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Review

Integration of Crops, Livestock, and Solar Panels: A Review of Agrivoltaic Systems

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Supplementary Information

Supplementary Information

Table S1. Summary of the AV systems considered in this review. Special attention has been given to those recent articles that include location, harvesting, % shading and % yield, but information has also been taken from the details of PV systems and some observations.

Reference	*Location*	*Crop*	*PV Details*	*Shading*	*Yield*	*Observations*
[1]	Naju, Jeollanam Province, South Korea	Broccoli (*Brassica oleracea*)	Height: 3–4 m, Bifacial panels	35%	-9%	Decrease in crop production and alteration in broccoli metabolites
[2]	Naju, Jeollanam Province, South Korea	Sesame (*Sesamum indicum*)	Height: 5.42m, Types: Bifacial and mono-facial	21%	-7%	Maize farming under bifacial with 21% shading selected as the best AV type
				26%	-14%	
				32%	-53%	
		Mung bean (*Vigna radiata*)		21%	-21%	
				26%	-44%	
				32%	-44%	
		Red bean (*Vigna angularis*)		21%	-26%	
				26%	-35%	
				32%	-37%	
		Maize (*Zea mays*)		21%	6%	
				26%	-21%	
				32%	-30%	
		Soybean (*Glycine max*)		21%	-13%	
				26%	-21%	
				32%	-30%	
[3]	Ongjin, Incheon, South Korea	Grape (*Vitis vinifera*)	Umbrella-shaped, Bifacial, Height: 2m, Tilt: 15°	30%	Not specified	No effect on berry weight/number except under opaque type. Delayed harvest

[4]	Daegu, Daegu Metropolitan City, South Korea	Rice (*Oryza sativa*)	Dummy panels, Height: 3.3m, Spacing: 1.5m	30%	-14%	Not specified
		Soybean (*Glycine max*)			-34%	
		Adzuki Bean (*Vigna angularis*)			-43%	
		Garlic (*Allium sativum*)			-19%	
		Onion (*Allium cepa*)			-14%	
		Rye (*Secale cereale*)			-9%	
		Maize (*Zea mays*)			-11%	
		Maize (*Zea mays*) mixed with soybean (*Glycine max*)			-13%	
[5]	Cheongju, Chungcheongbuk Province, South Korea	Potato (*Solanum tuberosum*)	Height: 4-4.5m	32%	-9%	Not specified
		Sesame (*Sesamum indicum*)		32%	-19%	
		Soybean (*Glycine max*)		32%	-19%	
				28%	-20%	
		Rice (*Oryza sativa*)		25%	-13%	
				32%	-14%	
				32%	-30%	
[6]	Naju, Jeollanam Province, South Korea	Kimchi cabbage (*Brassica rapa*)	Solar panels: Bifacial and Mono-facial, Height: 3.3m, Angle: 30°	41%	-18%	Sensory compounds unaffected in both crops
		Garlic (*Allium sativum*)			-15%	
[7]	Bierbeek, Flemish Brabant, Belgium	Pear (*Pyrus communis*)	Bifacial, static, tilted, semi-transparent	35%	-16%	Quality maintained

[8]	Jiangshan, Zhejiang, China	Multiple crops (kiwifruit, luffa, cowpea, broccoli, cabbage, zucchini, sweet potato, Chinese white cabbage)	Array spacing: 2.5 m, Height: 1.6 m	60%	-60%	AV designed to control erosion
[9]	Chengdu Plain, Sichuan, China	Kiwifruit (*Actinidia deliciosa*)	Translucent PV panels	19%	-5%	Reduction in leaf transpiration and water use efficiency with increased shading
				30%	-24%	
				38%	-34%	
[10,11]	Montpellier, Occitanie, France	Lettuce (*Lactuca sativa*)	Fixed, East-West, Height: 4m	30%	-27%	Managed panel control reduces water consumption, LER always > 1
			Solar tracking, Height: 5m	35%	-19%	
			Controlled tracking, Height: 5m	25%	-21%	
[12]	Montpellier, Occitanie, France	Durum wheat (*Triticum durum*)	Half density, Height: 4m, Tilt: 25°	28%	-8%	LER between 1,35 and 1,73.
			Full density, Height: 4m, Tilt: 25°	50%	-19%	
[13]	Montpellier, Occitanie, France	Lettuce (*Lactuca sativa*), Varieties "Kriribati" and "Emotion"	Half density: Height: 4m. Tilt: 25°	30%	-9%	Savings of 14-29% of evapotranspiration in AV systems
			Ful density: Height: 4m. Tilt: 25°	50%	-20%	
		Lettuce (*Lactuca sativa*), Varieties,	Half density: Height: 4m. Tilt: 25°	30%	-39%	

		"Model" and "Bassoon"	Ful density: Height: 4m. Tilt: 25°	50%	-53%	
[14]	Mallemort, Provence-Alpes-Côte d'Azur, France	Apple (*Malus domestica*)	Solar tracking, Height: 5m, Above canopy: 1.5m, 2019	53%	-32%	Improved yield and protection from frost in 2021
			Solar tracking, Height: 5m, Above canopy: 1.5m, 2020		-27%	
			Solar tracking, Height: 5m, Above canopy: 1.5m, 2021		90%	
[15]	Lavalette, Occitanie, France	Maize (*Zea mays*), full irrigated	Dynamic monocrystalline panels installed on north-south facing 19 m strips.	35%	-16%	Increased water use efficiency and reduced water consumption
		Maize (*Zea mays*), deficit irrigated			-20%	
		Maize (*Zea mays*), full irrigated	Fixed-tilt monocrystalline, 25° fixed tilt, aligned on 22.4 m east-west facing strips. Half density.	30%	-18%	
		Maize (*Zea mays*), deficit irrigated			-25%	
		Maize (*Zea mays*), full irrigated	Fixed-tilt monocrystalline, 25° fixed tilt, aligned on 22.4 m east-west facing strips. Full density.	50%	-34%	
		Maize (*Zea mays*), deficit irrigated			-15%	

[16-18]	Heggelbach, Baden-Württemberg, Germany	Potato (*Solanum tuberosum*), 2017	Bifacial modules, 5 m height, fixed, south-west orientation, 20° tilt.	53%	-18%	Protective effect observed in 2018. Crops slightly adapted to shade conditions
		Potato (*Solanum tuberosum*), 2018			11%	
		Celery (*Apium graveolens*), 2017			-19%	
		Celery (*Apium graveolens*), 2018			12%	
		Clover (*Trifolium spp*), 2017			-5%	
		Clover (*Trifolium spp*), 2018			-8%	
		Winter wheat (*Triticum aestivum*), 2017			-19%	
		Winter wheat (*Triticum aestivum*), 2018			3%	
[19]	Weihenstephan/ Freising, Bavaria, Germany	Chinese Cabbage (*Brassica rapa pekinensis*)	3.6 m over crops, tracking, no separation between PV models	Not specified	-41%	Not specified
	Weihenstephan/ Freising, Bavaria, Germany	Potato (*Solanum tuberosum*) and lettuce (*Lactuca sativa*)	Tubular PV modules		-15%	
	Rhineland-Palatinate, Germany	Apple (*Malus domestica*)	Fixed rows with tracking PV modules:		Not specified	It is an ongoing project (2022 and 2025). There is no performance data yet

			Semi-transparent, double-glass, 225 W.			
[20]	Nagpur, Maharashtra, India	Grape (*Vitis vinifera*)	PV mounting in vineyard spaces. Tilt: 21º	Not specified	0%	Economic value increased 15 times compared to conventional farming
[21,22]	CUTM, Odisha, India	Turmeric (*Curcuma longa*)	Polycrystalline PV modules: Portable and adjustable agrivoltaic system, 0.675 kWp.	73%	-15%	LER and payback period are 1.73 and 9.49 years respectively
[23]	Amrol, India	Wheat (*Triticum aestivum*)	East-West Oriented Strips, 3.7 m high on cement pillars, manually tiltable. A) Full density: 2.5 cm panel separation.	44%	-38%	Not specified
			B) Half density: 15 cm panel separation.	39%	-35%	
			C) Partial density: 25 cm panel separation.	36%	-29%	
[24]	CAZRI, Jodhpur, Rajasthan, India	Aloe vera (*Aloe barbadensis mill.*)	Polycrystalline silicon PV, East-West, 26° tilt	31.5%	-11%	Not specified
[25]	Melegnano, Lombardy, Italy	Basil (*Ocimum basilicum*)	Tinted semi-transparent,	43%	-15%	

		Spinach (*Spinacia oleracea*)	amorphous silicon, fluorine tin oxide coated		-26%	Financial gain observed in comparison to traditional agriculture
[26]	Monticelli d'Ongina, Emilia-Romagna, Italy	Soybean (*Glycine max*)	Stilt-mounted, biaxial full sun-tracking	27%	-8%	Increased plant height and leaf area under shaded conditions
				16%	4%	
				9%	-5%	
				18%	-12%	
[27]	North Italy, Emilia Romagna Region, Italy	Maize (*Zea mays*)	System built on suspended structures, solar track, varying density	14.6%	1%	Shading improves soil water balance and increases water saving; higher yields under agrivoltaic conditions
				12%	5%	
				32%	2%	
				28%	6%	
[28]	Valpolicella area, Veneto, Italy	Grape (*Vitis vinifera*), 2017	Fixed PV panels, Height: 2.6m - 1.9m	75%	-10%	Microclimate modification reduced transpiration and photosynthesis rates
		Grape (*Vitis vinifera*), 2018			-14%	
		Grape (*Vitis vinifera*), 2019			-14%	
[29]	North of Italy (Borgo Virgilio, Mantova)	Durum wheat (*Triticum durum*)	Bi-axial technology, Height: 4.5m	13%	-2%	Improved feed quality and nutrition with increased shading
				41%	-23%	
[30]	Puglia region, Italy	Tomato (*Solanum lycopersicum*)	Conventional Monocrystalline solar panel	80%	-58%	Reduced water demand for irrigation; impact on fruit quality varied
				50%	-45%	
			Semi-transparent panel	80%	-41%	
				50%	-28%	

			Stilt-mounted PV modules, 30º tilt, High Density		-4%	
[31]	Brenes, Seville, in southwestern Spain	Canola (*Brassica napus*)	Non-tracking and heightened structures, Fixed-tilt angle of 27°	30%	–20%	Not specified
		Carrot (*Daucus carota*)			–10%	
		Maize (*Zea mays*)			–7%	
		Faba bean (*Vicia faba*)			0%	
		Melon (*Cucumis melo*)			–17%	
		Onion (*Allium cepa*)			–6%	
		Pea (*Pisum sativum*)			–15%	
		Potato (*Solanum tuberosum*)			–23%	
		Tomato (*Solanum lycopersicum*)			–5%	
[11,32]	Almería, Spain	Lettuce (*Lactuca sativa*)	Mini-PV modules arranged in patterned designs, 3.5m above ground: A) Concentrated shadow	22%	-46%	Not specified
			B) Scattered shadow		-69%	
[33]	Chiang Mai, Thailand	Bok choy (*Brassica rapa subsp. chinensis*.)	Ground-mounted 25-kW PV power plant. Amorphous PV modules installed at 2.0 m	94%	-88%	Cultivation under PV panels reduced module temperature by 0.18°C, slightly increasing

						power generation by 0.09%
[34]	Tucson, USA	Chili (*Capsicum spp.*)	Raised solar PV panel array, 3.3m off the ground, 32° tilt	50%	300%	Cooler daytime temperatures under the panels, greater soil moisture retention, increased food production
		Tomato (*Solanum lycopersicum*)			200%	
		Jalapeno (*Capsicum annuum*)			0%	
[35]	Boston, USA	Blueberries (*Vaccinium spp.*)	Medium-to-large scale fixed bifacial AV array with custom E-W wings	34.10%	-33%	Not specified
[36]	Kansas, USA	Lettuce (*Lactuca sativa*)	Ground mounted	Not specified	0%	30% increase in economic value over traditional farming
			Height: 4 m, 6.4 m for half density interspacing		-10%	
			Height: 4 m, 3.2 m for full density interspacing		-31%	
[37]	Lahore, Pakistan	Okra (*Abelmoschus esculentus*)	Vertical bifacial agrivoltaic system, 10.5 kW, ~85 m²	18%	-16%	Increased soil moisture and reduced air temperature
		Calabash (*Lagenaria siceraria*)			-38%	
		Potato (*Solanum tuberosum*)			9%	

Table S2. Location and overall average LER (using real systems and models), used to create the map in Figure 4.

Location	*Average LER*	*Reference*
Montpellier, France	1.37	[11]
Odisha, India	1.73	[21]
Anhui, China	1.73	[38]
Kfar Qara, Israel	1.39	[39]
Junagadh, India	1.61	[40]
Belgium	1.10	[41]
Chiang Mai, Thailand	1.80	[42]
Västerås, Sweden	1.33	[43]
Lake Constance, Germany	1.72	[16]
Po valley, Northern Italy	1.59	[27]
Niger, África	1.23	[16]
Shelkovsky district, Chechen Republic, Russia	1.57	[44]
Corvallis, Oregon, USA	1.87	[45]
Jaén, Spain	1.71	[46]
Nagpur, India	2.1	[47]
Gelsdorf, Kressbronn, and Bavendorf, Germany	1.54	[48]
Córdoba, Spain	1.38	[49]
Cartagena, Spain	1.48	[50]
Nibong Tebal, Penang, Malaysia	2.17	[51]

Ragusa, Italy	1.64	[52]
Seine et Marne, France	1.51	[53]
Valverdiño, Portugal	1.37	[54]
Melides, Portugal	1.39	[54]

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