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Energy, Environmental, and Economic Evaluation of a Novel Building Integrated Green System: Insights from Residents and Social Perspectives

M. M. Naserian[1], R. Khodabakhshian[1*]

1- Department of Biosystems Engineering, Faculty of Agriculture, Ferdowsi University of Mashhad, Mashhad, Iran
(*- Corresponding Author Email: Khodabakhshian@um.ac.ir)

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Abstract

The buildings and the agri-food sectors nearly consume 40% and 21% of the world's total energy, respectively. This research aims to combine these two significant energy-consuming sectors to decrease the total society's energy consumption. For this purpose, a novel small-scale building integrated agriculture system was designed and constructed. In this research, the total energy and water consumption, annual CO_2 production, and the total cost of employing the novel system were analyzed from the building residents' and social points of view. Moreover, the results were compared with the total results of a building and a separate standard greenhouse with the same product. The results show that the total energy reduction because of using the novel system was 31.2%. According to the results, the novel system will cause approximately 3400 $kgCO_2$ emission reduction over a life cycle of 20 years. Moreover, yearly water consumption reduction was 19.2 L kg^{-1} of lettuce production. The payback period was approximately 5 years based on the cost analysis results comprising investment, operational, and social costs. Sensitivity and Scenarios analyses were conducted to better understand the effect of probable influential parameters and make the investment for the novel system secure and attractive.

Keywords: Energy modelling, Environmental analysis, Green Building, NPV, Vertical green system

Introduction

HVAC (Heating, Ventilation, and Air Conditioning) systems are responsible for 38% of the total energy consumption in residential sectors (González-Torres, Pérez-Lombard, Coronel, Maestre, & Yan, 2022). In this context, one of the key strategies to optimize energy usage is preventing energy waste (Kazemzadeh, Fuinhas, Koengkan, Osmani, & Silva, 2022). To address this, researchers have proposed various approaches, such as implementing Thermal Energy Storage (TES) technologies to minimize energy loss through building boundaries (Peker, Kocaman, & Kara, 2018). Phase Change Materials (PCMs) have gained significant attention in building construction due to their high thermal energy storage capacity (Tyagi *et al.*, 2021; Reyez-Araiza *et al.*, 2021). Approximately 50% of energy loss in buildings occurs through windows and doors. Therefore, smart window technology has been developed to intelligently regulate the amount of sunlight entering buildings (El-Deeb, Ismail, & Hassaan, 2020; Teixeira, Gomes, Rodrigues, & Pereira, 2020).

Numerous studies have explored the potential of vertical farming as an energy-efficient solution in buildings. In this context, the energy-saving potential of Vertical Green Systems (VGSs) has been thoroughly

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examined through both numerical (Šuklje, Medved, & Arkar, 2016; Pigliautile, Chàfer, Pisello, Pérez, & Cabeza, 2020) and experimental (Zheng, Dai, & Tang, 2020; Talaei, Mahdavinejad, Azari, Prieto, & Sangin, 2021) research across various climate regions globally. Sánchez-Reséndiz, Ruiz-García, Olivieri, and Ventura-Ramos (2018) analyzed the impact of installing living walls on the thermal performance of buildings in a semi-arid climate. They concluded that incorporating living walls on south-facing walls enhances the thermal efficiency of buildings. VGSs contribute to reducing building energy consumption in four key ways: by serving as a natural barrier against thermal sunlight, acting as an insulator (Lee & Jim, 2019), functioning as an evaporative cooler, and providing wind protection (Chen, Tsay, & Chiu, 2017).

In several research studies, the DesignBuilder software, a sophisticated and validated building energy simulation tool, has been utilized to model green systems. Alvarez-Sánchez, Leyva-Retureta, Portilla-Flores, and López-Velázquez (2014) conducted a numerical analysis of the thermal behavior of a greenhouse using DesignBuilder, finding the energy simulation results to be accurate and reliable. Karimi, Farrokhzad, Roshan, and Aghdasi (2022) explored both experimentally and numerically the impact of green walls as passive energy reducers in humid regions, using DesignBuilder for their simulations. They concluded that green walls effectively lowered the building's energy consumption, although the cooling capacity was influenced by plant type and building architecture. Wang and Iddio (2022) examined the energy performance of indoor farming with the EnergyPlus simulation software, reporting a 48.1% reduction in natural gas consumption due to the system. Additionally, Vox, Blanco, Convertino, and Schettini (2022) analyzed the effect of green façades on the winter HVAC system heating load, demonstrating that it decreases both conductive and radiative heat transfer, acting as a thermal barrier.

A comprehensive review of urban agriculture literature revealed that urban agriculture leads to reduced transportation needs for food procurement, thereby lowering transportation costs (Azunre, Amponsah, Peprah, Takyi, & Braimah, 2019). Additionally, a comparison between traditional soil-based vertical farming with natural lighting and indoor vertical farming suggested that vertical farming with natural lighting could be the most efficient urban farming system for producing large quantities of food in Singapore, considering resource usage and environmental impacts (Song *et al.*, 2022).

In addition to the building sector, the agricultural industry consumes 21% of the world's total energy, driven by the growing demand for high-quality and abundant agricultural products throughout the year (Benke & Tomkins, 2017). The increasing energy needs and the urgent concerns about climate change have led to a heightened interest in developing more sustainable agricultural systems. Nonetheless, a major challenge in adopting these systems is evaluating their financial viability. A comprehensive financial feasibility analysis is crucial to determine whether introducing new systems is practical. Regarding global food trade, the FAO (2020) reports that the monetary value of global food exports was approximately 1.38 trillion USD in 2018. This figure contrasts sharply with 380 billion USD in 2000, with vegetables and fruits making up the largest portion of these exports, accounting for 23%.

A range of case studies have focused on comparing the economic aspects of vertical farming in urban settings with traditional greenhouse methods (Pomoni, Koukou, Vrachopoulos, & Vasiliadis, 2023). Trimbo (2019) assessed the financial sustainability of vertical farming in indoor environments in São Paulo, finding that while such systems are more water-efficient and environmentally friendly, they involve a high initial capital expenditure. In contrast, the Interatomic Energy Agency (IEA) (2021) notes that achieving a low-carbon economy requires substantial investments in clean energy technologies and infrastructure. Gumisiriza, Ndakidemi, Nalunga, and Mbega (2022) explored the economic viability of producing lettuce using an outdoor vertical farming system in Africa, and their findings indicated that these small-scale systems are economically viable, sustainable, and contribute to enhancing food security in urban areas. Avgoustaki and Xydis (2020) examined multiple scenarios to evaluate the financial benefits of vertical farming in Denmark, revealing that vertical farming is considerably more profitable than traditional greenhouse methods. Furthermore, Chamroon and Aungkurabrut (2019) investigated an automated hydroponic greenhouse designed for household use, determining that the payback period for lettuce production in this system was 3.3 years.

An examination of existing literature highlights that both the building sector and the agri-food industry are major consumers of energy. While Vertical Green Systems (VGS) have shown promise as a means to enhance energy efficiency in buildings, there remains a notable research and practical gap in developing a new integrated system that combines building structures with urban agriculture. Such a system would ideally be economically viable and promote the seamless interaction between buildings and agricultural practices, with the goal of reducing overall energy and water usage as well as minimizing annual CO_2 emissions.

This paper aims to provide a detailed assessment of the energy, environmental, and financial viability of a new integrated agricultural system within buildings and explore its potential for widespread adoption. The unique features and performance metrics of this innovative system, as well as the associated challenges and opportunities related to energy use, environmental impact, and financial considerations will be examined. The study will unfold in several phases: First, a new multipurpose system that integrates building functions with agricultural activities and conducts initial experiments to evaluate its feasibility will be proposed. Subsequently, a numerical simulation based on the experimental data and existing research will be developed. This simulation will analyze the annual performance of the combined building and agricultural system, focusing on total energy consumption and yearly CO_2 emissions. Finally, an economic analysis, assessing key financial indicators such as the Levelized Cost of Lettuce (LCOC), Payback Period (PP), and Net Present Value (NPV) will be carried out. Different parameters and scenarios that affect financial metrics to understand the economic implications of the proposed system will also be simulated.

Materials and Methods

Experimental site

This study was conducted in Mashhad, a city positioned at 36.31° North latitude and 59.53° East longitude, with an elevation of 1037 meters above sea level during 2023. Mashhad has a cold semi-arid climate (Köppen: BSk), marked by hot summers and cold winters. The experimental system was installed at Ferdowsi University of Mashhad.

System configuration

The design of the novel system integrates indoor vertical farming with outdoor vertical green systems to ensure continuous air circulation for the plants while maximizing the use of natural daylight. The system's dimensions are 2.1 meters in length, 0.55 meters in width, and 1.2 meters in height. It encompasses a comprehensive framework that includes plant cultivation areas, a displacement mechanism, irrigation and rainwater collection systems, as well as measurement and control subsystems. Figure 1 illustrates the detailed setup of the system. The plant cultivation area is organized into three mobile pipe bases, each featuring three rows of U-shaped PVC pipes arranged 30 cm apart. These pipes are filled with a hydroponic substrate comprising a mixture of cocopeat and perlite. Each pipe is equipped with a 1 mm fine steel mesh filter and a drainpipe designed to collect and transfer excess water to a central reservoir. The pipes contain four apertures, each with a diameter of 0.06 meters and spaced 0.144 meters apart, intended for the insertion of hydroponic pots. The arrangement of the pipes on a stepped base prevents shading of lower rows by upper rows and ensures adequate sunlight exposure for all plants. Transparent components of the system are constructed from polycarbonate (PC) and Polymethyl Methacrylate (PMMA) sheets, with PC used for the side panels and a combination of PC and PMMA for the front panel. The displacement subsystem comprises two DC motors, a power supply, gear racks, and pinions. The recirculating irrigation subsystem includes three pumps, one air pump, and three water tanks. This subsystem operates in cycles of 20 seconds every 1.5 hours during daylight hours. The control subsystem manages irrigation timing, exposure durations, and the movement of the plant cultivation areas, ensuring optimized system performance.

The measurement and control system incorporated various devices such as thermocouples, a lux meter, digital timers, time counters, and data loggers. Temperatures of the indoor air in the rooms, the system's air temperature, and the ambient air temperature were recorded at five-minute intervals. Thermocouples of type K were employed to measure the indoor air temperatures, positioned at the same height in the center of each room and protected from direct sunlight. The accuracy of the experimental data was contingent upon the precision of the measuring instruments, with the overall uncertainty of the experiments calculated to be 2.34%. During the study, two types of lettuce—Batavia and Romaine—were grown within the system. The experiments were conducted over a period of 40 days, covering the entire growth cycle from planting to harvest, and were carried out in the spring.

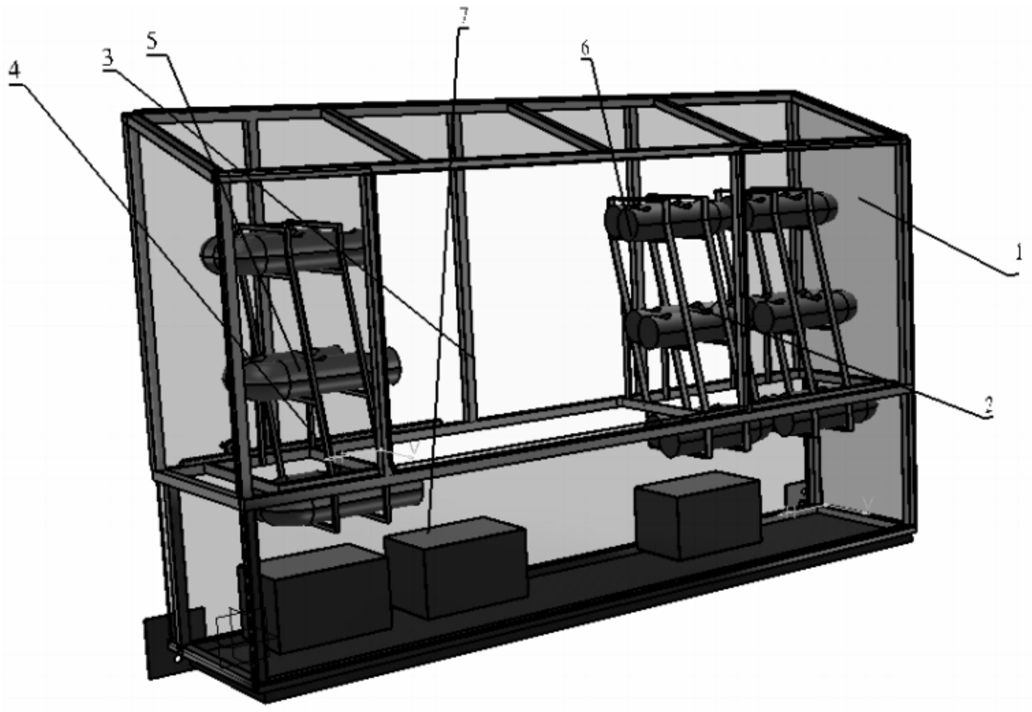


Fig. 1. System illustration: 1) Polycarbonate sheets, 2) Hydroponic pots, 3) Polymethyl Methacrylate (PMMA) sheet, 4) Pipe bases, 5) U-shaped PVC pipes, 6) The displacement subsystem, 7) Solution storage tank

Some key features of the novel system include:

- The system serves as a mobile natural canopy that can be positioned over windows.
- By being installed on the exterior surface of windows, the system occupies minimal interior space within living and working areas.

- As depicted in Figure 2, the system allows plants to move horizontally, optimizing natural light exposure within the room.
- The system can be set up independently from other units in the building or even within different rooms of the same apartment.
- Maintenance and plant cultivation are accessible solely through the building's window, which eliminates the need to enter the system. This design reduces the risk of contamination and prevents the introduction of pathogens via footwear.
- It supports the production of clean, organic food indoors, free from pesticides and chemical fertilizers.

Fig. 2. Horizontal plant mobility in the novel system

To evaluate the system's performance, two rooms were selected, each with identical dimensions of 3 meters by 1.7 meters by 2.5 meters. Both rooms were situated under the same conditions regarding orientation, sealing, and insulation. These rooms were located on the second floor of a building with a total height of 7 meters. Each room featured a south-facing window with dimensions of 1.2 meters by 0.9 meters, resulting in a window-to-wall ratio of 0.21. The novel system was installed prominently outside in front of the window in one of these rooms designated for plant growth.

Fig. 3. The experimental rooms

Computational model

To investigate the impact of plants on a building's energy consumption, it is crucial to first evaluate the energy performance of the plants themselves. This begins with analyzing the energy balance equation for plant leaves. The findings from this analysis are then incorporated into building energy simulation software to accurately simulate the interaction between the plants and the building. The steady-state energy balance equation for the plant tissue, assuming metabolic process energy losses are negligible (Jones, 2013), is given by equation (1).

$$\alpha_f I_s - C - Q_{rad} - L_f = 0 \qquad (1)$$

where, the parameters include the solar absorptivity of the plants (α_f), the solar irradiance (I_s), convection heat transfer (Q_{rad}), radiation heat transfer (L_f), and latent heat. The system was modeled using DesignBuilder software, with the plants functioning as window shading elements (Larsen, Filippín, & Lesino, 2015). The fundamental properties of both the window and the shading are outlined in Table 1. To incorporate the latent heat effect from plant transpiration into the simulation, modifications were made to the window and shading properties (Larsen *et al.*, 2015). These adjustments, detailed in equations (2-4), were then input into the software for accurate simulation. It is important to note that the plants were not continuously positioned in front of the window throughout the year. The performance schedule for the positioning of the plants is provided in Table 2.

Table 1- The window shade properties

Property	Reference	Value	Unit
Solar transmittance	(Larsen *et al.*, 2015)	0.2	---
Solar reflectance	(Larsen *et al.*, 2015)	0.3	---
Visible transmittance	Experimental Data	0.08	---
Visible reflectance	(Larsen *et al.*, 2015)	0.09	---
Thermal emissivity	(Larsen *et al.*, 2015)	0.95	---
Thermal transmittance	(Larsen *et al.*, 2015)	0	---
Thickness	Experimental Data	0.001	m
Conductivity	(Larsen *et al.*, 2015)	0.59	W (m °C)$^{-1}$
Shade to Glass Distance	Experimental Data	0.2	m

Table 2- Performance schedule of the system

January		**April**		**July**		**October**	
Until 06:00	1[*]	Until 05:00	1			Until 05:00	1
Until 17:00	0[**]	Until 21:00	0	Until 24:00	1	Until 18:00	0
Until 24:00	1	Until 24:00	1			Until 24:00	1
February		May		August		November	
Until 06:00	1			Until 05:00	0	Until 06:00	1
Until 17:00	0	Until 24:00	1	Until 22:00	1	Until 16:00	0
Until 24:00	1			Until 24:00	0	Until 24:00	1
March		June		September		December	
Until 07:00	1			Until 05:00	0	Until 06:00	1
Until 19:00	0	Until 24:00	1	Until 21:00	1	Until 17:00	0
Until 24:00	1			Until 24:00	0	Until 24:00	1

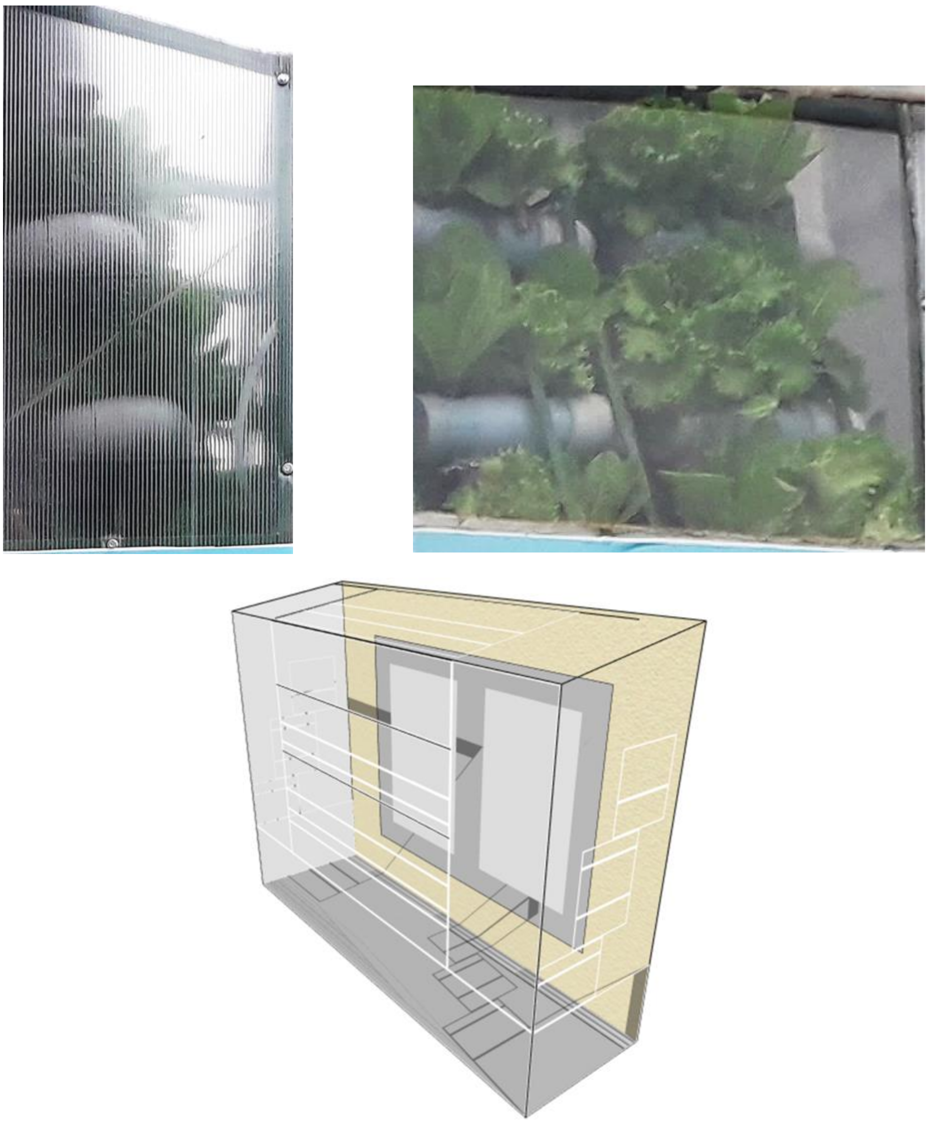
[*] It means the plants are placed in front of the window.

[**] It means the plants are not placed in front of the window.

Given that plants are three-dimensional objects, their shadows on both the sides and above are significant and affect the simulation. Therefore, in addition to modeling the front window shading, the simulation also included definitions for the upper and lateral shading around the window. To avoid shading lower rows with the upper ones, the plant rows were arranged in a stepped configuration, resulting in variable distances from the window (see Fig. 4). In the simulation, multiple windows were defined along each side of the plants, and the distances between these windows and the shadings were adjusted in accordance with the variable distances from the plants' rows to the windows. To accurately assess the total plant coverage from the front view, the Plant Coverage Rate (PCR) was analyzed. A photograph of the plants was taken on the 20th day after planting, the midpoint of the growing period. The coverage rate was then calculated using MATLAB code.

Next, the schematic of the rooms in DesignBuilder is shown in Figure 5. The weather data were obtained from the Iran Meteorological Organization (IRIMO) database.

b a



c

Fig. 4. Segmentation of the external cover of the novel system for precise positioning of window shadings in plant simulation: a) side view, b) front view, and c) 3D CAD

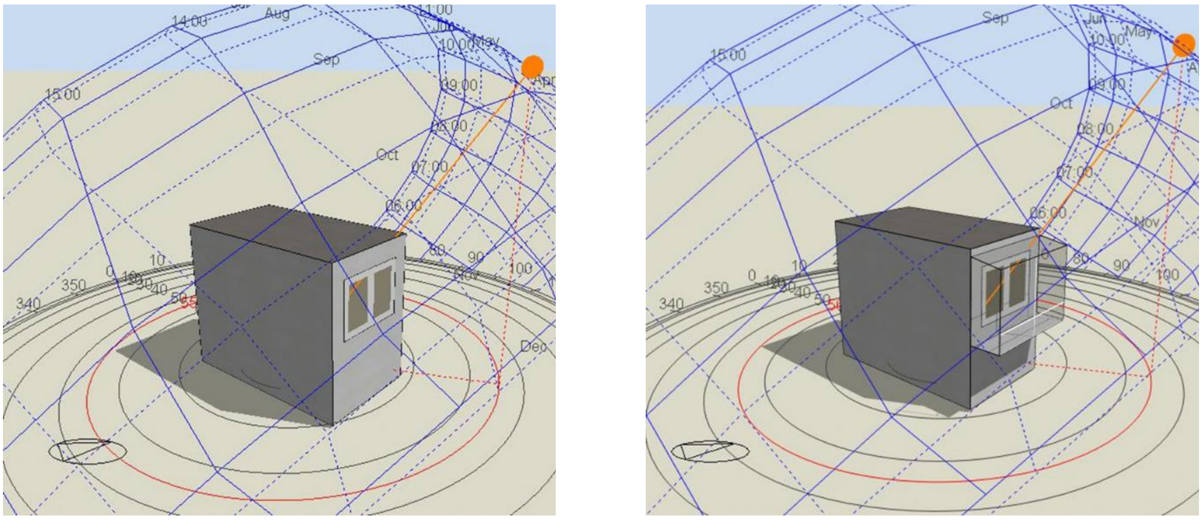


Fig. 5. The layout of the rooms as represented in the DesignBuilder software

Properties Modification

This section aligns with the study 'Solar Thermo-Visual Gain Optimization of a Building Using a Novel Proposed Nature-Based Green System' conducted and published by Naserian, Khodabakhshian, Kazemi, and Jozay (2024), with detailed information provided below:

"In contrast to blinds, the temperature of plants does not increase linearly with the amount of absorbed heat because some of this heat is transformed into latent heat. Consequently, both sensible and latent heat effects must be incorporated into the plant simulation simultaneously. While the impact of sensible heat can be addressed by incorporating window shading in the simulation, the effect of latent heat requires modifying certain parameters according to the equations outlined by Larsen *et al.* (2015). These modifications were applied using the specified equations."

$$\alpha_{mo} = \alpha_f (1-x) \tag{2}$$

$$\varepsilon_{mo} = \varepsilon_f (1-x) \tag{3}$$

$$\varepsilon_{w,mo} = \frac{\varepsilon_w (1-x)}{1-\varepsilon_w x} \tag{4}$$

where, α_f, ε_f, and ε_w represent the solar absorption and infrared emissivity of the plants and the room window glass, respectively. Additionally, x denotes the ratio of latent heat released by the plants to the total absorbed radiation, defined by the following equation.

$$x = \frac{\Lambda}{[\Lambda + \gamma(1 + r_s / r_a)]} \tag{5}$$

where, r_s and r_a denote the surface resistance of the natural canopy and the aerodynamic resistance, respectively. The methodology for calculating these resistances will be explained in the subsequent paragraph. Furthermore, γ represents the psychrometric constant, expressed in kPa/°C, while Λ is the slope of the saturation vapor pressure versus temperature curve, also measured in kPa/°C at the given air temperature. The air pressure (P) for the experimental region is 89,472 Pa.

$$\Lambda = \frac{4098\left[0.618Exp\left(\frac{17.27T_a}{T_a + 237.3}\right)\right]}{(T_a + 237.3)^2} \tag{6}$$

$$r_s = \frac{r_1}{LAI_{active}} \tag{7}$$

where, r_1 represents the stomatal resistance of the plant leaf, which is determined using equation (9) from Pollet, Bleyaert, and Lemeur (1998). The parameter LAI_{active} refers to the active leaf area index and is calculated as 0.5 times the leaf area index (LAI). The LAI is a key metric for evaluating the effectiveness of Vegetated Green Systems (VGSs) as passive cooling solutions, as discussed by Pérez, Coma, Sol, and Cabeza (2017). To assess this, the photosynthetically active radiation (PAR) was measured at various locations within the system using a PAR meter. These measurements were then used in equation (8) to indirectly determine the LAI of the system, as outlined by Zhang (2019)

$$LAI = \frac{-\ln\left(\frac{PAR_{below}}{PAR_{above}}\right)}{0.9} \tag{8}$$

$$r_1 = 164\left(\frac{31.029 + I_s}{6.740 + I_s}\right)(1 + 0.011(D-3)^2)(1 + 0.016(T_a - 16.4)^2) \tag{9}$$

where D and T_a are the vapor pressure deficit and the air temperature, respectively. D was calculated from the following equation (Pollet *et al.*, 1998)

$$D = e_{s(T)} - e = (1.0007 + 3.46\times10^{-8}P)\left(611.21 + \exp\left((18.678 - (T_a/234.5))T_a/(257.14 + T_a)\right)\right)(1 - RH) \tag{10}$$

where $e_{s(T)}$ and e are the partial pressure of saturation and the actual vapor pressure, respectively.

The aerodynamic resistance of the canopy in s/m is defined as equation (11) (Zhang, 2019).

$$r_a = 840\left(\frac{d}{|T_s - T_a|}\right)^{0.25} \tag{11}$$

where, d represents the leaf characteristic length, which was measured experimentally on the 20th day after planting, marking the midpoint of the planting period. The term $T_s - T_a$ denotes the temperature difference between the plant leaves and the ambient air, calculated as the average of the temperature differences observed under two extreme conditions: when the leaf surfaces were completely dry and when they were fully wet. For the dry leaf surface, $T_s - T_a$ is given by the following equation

$$T_s - T_a = \frac{I_s r_{HR}}{\rho_a C_P} \tag{12}$$

where r_{HR} is the heat and radiative resistance of the leaf surface (Graamans, Baeza, Van Den Dobbelsteen, Tsafaras, & Stanghellini, 2018) and was calculated from the following equation:

$$r_{HR} = \frac{r_a r_R}{r_a + r_R} \tag{13}$$

where r_R is the leaf radiative transfer resistance given by

$$r_R = \frac{\rho C_P}{8\varepsilon_L \sigma T_a^3} \tag{14}$$

where $\sigma = 5.67\times10^{-8} Wm^{-2}K^{-1}$ is the Stefan–Boltzmann constant, and ρ is the density of air and was considered temperature dependent and calculated as a function of the mean air temperature from the following equation:

$$\rho = \frac{P}{RT_m} = \frac{P}{287T_m} \tag{15}$$

where $T_m = T_a + (T_s - T_a)_{ave}/2$. The average measured temperature difference (i.e. $(T_s - T_a)_{ave}$) used for initial air properties calculations, was 11°C. For the wet leaf surface $T_s - T_a$ given by

$$T_s - T_a = -\frac{D}{\gamma + \Lambda} \tag{16}$$

For more details on the above equations, refer to (Vox *et al.*, 2022) and (Larsen *et al.*, 2015).

Cost analysis methods

The economic feasibility of the novel system is as important as its energy-saving potential and environmental benefits. The consumer is more willing to buy a product when the purchase cost and the economic savings that the purchase of that product entails during a certain period are known. In the current study, three cost analysis techniques were used to investigate the economic feasibility of the novel system:

Net present value (NPV)

The economic feasibility of the new system was assessed using the discounted cash flow method. Equation (17) was used to calculate the net present value of cost over the life span. F represents the future value of the payment.

$$NPV = \sum_{n=0}^{N} \frac{F}{(1+d)^n} - I, \quad F = AI - AC \tag{17}$$

where N is the project lifetime (20 years), n is the year, d refers to the discount rate (12%), AI is annual income, AC is the annual cost, and I is the investment cost (Lu & Yin, 2021).

Payback period (PP)

Recovering the initial investment for a project can take many years. The simple PP method determines the years it takes for the cash flow to be equal to the total investment. It considers the sum of the annual cash flows and the initial investment as the total investment cost.

Levelized cost of lettuce (LCOL)

It is defined to measure the average cost of a lettuce head concerning to the system lifetime. It describes the net present value of a lettuce head and is calculated from the following equation:

$$LCOL = \frac{\sum_{n=0}^{N} \frac{AC}{(1+d)^n} + I}{\sum_{n=0}^{N} \frac{YLP}{(1+d)^n}} \tag{18}$$

where YLP is the yearly lettuce head production of the system (Reichelstein & Rohlfing-Bastian, 2015).

Social costs

Social cost, or electricity external cost, is the hidden cost that is not included in consumer utility invoices. The climate change and human health problems, acid rain, and water pollution caused by emissions from fossil fuel power plants are some examples of this cost. Society must pay for these consequences (Watkiss & Hunt, 2012).

Results and Discussion

Based on equations (5-16), the average value calculated x was 0.53. This value was derived using the region's average ambient air temperature, solar irradiation, and relative humidity, which were 24.3°C, 465 W/m², and 50%, respectively. To account for the impact of fluctuating latent heat on the energy performance of the plants, these properties were adjusted according to equations (2-4). Subsequently, the modified values were applied in the DesignBuilder software.

In Figure 6, the experimental and simulated results for the same day are compared. The figure shows that the maximum difference between the results was around 0.7°C. Thus, Figure 6 serves as evidence of the accuracy of the simulation results generated by the DesignBuilder software.

Energy and environment investigation results

This section examines the impact of the novel system on energy and water consumption, as well as CO_2 production, from the perspectives of building residents and societal benefits. To achieve this, the annual energy simulation results are first presented in Table 3. On sunny days during hot seasons, the plants in the novel system function not only as canopies for windows but also as thermal barriers, maintaining air temperatures lower than the outside. During cold nights, the system's air is completely isolated from the external environment, acting as a thermal shield for the windows. Additionally, during the daytime in cold seasons, the plants increase the humidity of the system's air through transpiration, which in turn enhances the air's latent heat. The results show that the novel system can reduce the room's total energy consumption by up to 31.2%. The energy required for plant cultivation was 440.6 kWh, equivalent to 4.37 kWh per kilogram of lettuce produced (Lages Barbosa *et al.*, 2015). In comparison, the annual energy consumption for producing one kilogram of lettuce in a standard greenhouse under similar climatic conditions is approximately 6 kWh (Graamans *et al.*, 2018). Therefore, while the novel system does increase the building's overall energy consumption, it significantly reduces the total energy usage associated with both building operations and vegetable production from a broader societal perspective. The detailed calculations are provided in Table 4.

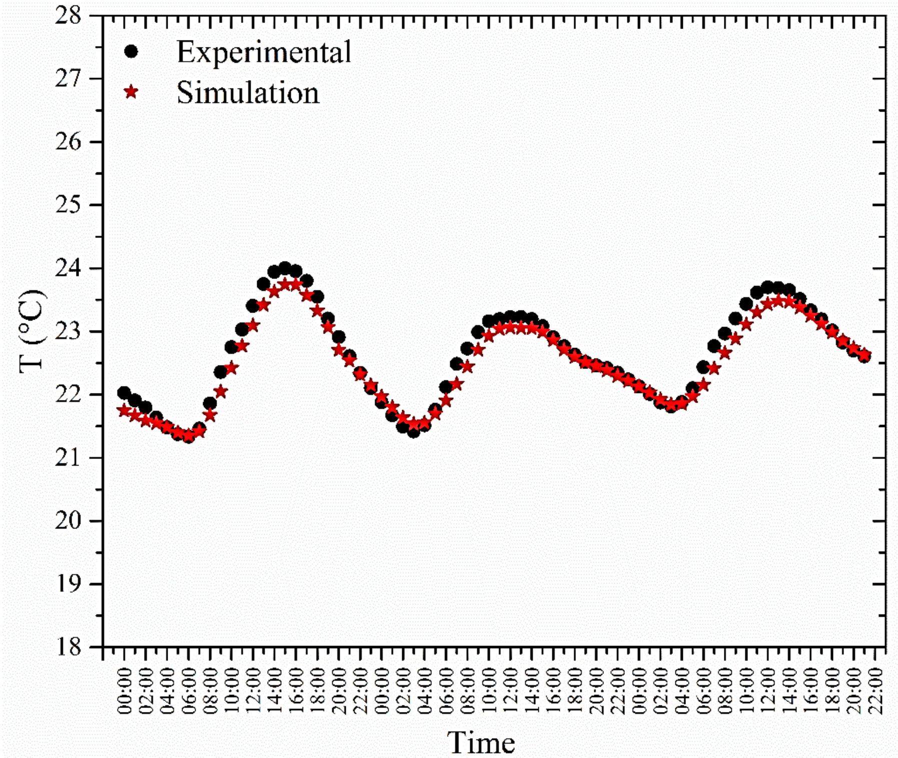


Fig. 6. Validation of the simulation

Table 3- The comparison of the energy performance of the rooms

Room	HVAC system	Lighting	Total
Plant	161.6 kWh	21.8 kWh	183.4 kWh
Control	253 kWh	13.8 kWh	266.8 kWh
Variation	-36.1 %	+65.21%	-31.2%

The results for electrical energy, water, and fuel consumption, as well as CO_2 production, are presented and compared in Table 4. In this analysis, the room equipped with the novel system was compared to the combined totals of a standard room and a separate greenhouse required to produce the same amount of lettuce, which in this case is 100.8 kg. The table shows that not only did the direct energy consumption for producing the crops decrease, but the indirect energy usage related to food miles and water extraction also saw a reduction.

Food miles refer to the distance between the farm and the final consumer, typically calculated by multiplying the distance by the mass of the food transported. To assess fuel consumption and the environmental impact of food miles, these distances are usually converted into vehicle fuel consumption related to food transportation (Smith, Watkiss, Tweddle, & McKinnon, 2005). In this study, food transportation was divided into two stages: from the farm to the food store (using diesel-fueled vehicles) and from the food store to the home (using gasoline-fueled vehicles) (Transportation and Energy Information of the Country, 2014). The findings align with the results of Gould and Caplow's (2012) study.

Table 4- The detail of the energy and environmental calculations

Resource	Content	Reference	Quantity (per year)
Energy (personal view)	The rooms HVAC and novel system	DesignBuilder software	(183.4-266.8) +440.6 = +357.2 kWh
Energy (social view)	The rooms HVAC, novel system, and standard greenhouse	DesignBuilder software, and Graamans *et al.* (2018)	(183.4-266.8) +440.6 (for the novel system) – 6*100.8 kWh kg^{-1} (for greenhouse) = -247.6kWh
Fuel (social view)	Transportation, and water extraction	Transportation and energy information of the country (2014); Iran Energy Balance Sheet (2020)	Diesel: -0.016 m^3*100.8 kg*0.104 L m^{-3} water (for water extraction) - 100.8 kg*0.046 L kg^{-1} (for transportation) = -4.84 L
		Transportation and energy information of the country (2014)	Gasoline: -0.06 L kg^{-1} *100.8 kg = -6.05 L
Fuel (personal view)	Transportation	Transportation and energy information of the country (2014)	Gasoline: -0.06 L kg^{-1} *100.8 kg = -6.05 L
Water (social view)	Agriculture and rain	Experimental Data, and Graamans *et al.* (2018)	-0.328m^3 (rain) + (252*0.42*20 L)/1000 (L m^{-3}) (for greenhouse) - 0.4 m^3 (for the novel system) = -2.04 m^3
Water (personal view)	Agriculture	Experimental data	+100.8 kg *0.004 L kg^{-1} = +0.40 m^3
Yearly CO_2 emission reduction (social view)	Energy reduction and transportation	Transportation and energy information of the country (2014); Iran Energy Balance Sheet (2020)	247.6 kWh *0.571 $kgCO_2$ kWh^{-1} + (4.84+6.05) L fuel*2.63 $kgCO_2$ L^{-1} fuel = 170.02 $kgCO_2$

The novel system offers significant environmental benefits by enabling food production within buildings, which drastically cuts down on transportation-related emissions compared to traditional farming methods. The results indicate that, over a 20-year life cycle, this system could lead to a reduction of approximately 3400 kg of CO_2 emissions.

The details of the fuel consumption data for food transportation, along with other environmental data used in Table 4, are presented in Table 5. These data were sourced from verified governmental resources, including the "Transportation and Energy Information of the Country" (2014) and the "Iran Energy Balance Sheet" (2020).

Cost analysis results

This section covers the capital expenditure required for constructing and setting up the novel system, along with the annual variable costs. Additionally, sensitivity analysis was used to identify the key parameters that could significantly impact the costs. Lastly, various cost scenarios are outlined and examined in detail. Table 6 details the total capital expenditure required for the novel system. The table indicates that an annual cost of $457 is necessary to produce 252 heads of lettuce. The system is designed to function for up to 20 years, provided it receives regular maintenance. Table 7 outlines the annual operational costs and revenue associated with the system. In this study, it is assumed that both the price of lettuce and annual operational costs will increase in line with inflation. To calculate the return on investment from the consumer's perspective, an intermediate electricity tariff of $0.011 per kWh (applicable to other uses) was used. From a societal perspective, the economic benefits were evaluated based on the cost of electricity production without subsidies. This cost was estimated using the price of crude oil, which was $51.50 per barrel at the time of the study. Given that each barrel of crude oil is equivalent to 1699.1 kWh, the cost per kWh of electricity was initially calculated as $0.030.

However, accounting for a power plant efficiency of 36.8% (Iran Energy Balance Sheet, 2020), the adjusted cost of electricity per kWh was determined to be $0.0824.

Table 5- The details of the data used in resources analysis

Reason	Resource	Unit	Reference
Fuel consumption from farm to store	Diesel	0.046 L kg^{-1} Food	Transportation and energy information of the country (2014); Iran Energy Balance Sheet (2020)
Fuel consumption from store to house	Gasoline	0.06 L kg^{-1} Food	Iran Energy Balance Sheet (2020)
Emissions due to fuel combustion	CO_2	2.63 kg L^{-1} Fuel	Transportation and energy information of the country (2014)
Emission due to electricity production in power plants	CO_2	0.571 kg kWh^{-1} Electricity	Noorpoor and Kudahi (2015)
Energy consumption in a typical greenhouse	Electricity	6 kWh kg^{-1} Lettuce	Graamans *et al.* (2018)
Water consumption in a typical greenhouse	Water	20 L kg^{-1} Lettuce	Graamans *et al.* (2018)
Fuel consumption for water extraction	Diesel	0.104 L m^{-3} water	Iran Energy Balance Sheet (2020)
Captured CO_2 due to the lettuce photosynthesis	CO_2	0.1 kg kg^{-1} Lettuce	Carvajal (2010)
Gasoline to electrical energy conversion	Gasoline	1.76 kWh L^{-1} Gasoline	Iran Energy Balance Sheet (2020) (considering 20% efficiency)
Diesel to electrical energy conversion	Diesel	3.69 kWh L^{-1} Diesel	Iran Energy Balance Sheet (2020) (considering 35% efficiency)

Table 6- The detail of the total capital cost of the novel system

Commodity	Unit cost	Quantity	Cost
Galvanized rectangular pipe	1 $ kg^{-1}	60 kg	$60
LED	4 $ $block^{-1}$	9	$36
Wire	0.2 $ m^{-1}	10 m	$2
18AWG cable	$7	1	$7
PC sheet	8 $ m^{-2}	6 m^2	$48
PVC pipe +fittings	5 $ m^{-1}	6 m	$30
Substrate	2 $ kg^{-1}	5kg	$10
Seedlings grow tray	$4	1	$4
PE pipe + fittings	1 $ m^{-1}	8 m	$8
PMMA sheet	15 $ m^{-2}	0.8 m^2	$12
Electrical motor	$12	2	$24
Switching power supply	$12	1	$12
Thermostat + Contactor	$25	1	$25
Timer	$12	2	$24
Water pump	$8	3	$24
Water tank	$4	3	$12
Air pump	$10	1	$10
Elastomeric insulation	4 $ m^{-2}	1.25 m^2	$5
Gear + pinion	7.5 $ m^{-1}	2	$15
Rail	$7	4	$28
Manufacture + Installation	$80	1	$80
Total investment cost			$476

Table 7- The details of annual operational cost and income of the novel system

Output	View point	Unit price	Quantity	Cost	Income
Water use	Personal	0.1 $ m^{-3} (Mohammadi, Naderi, & Saghafifar, 2018)	0.4 m^3	$0.04	0
Energy use (plants)	Personal	0.011 $ kWh^{-1} (Mohammadi *et al.*, 2018)	440.6 kWh	$4.85	0
Maintenance cost	Personal	2.5% capital cost	-	$11.9	0
Seeds + fertilizer	Personal	20$	1	$20	0
Energy consumption reduction	Personal	0.016 $ kWh^{-1} (Iran Energy Balance Sheet, 2020)	(-183.4 +266.8) kWh = 83.4 kWh	0	$1.33
	Social	0.0824 $ kWh^{-1}	247.6 kWh	0	$20.40
Energy Subsidy payment reduction	Social	(0.0824-0.016) $ kWh^{-1}	247.6 kWh	0	$16.44
Fuel consumption reduction	Social	0.5 $ L^{-1} gasoline 0.47 $ L^{-1} diesel	6.05 L diesel + 4.84 L gasoline	0	$5.26
	Personal	0.1 $ L^{-1} gasoline	4.84 L gasoline	0	$0.48
Fuel Subsidy payment reduction	Social	0.4 $ L^{-1} gasoline 0.37 $ L^{-1} diesel	6.05 L diesel + 4.84 L gasoline	0	$4.17
Water reduction	Social	0.5 $ m^{-3}	2.04 m^3	0	$1.02
CO_2 reduction (excluding power production)	Social	0.024 $ kg^{-1} (Ahmadi, Dincer, & Rosen, 2012)	10.89*2.63 = 28.64 kg	0	$0.68
Lettuce production	Personal	0.6 $ $head^{-1}$	252*0.96 = 242 heads (considering 4% poor quality product)	0	$145.20
Social cost (due to power production)	Social	0.054 $ kWh^{-1} (Karimzadegan, Rahmatian, Farsiabi, & Meiboudi, 2015)	247.6kWh	0	$13.37
Total	Personal view point annual cost and income			$36.8	$147.01
	Social view point annual cost and income			0	$61.34

The results presented in the table indicate that the annual societal income generated by the novel system amounted to $61.34, translating to $0.25 per head of lettuce. Based on the Net Present Value (NPV) analysis, the payback period for the system is approximately five years.

The table highlights several areas of cost savings from different perspectives. For building residents, these savings stem from lower costs for plant lighting at night due to reduced tariffs, decreased electricity usage during peak tariff periods, minimized urban transportation expenses for purchasing lettuce, and more cost-effective lettuce production. From a societal perspective, the cost savings include reductions in overall energy consumption, lower CO_2 emissions, and decreased social costs associated with energy and transportation.

The income derived from building energy savings is calculated based on the peak daily electricity prices, reflecting the reduction in energy consumption during periods of high demand. In contrast, the majority of the novel system's energy use occurs at night, when grid electricity consumption is at its lowest and electricity prices are reduced.

Sensitivity analysis

Sensitivity analysis involves examining how changes in one or more input variables impact the output of a model. It is a method for determining which input variables have the most significant effect on the output and understanding how variations in these inputs influence the results. This technique is often used in financial modeling to identify key variables that drive financial outcomes and assist decision-makers in focusing on these critical factors. In engineering design, sensitivity analysis helps evaluate how adjustments in materials or design choices affect the performance of a system, considering both cost and technical feasibility constraints.

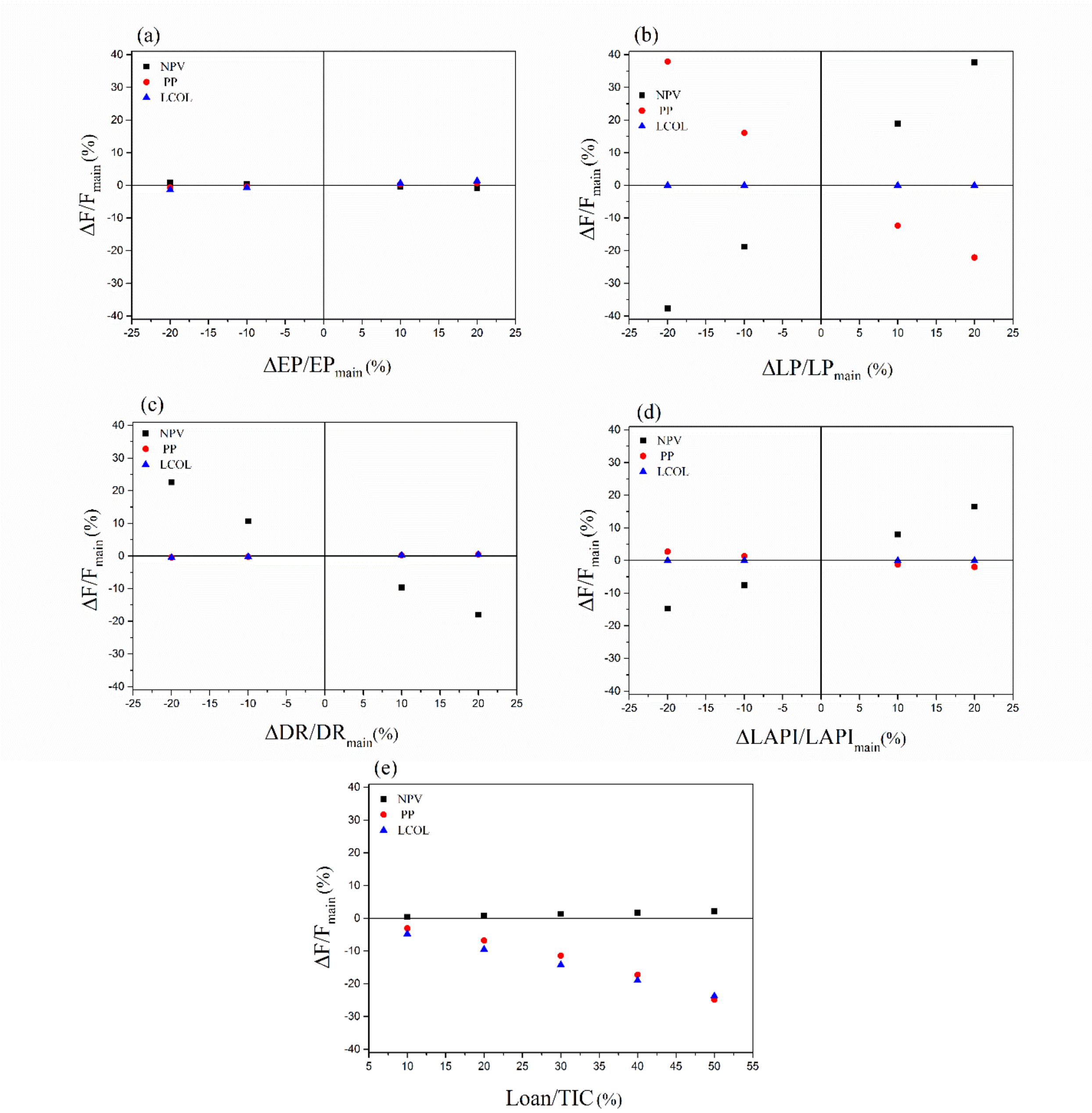


Fig. 7. Sensitivity analysis of the NPV, PP, and LCOL based on (a) EP, (b) LP, (c) DR, (d) LAPI, and (e) Loan/TIC (True Interest Cost) (%)

In this study, sensitivity analysis focused on several key parameters that are likely to influence the Net Present Value (NPV), payback period (PP), and levelized cost of lettuce (LCOL). These parameters include electricity price (EP), lettuce price (LP), discount rate (DR), and the annual increment in lettuce price (LAPI).

Figure 7 illustrates the results of the sensitivity analysis. It shows that the lettuce price (LP) is the most critical input parameter, while the electricity price (EP) is the least critical. Due to the substantial energy subsidies in Iran, the cost of electricity is relatively low (as noted in Table 7). Consequently, changes in EP have a minimal impact on economic calculations, making this finding consistent with expectations. The sensitivity of EP may vary in countries with higher electricity prices, and further investigation would be required in such contexts. Additionally, with the exception of EP and Loan/TIC (%), the Net Present Value (NPV) and Levelized Cost of Lettuce (LCOL) are notably sensitive to changes in input parameters. The annual rate of increase in lettuce prices significantly affects both NPV and payback period (PP). For instance, if lettuce prices do not increase annually, the payback period could extend to 5.72 years.

Analyzing the effect of varying the Loan/TIC (%), where the loan interest rate matches the inflation rate—on the performance metrics reveals that an increase in this parameter leads to a nearly proportional decrease in both the payback period (PP) and the levelized cost of lettuce (LCOL). However, once the Loan/TIC (%) exceeds 30%, the rate of decrease in the payback period accelerates with further increases in this parameter. Figure 7e demonstrates that government support in the form of loans can enhance the attractiveness of investment in this sector. The findings from the sensitivity analysis offer valuable insights for decision-makers, allowing them to develop informed strategies by understanding how changes in input variables affect the outcomes.

Scenario analysis

Investigating different scenarios for the financial support of a system is a crucial step towards achieving investment security and sustainability.

In this section, the results of investigating different scenarios for financial support of the novel system are evaluated. Through these results, policymakers, researchers, and stakeholders can identify the best financing models for the novel system to ensure the achievement of broader economic, social, and environmental objectives. Table 8 provides the results of different financial scenarios. According to the table, some of the results can be obtained:

1- Financial support is necessary for the development and implementation of novel systems. From the payback period point of view, the best supporting scenario is a direct payment of the annual income of society to the investors as subsidies. Granting 50% of the required capital in the form of a loan to the investor, with an interest rate equal to both the inflation rate and the discount rate, will be prioritized and executed concurrently. However, if the electricity subsidy is removed, the investment payback period will increase to 6.53 years, the worst scenario analyzed. Therefore, paying a subsidy for electricity would be a supportive tool for promoting such productive systems, so that if it is removed, the payback period will increase by 32.58%.

2- The indirect payment of subsidy scenario has a uniform constructive effect on all the examined parameters. Indirect payment of subsidy to the investors by supplying necessary consumables, such as seeds and fertilizer, would decrease the payback period from 4.93 to 4.12 years. Moreover, this scenario will lead to the lowest LCOL.

Table 8- Different considered financial scenarios

Scenario	0	1	2	3	4	5
Description / Parameter	**Main**	**Direct annual payment**	**No subsidy for electricity**	**Free seeds and fertilizer**	**50% loan with 5% interest rate with 5 years repayment period**	**50% loan with 8% interest rate with 5 years repayment period**
Annual subsidy ($)	0	61.34	0	0	0	0
Electricity price ($ kWh^{-1})	0.011	0.011	0.0824	0.011	0.011	0.011
Lettuce price ($ $head^{-1}$)	0.60	0.60	0.60	0.60	0.60	0.60
Lettuce annual price increment	5%	5%	5%	5%	5%	5%
Discount rate	8%	8%	8%	8%	8%	8%
Inflation rate	5%	5%	5%	5%	5%	5%
NPV ($)	1106.5	2118.9	734.5	1393.8	1145	1131
Payback period (years)	4.93	3	6.53	4.12	3.52	3.68
LCOL ($)	0.42	0.41	0.61	0.30	0.32	0.32
NPV variation (%)	0	+91.48	-33.63	+25.96	+3.54	+2.18
Period payback variation (%)	0	38.91	+32.58	-16.27	-28.49	-25.19
LCOL variation (%)	0	-1.87	+45.0	-28.59	-23.89	-23.89

Conclusion

In the current study, first a novel, economically feasible system that enables the constructive interaction of the building and urban agriculture sectors was proposed to reduce total energy and water consumption and annual CO_2 production. After that, a numerical simulation was developed based on the experimental results and previous related research works; then, the yearly simulation of a room equipped with the novel system was performed, and the total energy and annual CO_2 production results were obtained. The results were compared with the total results of a control room and a separate standard greenhouse with the same product. Finally, an economic study based on the analysis of the financial indicators, such as LCOC, PP, and NPV, was carried out, and the sensitivity of different parameters and scenarios was examined. The main conclusions of this study are as follows:

- The total energy consumption reduction from using the novel system was 31.2 %.
- The novel system will cause approximately 3400 $kgCO_2$ emissions reduction over a 20-year life cycle.
- The payback period was approximately five years based on the NPV results.
- Financial support is necessary for the development and implementation of the novel system.
- From the payback period point of view, the best supporting scenario is the direct payment of annual income of society to the investors as subsidies
- Indirect payment of subsidies to the investors by providing the system annual consumable material such as seeds and fertilizer would have a uniform and constructive effect on all the examined economic parameters.
- Paying a subsidy for electricity would be a supportive tool for promoting such productive systems.
- The society’s income from the novel system was calculated to be approximately $0.25 per lettuce head.

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Authors Contribution

M. M. Naserian: Simulation, Validation, Visualization, Data pre and post processing, Writing.

R. Khodabakhshian: Supervision, Methodology, Data pre and post processing, Statically analysis, Conceptualization, Review & editing, Funding acquisition.

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تحلیل انرژی، محیط‌زیستی و اقتصادی سامانه نوین سبز یکپارچه با ساختمان: دیدگاه ساکنان و جنبه‌های اجتماعی

محمد مهدی ناصریان[1]، رسول خدابخشیان کارگر[1*]

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چکیده

بخش ساختمان و بخش کشاورزی-غذایی به‌ترتیب تقریباً ۴۰٪ و ۲۱٪ از کل انرژی جهان را مصرف می‌کنند. این پژوهش با هدف ترکیب این دو بخش پرمصرف انرژی برای کاهش مصرف انرژی کل جامعه انجام شده است. برای این منظور، یک سیستم کشاورزی یکپارچه کوچک‌مقیاس با ساختمان طراحی و ساخته شد. در این پژوهش، مصرف کل انرژی و آب، تولید سالانه دی‌اکسید کربن و هزینه کل استفاده از سیستم نوین از دیدگاه ساکنان ساختمان (شخصی) و جنبه‌های اجتماعی مورد تحلیل قرار گرفت. علاوه بر این، نتایج با نتایج کلی یک ساختمان و یک گلخانه استاندارد جداگانه با همان محصول مقایسه شد. نتایج نشان داد که کاهش کل انرژی به دلیل استفاده از سیستم نوین ۳۱/۲٪ بوده است. بر اساس نتایج، سیستم نوین موجب کاهش حدود ۳۴۰۰ کیلوگرم دی‌اکسید کربن در طول یک دوره عمر ۲۰ ساله خواهد شد. همچنین، کاهش مصرف آب سالانه به میزان ۱۹/۲ لیتر بر کیلوگرم تولید کاهو به‌دست آمد. دوره بازگشت سرمایه بر اساس نتایج تحلیل هزینه که شامل هزینه‌های سرمایه‌گذاری، عملیاتی و اجتماعی می‌شود، حدود ۵ سال بود. تحلیل های حساسیت و سناریوها نیز به‌منظور درک بهتر تأثیر پارامترهای مؤثر احتمالی انجام گردید تا سرمایه‌گذاری برای این سامانه نوین را مطمئن و جذاب نماید.

واژه‌های کلیدی: آنالیز محیط‌زیست، ساختمان سبز، سیستم سبز عمودی، مدلسازی انرژی، NPV

۱- گروه مهندسی بیوسیستم، دانشکده کشاورزی، دانشگاه فردوسی مشهد، مشهد، ایران
(*- نویسنده مسئول: Email: Khodabakhshian@um.ac.ir)

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