lasts three years [93], preliminary data (Table 12).

Table 12. Freshwater aquaculture production in Croatia (t) (2017–2021).

Species	2017	2018	2019	2020	2021
Common carp	2039	1959	2037	1691	2738
Grass carp	169	141	122	133	266
Silver carp	73	36	141	161	212
Big-head carp	477	301	344	326	414
Catfish	31	23	20	32	32
Sander	9	7	7	6	4
Pike	12	7	9	2	3
Rainbow trout	395	336	364.5	379	335.6
Brown trout		34	7.5	12.4	15
Other	67	55	48	37	22
TOTAL (t)	**3272**	**2899**	**3100**	**2779**	**4040**

Source: [92].

According to [94] the analysis of spatial capacities and conditions for the use of the potential of renewable energy sources in the Republic of Croatia, as well as the considered criteria for determining the vulnerability of an area to the energy potential of the sun, encourages the development of the possibility of establishing hybrid photovoltaic systems and aquaculture. Mainly because of their symbiotic relationships, which include increasing the efficiency of energy conversion due to cooling and cleaning the surfaces of the PV modules, reducing the evaporation rate of the water surface, improving the growth rate of fish through integrated designs with PV-powered pumps to control oxygen levels, etc. [17].

4. Conclusions

Viticulture

In Croatia, 92.44% of producers have vineyard plots smaller than 1 ha, but, at the same time, their plots have a share of 32.12% in the total viticulture area in Croatia. Thus, 67.88%, or 12,026 ha, of the total vineyard area seems suitable for APV technology application. It is highly recommended to apply APV only in vineyards with a large area, precisely greater than 1 ha (1 ha is taken as the profitable limit for installing APV systems). The vast majority of recommended vineyard surfaces are located in five viticultural subregions (Croatian Danube, Slavonia, Croatian Istria, Middle and Southern Dalmatia, and Dalmatian Zagora), with a total surface of 10.402 ha. An average slope of 6.38% is not an obstacle for agrivoltaic construction. It was also not possible to obtain the exposure data of vineyards, but considering the grapevine as a long-day plant, it is assumed that all vineyards are on exposures suitable for setting up APV systems.

Fruit growing

Agrivoltaics in orchards has great potential in Croatia, especially in small- to medium-sized orchards (5–15 ha), such as family farms. Photovoltaic panels above fruit crops can reduce physiological disorders in plants and fruits (sunburn, heat stress, overcolor, etc.). At the same time, panels can be used as hail protection with no need for removal during the offseason (time- and labor-consuming). Panels are changing microclimate conditions (lower air temperatures during the day, higher temperatures during the night, diffusing sunlight, and changing the solar spectra that reach the plants) in orchards, but they also reduce damage and could even improve fruit quality. It is estimated that for at least 2/3 of plantations larger than 1 ha (some 200 plantations–950 ha), there could be a potential for installing agrivoltaics systems, either in the existing cultivation form or with a slight adjustment of agrotechnical measures in the plantation.

Aromatic plants

It is estimated that for at least three-fourths of plantations larger than 1 ha (about 500 plantations in CRO), there are assumptions about the potential for installing agrivoltaic systems, either in the existing cropping pattern or with a slight adaptation of agrotechnical measures in the plantation. Of course, apart from the production conditions of cultivation, not all medicinal and aromatic plants are of the same degree of convenience for setting up agrivoltaic systems. The possibilities for the current successful implementation of agrivoltaic systems in plantations of medicinal and aromatic plants are relatively small due to numerous circumstances, but one should not abandon their installation, even in small quantities.

Vegetable growing

In the Republic of Croatia, despite favorable agro-ecological conditions (pedological and hydrological), existing production is insufficient for the production of most vegetables and is often price uncompetitive with imported vegetables, and the export of domestic fresh and processed vegetables is low in terms of quantity and value. Insufficient production to meet the needs of the Croatian market is a result of fragmented cultivation areas, disorganized production infrastructure, a lack of heating, irrigation, hail and frost protection systems, and inadequate storage areas. All of this indicates that additional investment in modernization, such as agrivoltaic systems, is needed, to make vegetable production competitive and profitable. The use of solar panels in the construction of greenhouses or in open fields is considered the most environmentally friendly solution. Agrivoltaic offers advantages such as protection against hail, frost, and drought damage and eliminates the need for protective films and other materials. In Croatia, the chances for successful implementation of AgriPV systems in vegetable production are currently relatively low due to numerous limiting circumstances (fragmented cultivation areas, unorganized production infrastructure). In addition, growing vegetables with solar panels requires certain adjustments in cultivation practices focused on mitigation of light reduction (especially when growing melons, watermelons, and peppers) and selection and combination of crops with maximum radiation efficiency. Despite the limiting factors, it is recommended to start research projects in the form of "pilot projects" with the most commonly grown vegetables in the Republic of Croatia in order to analyze the possible impact of PV systems in terms of production, growth, yield, resistance to microclimatic changes both in the field and in greenhouses, etc.

Cereals industrial and fodder plants production

About 45% of the total utilized agricultural land in Croatia is used to grow cereals, industrial crops, and fodder crops, which include morphologically and physiologically very diverse plant species with different demands on agroecological conditions, agrotechniques, and agricultural management. Also, most of them, except some fodder crops like alfalfa or clovers, are annual plants with various growing seasons (winter and spring crops). Concerning necessary crop rotation practices and different cultivation requirements, the implementation of common field crops in AgriPV could be very challenging. Shade tolerance of the crop is one of the most important factors determining the economic result of AgriPV. From that point of view, maize and sunflower are probably the most unsuitable for cultivation in AgriPV.

Grassland and animal husbandry

One of the top three land covers associated with greatest agrivoltaics potential are grasslands. The highest potential of agrivoltaic systems is anticipated in semi-arid and arid regions. Here, grasslands often suffer from the adverse effects of high solar radiation and accompanying water losses. Grassland production under solar panels may benefit from increased water savings by a reduction in evapotranspiration and the adverse effects of excessive radiation, while economic viability is increased and rural electrification is made possible. The main disadvantage of photovoltaics is the shadows cast by the panels, which can affect plant productivity to varying degrees, requiring the selection of hardier plants and limiting those that rely more heavily on sunlight. This also limits the latitudes where agrivoltaics work best, as profitability can suffer in cooler areas where the intensity of sunlight varies throughout the year.

Aquavoltaics

To avoid increasing land use, the approach of aquavoltaics offers a solution in the dual use of land. Especially in countries with long periods of drought, the concept of aquavoltaics offers many synergies. The strong reduction in water loss due to lower evaporation rates is especially interesting. With a suitable system approach, aquavoltaics can contribute to sustainable water use and fulfill the concept of the food-water-energy nexus. The technical feasibility of integrating PV modules into water surfaces has been demonstrated, but solid studies on fish farming are still lacking. More research is needed to understand the effects of direct contact with pontoon structures and solar arrays on aquatic life. The total area of carp ponds in Croatia is currently 14,081.49 ha, while the production area in 2021 was 12,539 ha. Based on this value, it is difficult to estimate how much area is available for the installation of floating solar panels due to several variables. This is mainly due to the undefined extent and intensity of vegetation (sedges, woody vegetation, and copses) in certain places of the registered water area and the classification of production intensity (RAS systems, rearing cages, etc.). Large carp farms are located in the continental part of the Republic of Croatia, mainly in the area of major river courses, and are therefore important for the conservation of biodiversity. Warm freshwater farms (carp farms) represent areas of great natural value in Croatia and are designated as part of the ecological network EU-Natura 2000. Consequently, many different rules and laws apply in these places for the preservation and protection of nature. Maybe this consideration should also be taken into account as a kind of limiting factor for the installation of floating photovoltaics.

Overall conclusions

Agrivoltaics involves the integration of solar panels within agricultural fields, allowing for simultaneous land use for crop cultivation and solar power generation in Croatia. This approach provides numerous benefits, including increased land productivity, reduced water evaporation, and enhanced energy generation. Similarly, aquavoltaics explores the integration of solar panels in freshwater aquaculture systems, offering advantages such as improved water quality, reduced algae growth, and efficient renewable energy production. Through this research, Croatia can harness the synergy between renewable energy production and sustainable agriculture and aquaculture practices, promoting a greener and more resilient future. Further research can focus on optimizing the design and implementation of integrated systems, considering factors such as crop and fish species selection, panel orientation, and system efficiency. In addition, studying the economic viability and long-term sustainability of these approaches will be crucial for their widespread adoption. Collaboration between researchers, farmers, and policymakers can help develop tailored solutions for the Croatian context that maximize the benefits of renewable energy production while ensuring food and water security. Overall, future research in agrivoltaics and aquavoltaics has the potential to revolutionize the energy landscape and contribute to the sustainable development of the Croatian agricultural and aquaculture sectors.

Author Contributions: Conceptualization, D.M. and M.K.; Validation, D.M., M.K., T.T., S.R., J.R., G.F., H.Č., J.L., Ž.A., M.R. and I.V.; Formal Analysis, D.M., M.K., S.R., J.R., G.F., J.L., Ž.A., M.R. and I.V.; Writing—Original Draft Preparation, D.M., M.K., S.R., J.R., G.F., J.L., Ž.A., M.R. and I.V.; Writing—Review and Editing D.M., M.K., T.T., S.R., J.R., G.F., H.Č., J.L., Ž.A., M.R. and I.V.; Visualization, G.F., M.R. and I.V.; Supervision, M.K., T.T. and H.Č. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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