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Unleashing the potential of Agri-PV for cherry and apple production in Himachal Pradesh, India

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Abstract

With the increasing global demand for renewable energy, the challenge is identifying sustainable solutions´ avoiding land use conflicts. This study explores the potential of agrophotovoltaic (APV) systems, integrating photovoltaics with fruit production to simultaneously address energy generation and food production challenges. Focusing on the fruit orchards in Himachal Pradesh, India, a modelling study demonstrates the economic viability of APV systems, with relatively fast Return on Investment (ROI) of 5.3 and 5.9 years for cherry and apple production, respectively. The APV model, combining solar PV and fruit farms, is designed for a 1-hectare area. The dual-use structure optimizes sunlight exposure while facilitating traditional agricultural practices. The financial analysis reveals substantial profits from fruit production and energy sales, contributing to the economic sustainability of APV. The study emphasizes the potential for increased farmer income, enhanced grid reliability, and rural electrification. Considering the unique challenges Himachal Pradesh faces, including cultivating apples and cherries of inferior quality, the paper recommends adopting innovative approaches. By harnessing solar power through APV, farmers can improve fruit quality, increase revenue, and contribute to a more sustainable and widespread energy distribution. This study is a foundation for future experimental verification and broader implementation of APV systems in diverse agricultural landscapes.

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Introduction

The worldwide effort to expand solar energy sources is aimed at meeting global energy demands while reducing dependence on fossil fuels. However, this pursuit often comes with a significant requirement for extensive land usage. Additionally, the adverse impacts of climate change and a rapidly growing global population pose challenges to food security, leading to heightened competition for limited land resources. In light of these challenges, the integration of photovoltaics and plant cultivation, often referred to as agrophotovoltaic (APV) or agrivoltaic systems, has been suggested as a promising strategy to synergistically address both renewable energy generation and food production (Blankenship et al., 2011; Weselek et al., 2019). The idea of APV was introduced more than thirty years ago by Goetzberger and Zastrow (1982). Nowadays, there are several APV plants and small research facilities worldwide (Obergfell et al., 2017). Several studies have demonstrated that APV enhances land productivity and yields higher economic benefits (Dupraz et al., 2011; Elamri et al., 2018; Valle et al., 2017). This presents significant potential as an efficient and co-productive renewable energy system, particularly in regions characterized by dense populations or limited land availability, such as mountainous areas and islands (Dinesh & Pearce, 2016). Additionally, previous studies have shown an increase in water use efficiency beneath both traditional PV installations (Hassanpour Adeh et al., 2018). Beyond its numerous positive effects on crop production, the adoption of APV improves the financial viability of farming by generating additional, constant and realible income through energy production (Dinesh & Pearce, 2016; Malu et al., 2017). Furthermore, it has the potential to enhance rural electrification in off-grid areas as part of decentralized energy systems (Burney et al., 2010; Dinesh & Pearce, 2016; Harinarayana & Vasavi, 2014; Malu et al., 2017). Consequently, APV emerges as a crucial element in future renewable energy production systems, concurrently ensuring food production and the economic sustainability of agriculture (Dinesh & Pearce, 2016; Weselek et al., 2019).

India presents a particularly favorable region for Agri voltaic production due to its economy being largely composed of numerous agriculture producers, and the country is actively extending electrical services to the 21.3% of its population lacking any access to electricity, reflecting rapid expansion (Malu et al., 2017). Furthermore, the Indian government provides substantial support for photovoltaic (PV) production, contributing to the increasing solar capacities achieved (*Ministry of New and Renewable Energy*, 2023). Lastly, India benefits from a relatively high solar flux, especially in states like Maharashtra, Gujarat, Haryana, Punjab, Rajasthan, Andhra Pradesh, Orrisa, Madhya Pradesh, Bihar, and West Bengal. These states receive 4–7 kWh of solar radiation per square meter per day, equivalent to 2,300–3,200 hours of sunshine annually (Dinesh & Pearce, 2016; Malu et al., 2017)

Himachal Pradesh, the northernmost state of India, accounts for 90% of the total fruit crop in the state, covering about 109,533 hectares of land (F. A. Wani & Songara, 2019). The fruit sector in Himachal Pradesh makes a substantial contribution in the economics of the state, engaging over 1.7 lakh families and providing gainful employment to millions of residents (A. Sharma et al., 2022; F. A. Wani & Songara, 2019). Apple production in the year 2020/21 accounted for 2.2 million metric tons (MT) making India 5th largest apple producer (A. Sharma et al., 2022). Nevertheless, cherries, classified as fleshy stone fruit within the Prunus genus of the Rosaceae family, are emerging as a viable alternative (Bali, 2022). This is attributed to various advantages over competing fruit crops, including a shorter production duration, lower water requirements, and higher market value (Bali, 2022; Noor et al., 2020). In Himachal Pradesh, cherry cultivation is predominantly concentrated in the elevated areas of Shimla, Kullu, Mandi, Chamba, Kinnaur, and Lahaul & Spiti districts, situated at altitudes ranging from 6,000 to 8,000 feet above mean sea level (R. Sharma et al., 2022). Over the last three decades, there has been a significant transformation in the global production of cherries. Ongoing research and development initiatives have led to the adoption of new technologies and varieties, replacing older methods and introducing crucial inputs to enhance cherry production. The implementation of new rootstocks, aimed at controlling vegetative growth, facilitating high-density planting, and promoting earlier fruiting, has become a common practice. Additionally, the development of self-pollinating varieties has resulted in sturdier and larger fruits (Noor et al., 2020; R. Sharma et al., 2022). In India, cherry cultivation is predominantly concentrated in the North-Western regions of Jammu and Kashmir (J&K), Himachal Pradesh (H.P.), and Uttarakhand (R. Sharma et al., 2022). This cultivation not only diversifies crops but also contributes to additional income and economic prosperity, significantly impacting the socio-economic upliftment of resource-poor farming communities by generating employment and increasing productivity (Salvadores & Bastías, 2023; R. Sharma et al., 2022).

Despite the substantial production levels, a notable challenge in the state lies in the cultivation of apples and cherries of inferior quality. This issue has led to a shift in consumer preferences towards imported fruits within the country (Mohan Kathuria & Singh, 2016). Various factors contribute to this issue, such as the prevalence of monoculture with a limited selection of old cultivars, inadequate pruning and training practices, and ineffective pest and disease control (R. Sharma et al., 2022; F. A. Wani & Songara, 2019). However, the most pressing issue is the absence of high-density production with optimum covers, coupled with financial inadequacies. (F. A. Wani & Songara, 2019; S. A. Wani et al.,2022). The use of protective covers on fruit orchards offers protection from adverse weather conditions, such as hailstorms, heavy rains, and extreme temperatures which can cause physical damage to flowers bearing fruit and disrupt the growth cycle. Producing high quality cherries, requires protection from rain, hail, especially right before harvest, to prevent them from bursting and rotting (Salvadores & Bastías, 2023). With rising temperatures and increased solar radiation, the fruit is more often experiencing heat damage (Hörnle, 2021). One primary issues in cherry production are vinegar flies, which can adversely affect the cherry quality (Hörnle, 2021). Cherries and apples, especially when exposed to environmental stressors before harvest without protective covers, may develop smaller sizes that fail to meet market expectations (Salvadores & Bastías, 2023). Inadequate coloration is also a prevalent concern, negatively impacting the visual appeal and market value of the fruits (Mohan Kathuria & Singh, 2016). Several studies have discussed the positive effects of the use of cover in enhancing the fruit quality (McCormick et al., 2021; Salvadores & Bastías, 2023). By enhancing fruit quality, the protective covers also reduces several physiological disorders induced by cracking and poor fruit set in cherries (Hörnle, 2021). Simultaneously, the use of protective covers proves beneficial in reducing the dependency on various pesticides (Demestihas et al., 2017).

Therefore, there is a need to introduce innovative methodologies aimed at enhancing fruit quality within the state. Considering the prevalent socio-economic circumstances, where Indian farmers contend with restricted financial resources and seek prompt returns on investments (F. A. Wani & Songara, 2019), an investigation into the viability of Agri-PV in apple and cherry production becomes essential. This study illustrates the potential efficacy and viability of integrating Agri-PV systems into the cultivation of apples and cherries within in Himachal Pradesh, India.

Materials and Methods

A combination solar PV and apple and cherry farm APV system is modeled on existing apple and cherry orchards to study the energy aspects and expected output per hectare of farmland with the dual use of land in Shimla district of Himachal state of India (Latitude: 31° 16' 12.00" N Longitude: 77° 27' 0.00" E Alt: 2206 m). The farm considered for this case study is a square farm of 1 ha (i.e. 10000 square meters).

Figure 1: Map of Himachal Pradesh, India, indicating the location of Shimla district

The Agri-voltaic structure is made from steel and aluminum profiles. A spacing of approximately 4.5 meters x 1.8 meters between rows is considered sufficient to ensure ample sunlight reaches the crop canopy while maintaining satisfactory energy yields. In the course of patent development (Fraunhofer ISE patent EP 2811819 B1), Beck et al., (2012) noted in their simulation that orienting the PV arrays towards the southwest or southeast proved to be the most effective approach for achieving uniform light conditions beneath the panels. Fig. 1 shows the arrangement of solar modules, as recommended by the Kompetenzzentrum Obstbau Bodensee and Fraunhofer in 2022 (Fig. 1). The clearance height of 3.2 m enables the fruit growers to use standard agricultural machinery to maintain their crops (Fig.1), The cover is to be made of the bifacial PV modules, which enables to generate electricity and protect the crops underneath from the sun and the elements. The cabling runs only over the cover to avoid any hindrances during agricultural activities (Fig.1). Beneath the installation, cherries and apple are to be planted in ridges around the supporting structure, with each roof apex covering a ridge. The drip edge for each roof panel is positioned between each ridge. Rainwater infiltrates the facility and is captured in drains where it is then prepared for reuse.

The assumptions regarding the efficiency and performance of Agri-PV panels are based on the assertions made by Fraunhofer in Germany (*Fraunhofer ISE*, 2023). As the company is based in Germany, adjustments have been made to the calculations considering the solar specifications in the Narkanda region in Shimla. Unfortunately, the specific photovoltaic power output data for the Narkanda region is unavailable. Therefore, data for the Shimla region, specifically 1500 KWh/KWp according to (Solargis, 2023), has been utilized as a substitute.

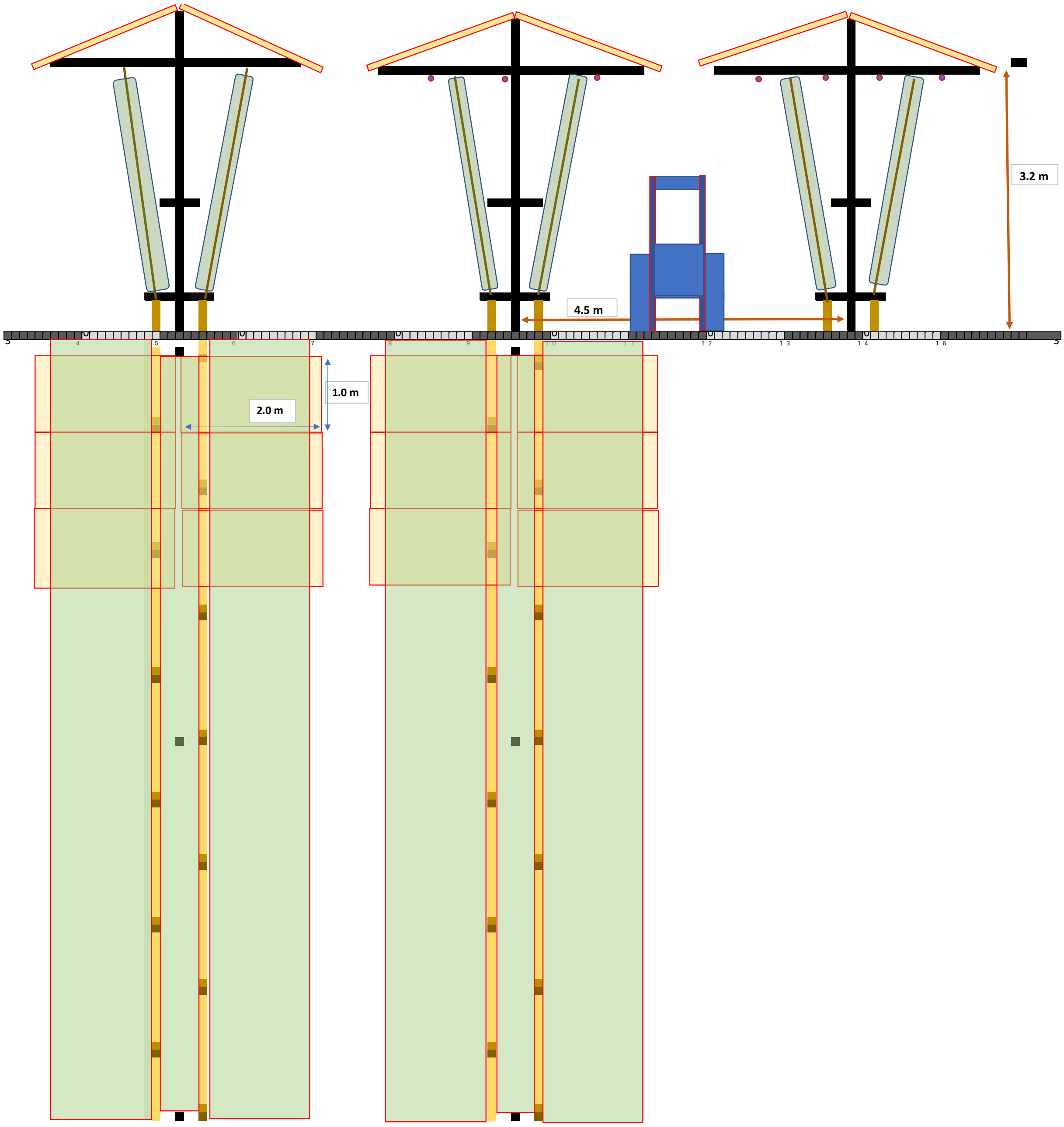

Figure 2: Schematic representation of the planned APV model farm of 1 ha field for cherry and apple orchard

The solar module under consideration is produced by HT-SAAE company (*Shanghai Aerospace Automobile Electromechanical Co. Ltd.*, 2024), installed by Farunhofer, Germany. The module has a power output ranging from 300W to 320W, with an efficiency between 11.6% and 12.3%. The dimensions of the module are 2000 mm x 1000 mm x 30mm. The module comprises 80 cells arranged in a 4x20 configuration; The solar cells used in the module are Monocrystalline type (182mm x 91 mm).

The module set up claims to provide a maximum voltage of up to 1500V DC. It is important to note that this module is used as an example, and adjustments can be made based on the specific requirements of the region. The price for electricity has been derived from Himachal Pradesh state electricity board limited, India (HPSEB, 2023). The cost assumptions for related to agriculture has been estimated after a telephonic conversation with a fruit grower farmer in the Narkanda region. It is important to highlight that the case study pertains specifically to the Shimla region. This region experiences annual solar irradiation levels that exceed the average solar irradiation for India. Consequently, there exists significant geographic variability in solar potential based on different locations. Conducting a more targeted GIS-based study would enable a thorough determination of solar potential variations across various geographical areas. However, with the provided data it is possible to calculate the economic analysis for implementing APV on cherry and apple orchards for a hectare of land.

Results and Discussion

The economic analysis calculations are conducted in Indian rupees (INR) to enhance comprehension for the Indian audience. For cherry production, the associated costs, encompassing plant protection, fertilizer, energy, labor for harvesting and caretaking, management of the orchard, and material packing, total 9,60,000 INR. Considering a 1-hectare area, the average yield of 10,000 kg at a price of 400 INR^{-kg} results in annual sales of 40,00,000 INR (Table 1). Consequently, the net profit from cherry production amounts to 30,40,000 INR. It is important to highlight that the cherry price considered in this study reflects what farmers receive for cherries produced without covers, often resulting in smaller sizes and poor coloration. Nevertheless, employing covers for cherries frequently provides additional advantages, including protection against vinegar flies, larger sizes, and improved sugar and color content (Bali, 2022; Bhat et al., 2017; Hörnle, 2021). Moreover, with the increasing risks of pests and birds integrating PV in cherry production and to assume will be increasingly necessary in the future

(Hörnle, 2021; Salvadores & Bastías, 2023). Regarding energy production, with a power capacity of 1,000 kW per hectare and solar radiation of 1,500 kWh/KWp, the annual energy production is calculated to be 15,00,000 kWh. Considering a price of 5.40 INR/kWh (HPSEB, 2023), the sales or own savings from energy production is at 81,00,000 INR per year. Despite a significant initial investment of 6,00,00,000 INR, the annual depreciation, annual costs (including insurance), contributes to a profit of 50,00,000 INR. The return on investment (ROI) for this section is achieved in 7.5 years, showcasing the economic viability of the energy component.

The total from the profits and depreciation from both cherry production and energy sums to be 1,13,40,000 INR, with an overall ROI of 5.3 years (Table 2). The profits and relatively quick ROI demonstrate the economic sustainability and attractiveness of the APV, emphasizing its potential as a viable and profitable venture for agricultural and energy integration.

Table 2 comprises of economic viability of APV for apple production for a 1-ha area. The average yield of 30,000 kg, priced at 80 INR/kg, results in annual sales of 24,00,000 INR. The associated costs, covering plant protection, fertilizer, energy, labor for harvesting, pruning, management of the orchard, and material packing, amount to 5,00,000 INR. Consequently, the net profit from apple production is 19,00,000 INR. On energy side, power capacity of 1,000 kW per hectare and solar radiation of 1,500 kWh/KWp, the annual energy production is calculated to be 15,00,000 kWh. For 5.40 INR/kWh, the sales or own savings from energy production amount to 81,00,000 INR annually. Despite a considerable investment of 6,00,00,000 INR, annual depreciation, annual costs contribute to a noteworthy profit of 50,00,000 INR. However, these calculations are made excluding the interest rates. The return on investment (ROI) for this section is achieved in 7.5 years, indicating the high economic viability of the energy component. When combining the profits and depreciation from apple production and energy, the total amounts to 1,02,00,000 INR, with an overall ROI of 5.9 years. It is important to highlight that the calculations presented in this study excludes any subsidies. Nevertheless, it is clear that the Indian government has a substantial support system for PV production aimed at encouraging the adoption of renewable energy (Malu et al., 2017; *Ministry of New and Renewable Energy*, 2023). This study affirms the considerable potential of Agri-PV in enhancing the livelihoods of farmers, and it is anticipated that the Indian government will eventually implement a dedicated subsidy system for such projects (Dinesh & Pearce, 2016; Marcheggiani et al., 2013).

By harnessing solar power through APV farms, farmers can not only secure an additional income stream but also play a crucial role in enhancing grid reliability. During peak demand periods, these farms can supply electricity to neighboring industries, reducing the reliance on conventional fossil-fuel power plants and consequently lowering greenhouse gas emissions. This dual benefit not only supports farmers economically but also aligns with India's high demand for electricity. In a country where individual electricity consumption reached 1010 kWh per capita in 2014, APV has the potential in extending electricity access to off-grid rural areas, contributing to a more sustainable and widespread energy distribution. Moreover, integrating photovoltaic (PV) technology into agriculture offers additional advantages for fruit production. The shade created by PV modules proves beneficial by mitigating water evaporation, particularly during the dry season and hot summers. Studies indicate that shading can lead to water savings ranging from 14% to 29%, with potential significance in areas grappling with severe droughts intensified by climate change (Marrou et al., 2013; Weselek et al., 2019). Additionally, PV modules contribute to reducing soil erosion by minimizing moisture evaporation (Fraunhofer, 2022).

Conclusion:

Addressing the challenge of expanding the world's food supply while transitioning to more land-intensive energy sources can be facilitated by the dual use of land in agrivoltaic systems. This preliminary modeling study demonstrates the viability of Agro-Photovoltaic (APV) systems for cherry and apple production, revealing a notably quicker Return on Investment (ROI) of 5.3 and 5.9 years, respectively. The calculated annual electricity production from 1 hectare of APV amounts to 1,500,000 kWh, thereby positively impacting farmers' livelihoods and contributing to the nation's goal of doubling farmers' income. To further advance this concept, future research should focus on experimental verification, enabling the implementation of agrivoltaic systems in rural areas and villages. This not only provides electrification but also offers the additional benefit of increased revenue generation.

Table 1: Financial analysis of Cherry Production and Solar Energy Integration for Sustainable Agriculture

Cherry Production			Calculation per 1 ha area		
Sales			per annum		
Yield avarage	10,000	kg			
Price	400	INR/kg			
Annual Sales per ha				40,00,000	**INR**
Costs					
Plant protection, fertilizer, energy				1,00,000	**INR**
Labor		hours	wages/hour		
Harvest		500	70	35,000	**INR**
Horticultural Activities (pruning, hoeing etc)		250	300	75,000	**INR**
Management orchard		50	1,000	50,000	**INR**
Material packing	boxes	per box			
	10000	50	INR	5,00,000	**INR**
Investment/Depreciation					
Depreciation machinery etc.	10,00,000	10	years	1,00,000	**INR**
Depreciation Investment cultivas	15,00,000	15	years	1,00,000	**INR**
Costs total				9,60,000	**INR**
Profit				**30,40,000**	**INR**
B. Electrical energy					
Power per ha	1,000	kW			
Solar radiation	1,500	Kwh/KWp			
Energy production per annum	15,00,000	kWh			
Price electric energy	5.40	INR/kWh			
Sales or own savings	81,00,000	INR/year			
Investment	6,00,00,000	INR			
Depreciation	20	years			
Depreciation/Annum				30,00,000	**INR**
Annual costs (insurance etc.)				1,00,000	**INR**
Profit				**50,00,000**	**INR**
ROI no interests				7.5	**years**
ROI Sum section A and B					
Sum Profit and depreciation total			1,13,40,000	**INR**	
ROI				5.3	**years**

*The currency specified in this table is Indian Rupees (INR). The conversion to USD can be performed using an exchange rate of 1 USD = 82.80 INR**

Table 2: Financial analysis of Apple Production and Solar Energy Integration for Sustainable Agriculture

Apple Production			Calculation per 1ha area		
Sales			Per annum		
Yield avarage	30,000	kg			
Price	80	INR/kg			
Annual Sales per ha				24,00,000	**INR**
Costs					
Plant protection, fertilizer, energy				1,00,000	**INR**
Work		hours	wages/hour		
Harvest		300	150	45,000	**INR**
Horticultural Activities (pruning, hoeing etc)		100	300	30,000	**INR**
Management orchard		95	1,000	95,000	**INR**
Material packing	boxes	per box			
	3000	10	INR	30,000	**INR**
Investment/Depreciation					
Depreciation machinery etc.	10,00,000	10	years	1,00,000	**INR**
Depreciation Investment cultivars	15,00,000	15	years	1,00,000	**INR**
Costs total				5,00,000	**INR**
Profit				**19,00,000**	**INR**
B. Electrical energy					
Power per ha	**1,000**	**kW**			
Solar radiation	1,500	Kwh/KWp			
Energy production per annum	15,00,000	kWh			
Price electric energy	5.40	INR/kWh			
Sales or own savings	81,00,000	INR/Year			
Investment	6,00,00,000	INR			
Depreciation	20	years			
Depreciation/Annum				30,00,000	**INR**
Annual costs (insurance etc.)				1,00,000	**INR**
Profit				**50,00,000**	**INR**
ROI no interests				7.5	**years**
ROI Sum section A and B Sum Profit and depreciation total				1,02,00,000	**INR**
ROI				5.9	**years**

*The currency specified in this table is Indian Rupees (INR). The conversion to USD can be performed using an exchange rate of 1 USD = 82.80 INR**

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