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Full Heads or Cut and Come Again? Economic Analysis of Leafy Green Cultivation in Solar-Powered Indoor Vertical Farms

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Abstract: Although vertical indoor farming (IF) offers higher yields, reduced weather risk, and water savings, it requires higher capital expenditures (CapEx) and energy and labor-related operational expenditures (OpEx), causing many to fail economically. The solar-powered agrivoltaic agrotunnel offers a promising solution to the elevated and unstable energy costs of IF, although a comprehensive economic analysis of such facilities with a specific focus on other operational and capital expenditures has not been done. To address this gap, this study investigates the profitability of two market options, each requiring different labor levels, for agrivoltaic agrotunnel-based IF lettuce production using experimental data: (1) one-cut head Romaine lettuce, involving minimal labor during harvesting, and (2) labor-intensive "cut and come again" spring or green mix of Romaine, Red Oakleaf, and Red Outrageous lettuces. Differences in harvesting labor, yield, market value, consumable materials, and water consumption are evaluated using economic indicators of net present cost, net present value, return on investment (ROI), internal rate of return, and discounted payback period. While the maintenance costs of both agrotunnel and solar agrivoltaic systems were included, the energy cost was minimized to zero by designing a net-zero energy grid-connected photovoltaic system. A sensitivity analysis was conducted on all economic expenditures with a specific focus on the labor rate and the CapEx. Comparing the economic indicators showed that head Romaine, with the annual yield and labor requirement of 3272 kg/year and 2042 h/year, respectively, was only feasible when both CapEx and OpEx were kept at the minimum possible levels, and revenue was maximized. Spring mix, however, had a more reasonable feasibility range despite higher labor (3580 h/year) due to greater yield (5501 kg/year) as a result of more intensive harvesting activities. ROI above 10% were achievable when labor rates were near minimum wage ($\leq$ \$14 USD/h) and CapEx under \$500,000 USD.

Keywords: economics, vertical farming, indoor farming, leafy greens, agrivoltaics

1. Introduction

Controlled environment agriculture (CEA), including indoor farming (IF) and vertical farming (VF), provides higher yield while addressing issues in traditional farming such as high water use [1], high levels of emissions [2, 3], and limited-time productivity [1, 4, 5]. IF systems, however, have much higher energy and labor costs [6], causing many to fail economically [7]. According to Newbean Capital's report on the analyzed data from 56 indoor farms in the USA and Canada, electricity and labor were identified as key cost expenditures [8]. Hence, there is a significant necessity for economic or technoeconomic evaluation of various IF or VF structures to identify the key economic expenditures and further investigate opportunities for labor and energy optimization. Lettuce, in the family of leafy greens, is one of the most common products in IF systems [9]. A US case study across seven locations [10] showed minimal savings in land and water, while VF brought

about much higher energy (USD 0.464/kg vs 0.046/kg) and labor costs (USD 0.995/kg vs 0.209/kg), with the average lettuce production cost of 2.5 times higher than that in traditional farming. Even without considering the effect of labor and transportation costs in the economic modeling, the specific cost of products in a distributed office-based IF unit was more than twice as expensive compared to commercial vertical farm and open-farm agriculture [11]. In one other study [12], IF showed higher profitability and shorter payback period than the greenhouse. The labor intensity, however, was assumed to be equal in both these CEA cases. In a lettuce greenhouse vertical farm fed by natural sunlight, although the average revenue was three times higher than that in the horizontal (conventional) equivalent, the initial cost of vertical structure was also 3-fold of the horizontal one's, emphasizing the place of investment costs in the profitability of such agricultural systems [13]. Similarly, the profitability index of 1.1% with an internal rate of return (IRR) of 12.57% for a hydroponic leafy green production was compared against the 1.45% profitability and 20.96% IRR for conventional farming. The contribution of initial investment cost for both cases, however, was approximately negligible

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[14]. Another study investigated and compared how profitable VFs and greenhouses were for growing lettuce year-round near Quebec City, Canada [15]. For an equal labor costs level, VFs turned out to yield slightly higher gross profits, mainly due to lower heating and land costs offsetting higher lighting expenses. These conclusions show that the economic analysis and optimization can guide engineers and policymakers in improving IF viability [16, 17]. For this, despite technological advances, VF remains significantly more expensive than traditional farming, even though it may be profitable for some selected crops. The high level of profitability has been previously achieved by targeting a high-value crop, showing the payback period of around 2 years [18]. According to research conducted on vertical lettuce cultivation in Bangladesh [19], changing the variety of cultivar (product sale option) could significantly boost the economic outcomes. From a market analysis perspective, cultivating salad varieties with potential organic certification and higher market value could significantly enhance the revenue obtained by indoor lettuce production systems in North America [20]. For leafy green production in a home IF in Germany, the profitability of 40% was achievable [21]. Similarly, a low-cost, sun-fed urban family vertical farming (UFVF) system [22] showed a 30% ROI with a 3.5-year payback period, attributed to strategic crop choices like leafy greens and strawberries. Last but not least, in a very recent study on the integration of different variables on the economic viability of an indoor lettuce farm, it was revealed that light intensity, CO_2 level, and temperature had the highest impact on the economics of the farm, which was mainly led by crop growth and yield [23]. The light intensity, CO_2 level, and temperature for lettuce should not go beyond 250 $\mu mol/m^2 \cdot s$, 1400 ppm, and 24 °C, respectively, to have the most optimized economic viability.

Other studies have emphasized the impact of variables such as vertical shelving configuration [24], rotational cultivation [25], photoperiod [26], light intensity [20], and total electricity consumption [11] on the profitability of lettuce cultivation in IF systems. As a key factor in managing energy costs, the integration of renewable energy sources can substantially reduce expenses and improve the economic viability of small urban indoor farms [11]. IF operators can reduce electricity costs by utilizing low-cost, easily deployable renewable energy sources [27], most notably solar photovoltaic (PV) technology, without compromising profitability [28]. PV systems have been integrated into agriculture increasingly through agrivoltaic applications [27, 29]. A recent advancement, the agrivoltaic agrotunnel [7], demonstrated the potential for net-zero energy IF building across various locations in Canada and the USA using grid-tied solar PV systems. Agrivoltaics with or without battery storage could play the best economic and environmental role in powering a small-scale leafy green IF building compared to the grid-tied option [30].

As a conclusion on the reviewed literature, energy [6, 8, 10], labor [6], and initial costs [13, 14] are the main contributors to compromising the profitability of IF or VF systems, particularly the ones dedicated to the production of leafy greens. The systems that appear to have succeeded have overlooked or neglected either the labor or investment costs [11, 12, 14]. The market value of products, or the sale options, as the major revenue driver, was studied and highlighted as another key economic parameter [19–23]. Agrivoltaics can address the energy challenge in IF facilities, whose studies are scarce in the literature [7, 18, 30]. The existing literature also lacks comprehensive economic studies on the perspectives of product sales options and labor and investment costs analytical approach. This highlights a significant gap, particularly in optimizing cost/revenue drivers and labor-intensive tasks in IF systems. To address these gaps, the present study focuses on the two most critical cost components, energy and labor, by optimizing crop selection (specifically leafy greens, with an emphasis on Romaine, Red Oakleaf, and Red Outrageous lettuce) and harvesting strategies within an agrivoltaic agrotunnel, an IF facility, 100% powered by PV technology. The main objectives of this study are to identify the most economically viable crop and harvesting method with the minimum capital and operating costs and maximum profitability and to analyze capital and operational expenditures associated with the indoor cultivation of different product sale options of leafy greens.

2. Methods

This section enlightens the experimental and analytical procedures carried out in current research:

1) First, experimental details about location, structural features, cultivated crops, environmental conditions, and cultivation scenarios will be provided.
2) Second, the software used for sizing the agrivoltaic system will be introduced.
3) Third, the details of the economic model including all assumptions, cost expenditures, governmental standards, and income sources will be elaborated.

Romaine, Red Oakleaf, and Red Outrageous lettuces were selected as the most compatible cultivars based on previous revenue analysis of leafy greens grown in the agrivoltaic agrotunnel [20], a true vertical farm, in which the plants are vertically placed and maintained by a hybrid hydroponic-aeroponic system rather than horizontally layered hydroponic systems [31]. This facility is located at the Western Innovation for Renewable Energy Deployment (WIRED) field at the Institute for Chemicals and Fuels from Alternative Resources (ICFAR) in Ilderton (London), ON [32]. Yield, labor, and energy data from experimental trials were extrapolated to a commercial-scale agrotunnel (MAX version), which includes 12,816 growing ports across its vertical walls.

Experiments were carried out twice on a single vertical grow wall, maintained with consistent watering cycles and nutrient levels to isolate the effect of harvesting strategies on the yield values. The crops were grown in an environment with 55–60% relative humidity and temperatures maintained between 21 and 24°C. Both sides of the grow wall, each containing 312 active ports out of 360 ports, were planted with the same cultivars, as shown in Figure 1. The cultivation cycle lasted two months for each experiment, with harvesting occurring weekly over four to five rounds beginning after the first month. As a result, replicating the greens cultivation six times a year is possible in commercial applications.

The first variable tested was harvesting strategy. One side followed a low-labor method, cutting the entire lettuce head, which mirrors conventional practices outdoors, while the other followed a high-labor method, selective harvesting of mature leaves. It should also be noted that the high-labor section employed a multiple-crops-per-pot planting strategy, while the low-labor section utilized a single-crop-per-pot approach. The impacts of these planting methods on harvesting time and consumable usage were also considered in the analysis. The labor time required for these two strategies differed significantly, with 682 and 2220 h/year/agrotunnel, respectively, for low-labor cutting single Romain heads and high-labor leaf picking of multiple lettuce crops. The standard deviation for these calculations was about ±5%. This parameter was calculated for labor time and the yield values using the average error obtained by comparing the data from all experimental runs.

Figure 1

The cultivars under study on both sides of a vertical grow wall in the agrivoltaic agrotunnel: (a) left side (high-labor and multiple crops per pot), (b) right side (low-labor and single crop per pot)

(a) (b)

2.1. Solar photovoltaic system sizing

The agrivoltaic agrotunnel is equipped with various technical systems, including LED grow lights, vertical grow walls, micro-green racks, water pumps, dehumidifiers, and heat pumps, all placed in an insulated structure. The modeling approach for estimating these loads has been established in the previous research work [7]. Using the same model, the hourly load of the MAX agrotunnel is anticipated.

To determine the optimal size of the PV system required to meet the agrotunnel's electrical demand, the open-source Solar Alone Multi-objective Advisor (SAMA) is utilized [33]. The Python-based version of this optimization and analysis tool is used to identify the most suitable system configuration based on the agrotunnel's energy requirements and local environmental conditions. The PV system is designed as a net-zero, grid-connected installation, following Ontario's net-metering regulations.

2.2. Economic analysis

Although some results are presented for the specific case of London, Ontario, a broader sensitivity analysis is conducted to offer insights applicable to researchers, technical designers, and investors globally. To improve the international relevance and comparability, all financial values are reported in US dollars (USD), using a CAD/USD exchange rate of 0.70[1]. The economic analysis includes both revenue and expenses, which include capital (CapEx) and operational (OpEx) costs. CapEx covers the full cost of the agrotunnel, developed by FSSC [34] as a turnkey solution, possibly for a range of $255,000 to $555,000 USD, and the on-grid PV system, which includes PV modules, balance of system components (wiring, racking, inverters, meters, switches), installation, and monitoring. OpEx consists of labor, supplies, consumables, maintenance (both agrotunnel and the PV system), and marketing and distribution costs. The net-zero PV system design eliminates energy costs from the operating expenditures of the IF system. The agrivoltaic agrotunnel operates without using electricity or gas from the grid. In addition, fixed water and wastewater infrastructure costs are assumed to be covered by the farm owner for the already existing farm, so only variable costs based on actual water use are considered.

By extrapolating the pilot data, the MAX agrotunnel uses 11,000–14,500 L/month for single to multiple crops. Greywater discharge is equal to 3000–5000 L/month approximately. In London, water and wastewater rates are $1.81 USD and $1.74 USD per cubic meter, respectively[2]. It is important to note that the first 7 m^3 of water and wastewater usage is free of charge so that the utility rates are applied only to the volume exceeding this threshold, calculated by subtracting 7 m^3 from the total monthly consumption values.

Consumables are categorized into two groups: fixed and variable. Fixed consumables, such as peat cups, growing substrate,

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and cleaning materials, induce an estimated cost of approximately $12,000–14,000 USD. Variable consumables, mainly including nutrients and seeds, range from $4,500 to $6,000 USD, depending on the planting strategy (i.e., single vs multiple crops per pot). Consequently, the total consumables cost is estimated to be within the range of $16,500–18,500 USD for a single crop and $18,000–20,000 USD for multiple crops per pot, respectively.

Hiring one or more growers is required to maintain the plants in the agrotunnel. The total number of growers required and the associated labor costs can be estimated using the information presented in Table 1, in which all essential tasks are identified and their execution times are reported. Table 1 presents the labor hours needed to carry out these operational tasks (excluding harvesting, which was detailed previously for a MAX agrotunnel per year) on an hourly basis. An additional 15% of the base payroll is allocated for employee benefits and overhead costs for full-time workers in Canada. Full-time employees are limited to a maximum of 40 working hours per week. Hence, any additional labor requirements will be fulfilled by part-time staff, who do not necessarily receive the same benefits. In Canada, part-time staff can work up to 30 h per week. The minimum wage in Ontario is assumed to be $12.0 USD/h[3]. Since labor rates vary by region and indoor farms can be run in different ways (e.g., self-employed, owner-operated, and family-run systems, or education-based foundations), a sensitivity analysis was done to check how total costs change across a labor rate range from 0.0 to 50 USD/h, as the average maximum wage in the related fields. Necessary data sources are provided for all the mentioned assumptions.

The agrotunnel and PV system are assumed to have a 25-year operational lifetime as most PV systems are warranted for 25 years[4] and the agrotunnel shell has a 50-year lifetime, but the subsystems would all have lifetimes on the order of 25 years. The total capital cost of the PV system, including modules, inverters, wiring, racking, circuit and power boxes, permitting, design, and installation, is estimated at $1.8–2.5 USD/W, based on Canadian government data and commercial quotes. Annual OpEx costs for the PV system are set at $13–25 USD/$kW_{dc}$. For the indoor vertical farming facility, total maintenance (repair and replacement) costs are assumed to be within the range of 8–10% of total OpEx, with 4–5% of total OpEx allocated to marketing and distribution. Necessary data sources are provided for all the mentioned assumptions.

Table 1
Breakdown of tasks and associated labor time in the agrotunnel

Task	Hour per wall per cultivation period
Cup and grow media preparation	$2 \pm 5\%$
Planting	$2 \pm 5\%$
Watering	$6 \pm 3\%$
Deep cleaning frequencies	6 (times/wall/year)
Deep cleaning	$1.5 \pm 5\%$
Light cleaning frequencies	6 (times/wall/year)
Light cleaning	$0.75 \pm 5\%$

The revenue (*Re*) in USD generated from selling green products (*Y*) in kg can be calculated using Equation (1) [20].

$$Re = Y \times Pr \tag{1}$$

All crops grown in the agrotunnel follow organic practices, even if they cannot be officially certified as organic due to antiquated regulations requiring the organic labeling to be attributed to soil-based cultivation only[5]. The seasonal price (*Pr*) of organic head lettuce and spring (green) mix in Ontario's markets is as follows. Necessary data sources are provided for all below assumptions:

1) Organic head lettuce:
   Average summer price: $7.15 USD/kg; average winter price: $10.0 USD/kg.
2) Organic spring mix:
   Average summer price: $16.8 USD/kg; average winter price: $24.1 USD/kg.
   *May–Oct is summer, and Nov–Apr is winter[6].
   ** It is assumed that the average weight of each organic Romaine is equal to 333 g [35].

A few key indicators are used to evaluate the economic viability of lettuce cultivation in the agrivoltaic agrotunnel under different harvesting strategies and market scenarios: first-year total cost (FYC), net present cost (NPC), net present value (NPV), return on investment (ROI), IRR, and discounted payback period (DPP). These metrics consider all capital and operational costs, providing a comprehensive assessment of system viability. NPV is calculated using Equation (2), where $CF_{net,t}$ stands for the net cash flow or net profit (revenue minus OpEx) in USD, CapEx is in USD, *r* is the discount rate (2.75% for Canada[7]), *t* shows the year, and *n* is the system's lifetime (25 years). *CapEx* is defined as shown in Equation (3), incorporating the total investment cost of the agrotunnel (C_{Agt}) and the PV system (C_{PV}). In the following, $CF_{net,t}$ is also defined as explained in Equation (4), the subtraction of all operating and maintenance costs, including labor (O_L), OpEx of PV (O_{PV}), water consumption (O_W), other consumable materials (O_{mat}), maintenance (O_{main}), and marketing (O_{market}), from the revenue (*Re*).

$$NPV = \sum_{t=1}^{n} \frac{CF_{net,t}}{(1+r)^t} - CapEx \tag{2}$$

$$CapEx = C_{Agt} + C_{PV} \tag{3}$$

$$CF_{net,t} = Re - O_L - O_{PV} - O_W - O_{mat} - O_{maint} - O_{market} \tag{4}$$

The FYC represents the total initial investment provided by the owner for the installation and operation of the agrivoltaic agrotunnel in the first year. It is calculated using the formula in Equation (5).

$$FYC = OpEx_{first\ year} + CapEx \tag{5}$$

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[3]Minimum Wage by Province – Retail Council of Canada (2025).

[4]US EPA – www.epa.gov/end-life-solar-panels-regulations-and-management

[5]Regulating organic products in Canada – www.inspections.canada.ca

[6]Climate zones and planting dates for vegetables in Ontario – www. ontario. ca

[7]Interest rates – Bank of Canada

In addition, NPC represents the total investment needed to install and operate the agrotunnel over its entire lifetime. This calculation accounts for the discount rate, as defined in Equation (6).

$$NPC = \sum_{t=1}^{n} \frac{OpEx_t}{(1+r)^t} + CapEx \qquad (6)$$

The ROI metric can be used to highlight the profitability of the system by demonstrating the ratio of net profit generated ($CF_{net,tot} - CapEx$) to the associated costs paid (NPC), as presented in Equation (7).

$$ROI = \frac{CF_{net,tot} - CapEx}{NPC} \times 100 \qquad (7)$$

The DPP is defined as the year when the cumulative net cash flow equals the initial investment cost ($CapEx$). It can be determined by modifying the NPV formula, setting n to represent the DPP, as shown in Equation (8). In the definition of simple payback period (SPP), the influence of the discount rate is neglected.

$$if \sum_{t=1}^{DPP} \frac{CF_{net,t}}{(1+r)^t} \geq CapEx \qquad (8)$$

With a similar approach, IRR can be obtained as the discount rate when the NPV equals zero at the end of the system lifetime, as expressed in Equation (9).

$$\sum_{t=1}^{25} \frac{CF_{net,t}}{(1+IRR)^t} = CapEx \qquad (9)$$

3. Results

This section presents the results of the business model developed to assess the economic viability of an agrivoltaic agrotunnel under various sales options and labor strategies for lettuce cultivation. The sensitivity of key economic indicators is analyzed based on variable ranges; however, for the base case study, the average values within these ranges are used, except for the labor costs, which are calculated by considering the minimum wage rate in Canada, $12 USD/h.

Seasonal variations in market price are incorporated into the business model, with the resulting annual revenue presented in Table 2. To maximize yield for spring mix packs, a multiple-crops-per-pot approach has been recommended [20], while single-crop-per-pot planting produces better-shaped baby Romaine lettuces. As a result, yields differ for different types of products and harvesting strategies. Also, market price has the greatest influence on total revenue, with spring mix priced at approximately 2.4 times that of head lettuce since it offers the ready-to-eat option for consumers.

Table 2
Annual yield and revenue obtained by selling organic head Romaine and spring mix lettuce packs

	Annual yield (kg)	Annual revenue (USD)
Head Romaine lettuce	3,272 ± 5%	28,057
Spring mix	5,501 ± 5%	112,440

Table 3
Total annual labor required to maintain the agrotunnel for head Romaine and spring mix lettuce products

	Annual labor (h/year)	Full-time grower	Part-time grower
Head Romaine lettuce	2,042 ± 5%	1	0
Spring mix	3,580 ± 5%	1	1

A similar type of comparison for total annual labor time dedicated to maintenance of crops is provided in Table 3. As shown, producing spring mix requires approximately 1.75 times more labor than head Romaine lettuce due to the differences in harvesting time. Therefore, the number of growers who are required to maintain the agrotunnel varies depending on the type of product.

The optimal net-zero PV size was determined by SAMA to be equal to 126 kW to supply the 153,018 kWh load under a net-metering policy, along with the system's associated CapEx ($226,800–315,000 USD) and OpEx ($1,638–3,150 USD/year).

The first phase of the comparative analysis, as shown in Figure 2, evaluates the FYC and NPC breakdowns for two product types. CapEx makes up a dominant share of the FYC, over 89% for both cases, but declines to below 41% in the NPC, reflecting the distribution of long-term costs. During the system's lifetime, labor remains the most significant cost component, exceeding 30% of the NPC, followed by consumables being at over 16%. This underscores the critical role of labor and materials in the long-term economic situation of the system. A key positive point of the agrivoltaic IF setup is its minimal PV maintenance cost, which remains under 3% of total operating expenses throughout the system's life. Comparing the two sales strategies highlights that labor costs for spring mix are clearly higher than for head Romaine lettuce, 6.3% vs 3.9% in the first year, and 40.5% compared to 30.7% over 25 years. Water costs remain the lowest among all OpEx items, due to limited consumption and the relatively low water utility rates in Ontario, Canada.

The economic comparison between the two product options is detailed in Table 4. Table 4 presents cost breakdowns and key performance indicators for three cases: the best, the base, and the worst. As was expected, the total OpEx for spring mix cultivation is approximately 1.4 times higher than that of head Romaine lettuce in the base case, mainly due to increased labor and material requirements. The results reveal that cultivating Romaine lettuce with the one-cut harvesting method is feasible only under the best economic conditions when evaluating the simple payback period as the economic indicator. While the one-cut method for head Romaine lettuce yields a negative NPV, spring mix cultivation demonstrates a positive NPV of $1,416,932 USD over 25 years in the best case. Therefore, the feasibility of the spring mix cultivation in the agrivoltaic agrotunnel is achievable for both the best and the base cases, with more economic attractiveness under the best-case conditions (zero labor, minimum CapEx and OpEx, and maximum revenue).

The results indicate that under current conditions, head lettuce cultivation is not economically feasible until the labor, materials, and other maintenance costs are retained at the minimum level and the revenue is kept at the maximum (the products are being sold with the maximum seasonal market price for the whole year); otherwise, revenues do not offset operating costs.

To illustrate the significance of various economic components in the profitability of the two studied systems, Figure 3 is provided.

Figure 2
Cost share distribution for different sale products in the first year of operation and at the end of the system's lifetime: (a) head Romaine lettuce FYC, (b) spring mix FYC, (c) head Romaine lettuce NPC, (d) spring mix NPC
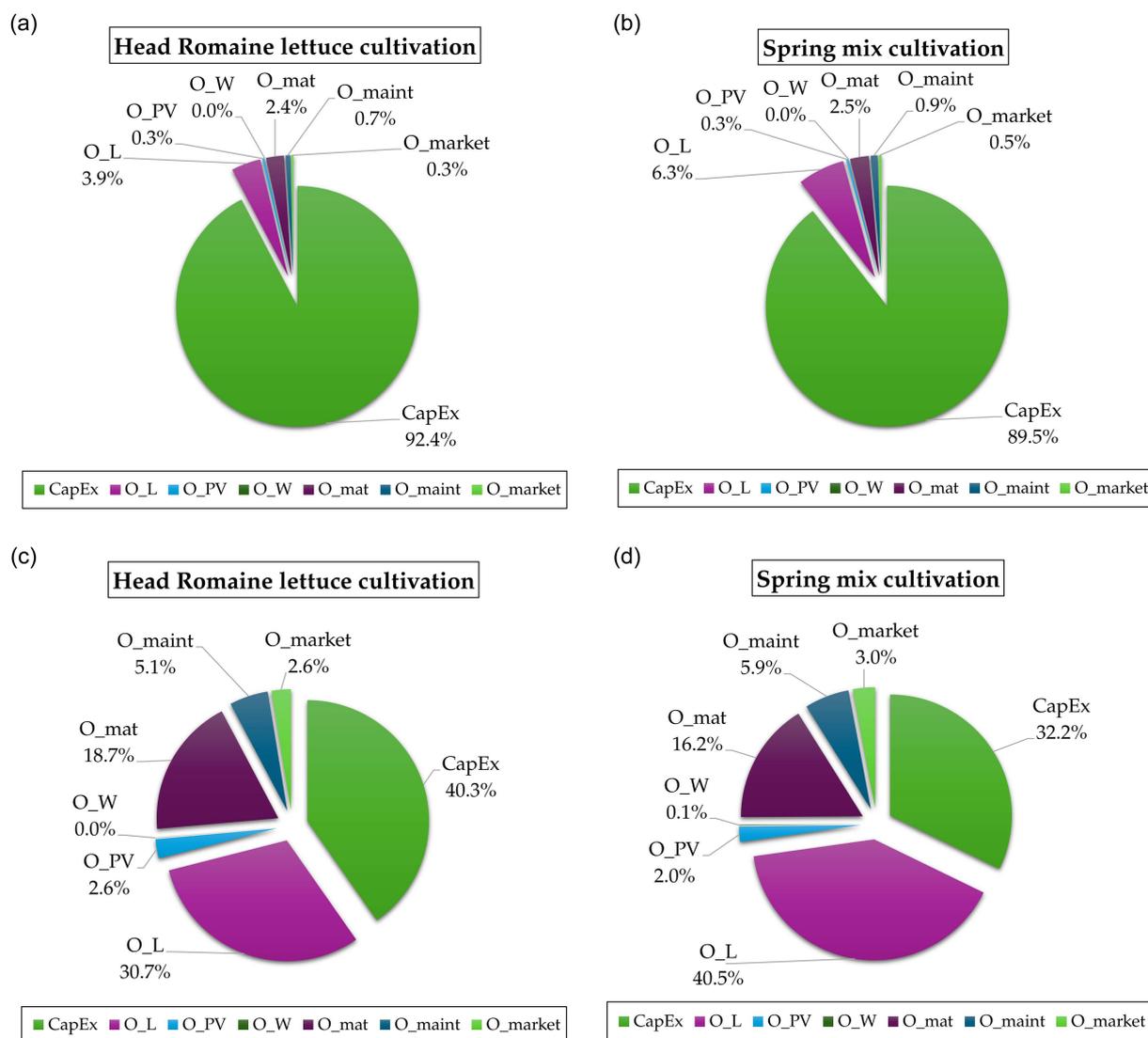
(a)

Head Romaine lettuce cultivation

O_W 0.0%
O_mat 2.4%
O_maint 0.7%
O_PV 0.3%
O_L 3.9%
O_market 0.3%
CapEx 92.4%

■ CapEx ■ O_L ■ O_PV ■ O_W ■ O_mat ■ O_maint ■ O_market

(b)

Spring mix cultivation

O_W 0.0%
O_mat 2.5%
O_maint 0.9%
O_PV 0.3%
O_L 6.3%
O_market 0.5%
CapEx 89.5%

■ CapEx ■ O_L ■ O_PV ■ O_W ■ O_mat ■ O_maint ■ O_market

(c)

Head Romaine lettuce cultivation

O_maint 5.1%
O_market 2.6%
O_mat 18.7%
O_W 0.0%
O_PV 2.6%
O_L 30.7%
CapEx 40.3%

■ CapEx ■ O_L ■ O_PV ■ O_W ■ O_mat ■ O_maint ■ O_market

(d)

Spring mix cultivation

O_maint 5.9%
O_market 3.0%
O_mat 16.2%
O_W 0.1%
O_PV 2.0%
O_L 40.5%
CapEx 32.2%

■ CapEx ■ O_L ■ O_PV ■ O_W ■ O_mat ■ O_maint ■ O_market

Table 4
The economic indicators and cost breakdowns of head Romaine lettuce and spring mix production in agrivoltaic agrotunnel

	The best case	The base case	The worst case
Head Romaine lettuce cultivation			
CapEx (USD)	451,800	675,900	870,000
OpEx (USD/year)	22,889	55,837	151,467
FYC (USD)	504689	731,737	1,021,467
NPC (USD)	891,698	1,675,847	3,582,524
Labor cost (USD/year)	0	28,704	119,600
PV maintenance cost (USD/year)	1,638	2,394	3,150
Water cost (USD/year)	3	24	45
Consumable materials cost (USD/year)	16,500	17,500	18,500
Agrotunnel's maintenance cost (USD/year)	2,646	4,810	7,453
Marketing and distribution cost (USD/year)	2,101	2,405	2,719
Revenue (USD/year)	32,720	28,057	23,395

(*Continued*)

Table 4
(*Continued*)

	The best case	The base case	The worst case
NPV (USD)	−305,738	−1,173,386	−3,163,563
DPP (year)	>100	Not viable	Not viable
SPP (year)	41.3	Not viable	Not viable
ROI (%)	−26.5	Not viable	Not viable
IRR (%)	−4.6	Not viable	Not viable
Spring mix cultivation			
CapEx (USD)	451,800	675,900	870,000
OpEx (USD/year)	26,549	79,300	235,509
FYC (USD)	508,358	755,201	1,105,509
NPC (USD)	957,414	2,096,041	5,087,576
Labor cost (USD/year)	0	47,424	197,600
PV maintenance cost (USD/year)	1,638	2,394	3,150
Water cost (USD/year)	79	100	121
Consumable materials cost (USD/year)	18,000	19,000	20,000
Agrotunnel's maintenance cost (USD/year)	3,808	6,922	10,725
Marketing and distribution cost (USD/year)	3,024	3,461	3,913
Revenue (USD/year)	132,574	112,495	92,417
NPV (USD)	1,416,932	−81,436	−3,432,546
DPP (year)	4.9	25	Not viable
SPP (year)	4.5	20.4	Not viable
ROI (%)	226.6	7.3	Not viable
IRR (%)	21.9	1.65	Not viable

Figure 3
Tornado diagram presenting the significance of effective economic expenditures: (a) head Romaine lettuce cultivation, (b) spring mix cultivation
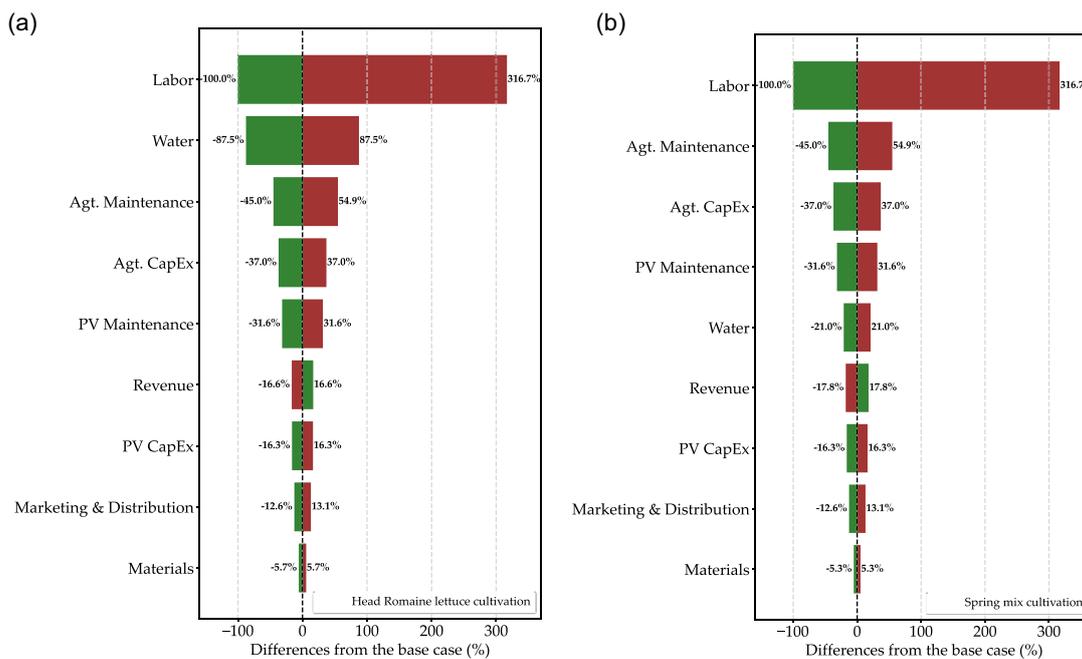
As shown in Figure 3, the labor rate is the most critical variable, directly impacting labor costs. The capital and the maintenance costs of the agrotunnel rank next in sensitivity for the case of spring mix growing. For lettuce cultivation, however, the sensitivity range of the water costs is the highest after the labor cost, which is due to the considerable variability of water-related expenditures compared to the total financial outlay. One of the most interesting findings in Figure 3 is the capital cost of the solar PV system, which appears among the least influential cost factors, supporting the rationality of powering the IF facility with solar technology. All four remaining parameters can be retained at a constant level for the same size and structure of the agrotunnel.

Reducing the total capital costs of the agrotunnel to $255,000 USD and PV system to $226,800 USD leads to a substantial 140.5% increase in net present value of spring mix cultivation, from −$277,536 to $112,464 USD, changing the viability fate of the whole investment. Figure 4 illustrates the significance of the initial costs' influence on the NPV. Accordingly, the DPP is reduced by 60.2%, decreasing from 47.2 to 18.8 years. In Figure 4, it is revealed that for the base case with the minimum official wage of 12.0 USD/h, the total CapEx must be less than $579,500 USD to have a total investment return within the lifetime of the system. More rigidly, to have DPP less than 20 years, the total CapEx must be lower than $501,500 USD.

As shown in Figure 5, analyzing the sensitivity of NPV and DPP to variations in labor cost, ranging from zero-cost labor to the maximum viable value, highlights the critical role of labor availability in determining the economic viability of new IF businesses. According to Figure 5, zero to $1 USD/h labor rates (e.g., for education-based foundations) at the base case for the CapEx of a spring mix producing agrivoltaic agrotunnel leads to a remarkable reduction in payback period, dropping into the range of less than 10 years. This is achievable for the labor rates of less than $6 USD/h if the initial investment cost of the whole system stays at the minimum margin ($481,800 USD).

ROI and IRR for the investment on the spring mix cultivation in the agrivoltaic agrotunnel have been evaluated in Figure 6 for both the base and the best cases of CapEx.

In Figure 6(a), ROI values greater than 10% can be achievable with the average CapEx level and the labor rate of less than $11 USD/h. This is also achievable with the labor rate of up to $14

Figure 4
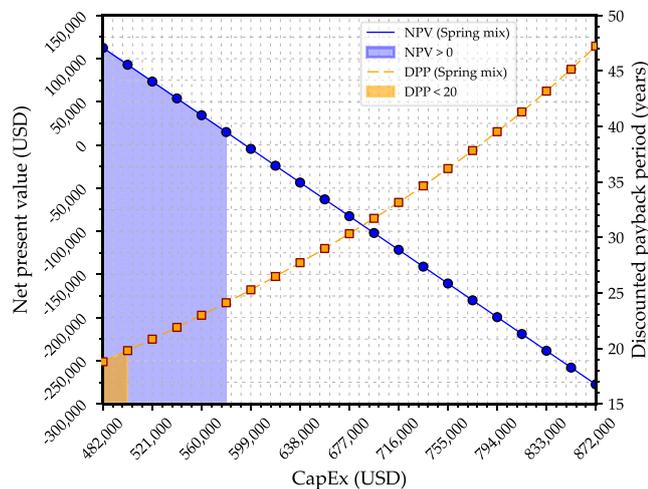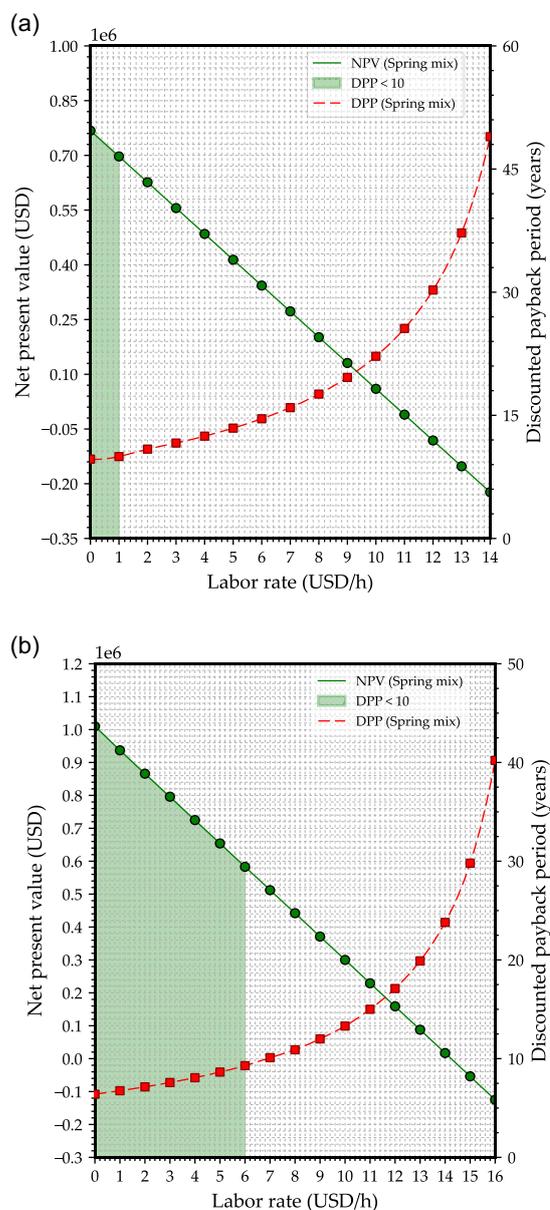**Variations of NPV and DPP vs CapEx in spring mix producing agrotunnel**

Figure 5
Variations of NPV and DPP vs labor rate in spring mix producing agrotunnel: (a) the base case, (b) the best case

USD/h with the minimum possible CapEx of $481,800 USD, as shown in Figure 6(b). While ROI is a simple method of profitability calculation, IRR is a more complex calculation that considers the time value of money. Therefore, the labor rate thresholds, below which the IRR values are higher than 10%, are < $1 USD/h and < $7 USD/h, respectively, in the base and best cases. These ranges are reasonably close to the thresholds corresponding to the DPP of less than 10 years in Figure 5.

To illustrate how effectively the CapEx and labor rate are impacting the profitability of the spring mix producing system, Figure 7 is provided for the economically viable ranges, identified by Figures 4 and 6. In Figure 7, it is clearly shown that among the two most effective variables, labor rate has the highest impact on the net present value, implying the necessity of further studies on reducing/automating labor-intensive activities.

Figure 6
Variations of ROI and IRR vs labor rate in spring mix producing agrotunnel: (a) the base case, (b) the best case
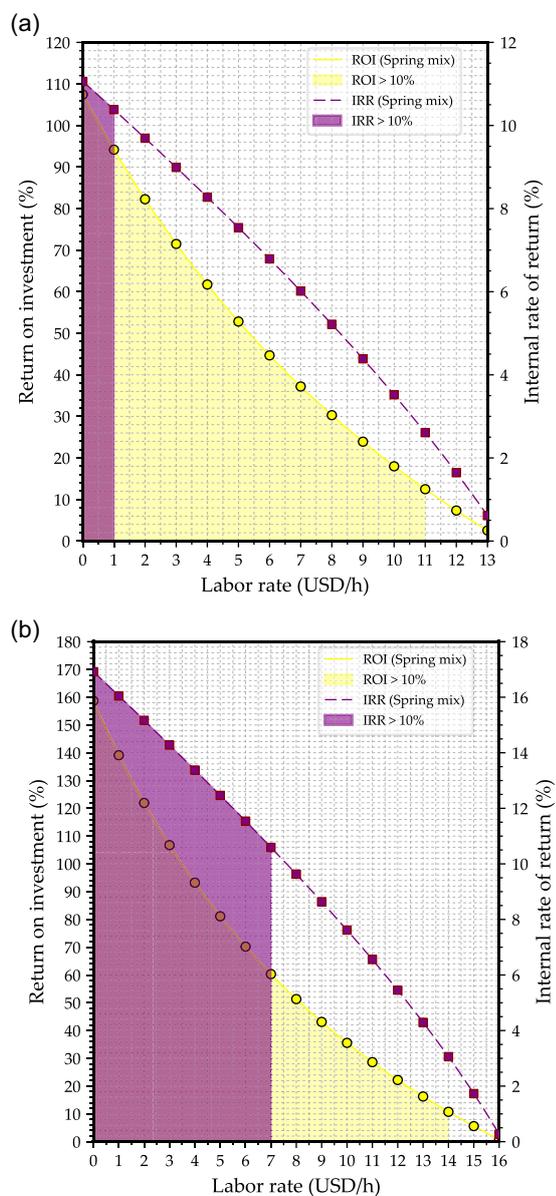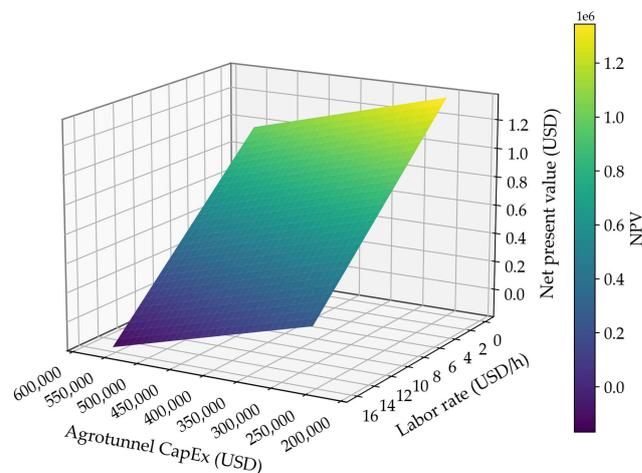

Figure 7
Variations of NPV vs the agrotunnel's CapEx and labor rate in the spring mix producing system (the best case)

4. Discussion

An economic analysis was conducted on the agrivoltaic agrotunnel for growing different lettuce types, including Romaine, Red Oakleaf, and Red Outrageous. Two main market options, head Romaine lettuce and spring (green) mix packs, were examined for economic viability. Head Romaine was produced using a one-plant-per-pot strategy, while spring mix used a multiple-plants-per-pot strategy. Yield, harvesting time, market value, and water consumption varied due to different planting and harvesting methods, as well as socio-economic perceptions. As noted in similar studies [19, 20, 22], analyzing these cultivars highlights the pros and cons of the agrotunnel's application for leafy greens.

Spring mix offered better economic viability due to higher yield and market value, despite being about 1.5 times more labor-intensive than head Romaine. The specific electricity consumption (SEC) value for spring mix production in the current system is 27–30 kWh/kg, which is within the reasonable range of small-scale distributed and experimental facilities [36]. As a commercial reference, the lowest range of SEC is achievable in factory-scale indoor vertical farms with the value of 7–10 kWh/kg, while it varies between 10 and 20 kWh/kg for typical facilities [36]. This study aimed to identify acceptable CapEx ranges and labor rates to make the model feasible for startups like self-employed growers, family-run greenhouses, or educational operations. While not viable under all CapEx and labor scenarios, spring mix showed potential for such startups, common in North America. VF systems provide key growth needs, sunlight, CO_2, and water, which are free in nature but costly in VF systems, making high-value crops essential. According to SWOT analysis [37], promising markets for this technology are in harsh environments like deserts and polar regions, where natural resources are lacking and food prices are high. Similarly, in the Russian Arctic [38], vertical greenhouses were proposed as food security solutions and part of the circular economy. Labor was the most crucial factor in overall feasibility. A wide labor rate range, from self-employed ($0/h) to paid staff, could enable viability depending on CapEx and payback period. Similar outcomes were reported in the literature [10, 12]. Family-run enterprises can enhance small-scale farming [39, 40], with household wealth, education, and composition affecting labor demand. Econometric analysis shows that farmers are less likely to quit when running their own farms [41]. Transitioning to individual farms improves management and labor efficiency, especially in labor-intensive systems [42], reducing labor outflow from agriculture due to stronger land ties and better human capital use. CapEx of the agrotunnel, the second major cost, should be minimized through optimal materials and manufacturing efficiency. Agrivoltaic agrotunnels can serve as a branch in the urban agriculture (UA) sector, which is promoted to reduce food costs, thereby addressing urban inequality. Underdeveloped planning frameworks and limited policy support hinder implementation. UA is a relatively new field that is still just being supported by formal legislations [43]. Government incentives for production and implementation of IFs such as procurement rebates and labor subsidies can significantly affect UA's economic viability.

The average labor per area per year for the spring mix production in the agrotunnel was equal to 32.25 h/m^2. This value for a high-tech modern plant factory is equal to 1.6 h/m^2 [44]. This further highlights the labor intensity of tasks in the agrotunnel and the necessity of implementing automation in similar farms. A key labor-intensive task was manual watering of the grow walls. As also suggested by [10], this will be addressed by integrating semi- or fully-automated watering systems in future work.

Another advantage of spring mix production is reusing plant residue as biodigester feedstock, enhancing CO_2 self-sufficiency.

This study used experimental data, not commercial-scale conditions. In practice, optimized setups with better materials, nutrients, fertilizers, and professional sanitation alongside operating the system by well-experienced growers would likely improve productivity.

Peat pots, used in this study, were expensive single-use items. Switching to reusable plastic cups could significantly reduce OpEx and will be explored in future life cycle and economic assessments.

One major IF cost driver, energy, was largely eliminated by the agrivoltaic concept [7], which integrates solar PV with agriculture. This approach is supported in prior studies [11, 27–29]. Although PV CapEx was the least sensitive factor, it could still be reduced by shortening photoperiods from 24 to 16–18 h/day, a topic for future research.

5. Conclusions

The agrivoltaic agrotunnel offers a promising solution to the elevated energy demands of indoor vertical farming systems. Labor-intensive tasks, however, impose significant costs on IF owners. This study investigated the profitability of two market options for indoor lettuce production. One-cut head Romaine lettuce, requiring minimal harvesting labor, was compared economically with a labor-intensive spring mix of Romaine, Red Oakleaf, and Red Outrageous lettuces. Differences in harvesting labor, yield, market value, and water consumption were evaluated using economic indicators.

Head Romaine yielded 3272 kg annually, generating $28,057 USD revenue, while spring mix yielded 5501 kg and $112,400 USD. Spring mix required 1.5 times more labor due to its harvesting strategy. Consequently, 42.2% of the total NPC was labor for spring mix, compared to 31.1% for head Romaine. Labor rate (hourly wage) was the most sensitive factor, with a 416.7% variation when ranging from $0 to $50 USD/h. Capital cost of the agrotunnel was the next most significant factor, while PV system cost had the least impact. Other OpEx – water, materials, marketing, and maintenance – remained relatively constant.

Economic comparisons showed that head Romaine was only feasible when CapEx and OpEx were minimized and revenue was maximized. Spring mix had a broader feasibility range. ROI and IRR > 10% were achievable when labor rates were below $14 and $8 USD/h, respectively, with minimum capital costs of $255,000 (agrotunnel) and $226,800 (PV system). Under base CapEx of $405,000 (agrotunnel) and $270,900 (PV), achieving > 10% ROI and IRR required labor rates of $12.5 and $2.5 USD/h. Payback periods < 10 years were possible when labor rates were $7 and $1 USD/h for the best and base cases.

6. Recommendations

Reducing total capital cost below $579,500 enabled positive returns within the system's lifetime. The agrivoltaic IF model is viable for self-employed, family-run, or educational operations.

Ethical Statement

This study does not contain any studies with human or animal subjects performed by any of the authors.

Conflicts of Interest

The authors declare that they have no conflicts of interest to this work.

Data Availability Statement

The data that support the findings of this study are openly available in Open Science Framework at https://osf.io/mrvxg/files/osfstorage and https://doi.org/10.17605/OSF.IO/MRVXG.

Author Contribution Statement

Nima Asgari: Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Joshua M. Pearce:** Conceptualization, Methodology, Validation, Formal analysis, Resources, Data curation, Writing – original draft, Writing – review & editing, Supervision, Project administration, Funding acquisition.

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