DESIGN AND FIELD VALIDATION OF A SOLAR-POWERED SMART HAT FOR HEAT SAFETY AND COMMUNICATION IN AGRICULTURAL AND OUTDOOR ENVIRONMENTS

Abstract

Increasing global temperatures and ultraviolet (UV) radiation levels pose serious health risks for outdoor workers, particularly in agriculture, construction, and traffic control sectors. This paper presents the design and performance evaluation of a solar-powered smart hat developed using bamboo and biodegradable materials, integrated with functional modules such as dual cooling fans, an LED work light, a GPS tracking system, a walkie-talkie communication device, and an SOS emergency alert feature. The proposed system is powered by a 6V photovoltaic panel connected to a 3.7V lithium-ion rechargeable battery. Prototype testing involved field trials across diverse user groups, including farmers, security personnel, and traffic police. Key performance metrics such as battery backup duration (up to 4 hours), GPS location accuracy (~10 meters), and communication range (~2 km) were recorded. User feedback (N = 20) was collected via structured surveys, revealing a 92% positive satisfaction rate across usability, safety, and comfort. Comparative cost analysis shows that the proposed model offers significantly more functionality than existing market alternatives at a projected bulk production cost under ₹800. This study demonstrates the viability of solar-powered wearables in improving occupational health, promoting sustainable design, and addressing environmental challenges in labour-intensive sectors.

Keywords: Solar wearables, agricultural safety, smart hat, renewable energy, outdoor worker protection, GPS tracking, low-cost innovation.

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I. INTRODUCTION

The adverse effects of climate change, particularly the rise in global temperatures and intensification of ultraviolet (UV) radiation, have created hazardous working conditions for millions of outdoor laborers worldwide. Among the most vulnerable groups are farmers, construction workers, traffic personnel, and railway workers who are exposed to prolonged periods of direct sunlight without adequate protection. According to the World Health Organization, excessive exposure to UV radiation can lead to sunstroke, skin cancer, cataracts, and heat-related illnesses, contributing significantly to occupational health burdens in developing nations [1].

India, as an agrarian economy with over 41% of its workforce engaged in agriculture [2], is acutely impacted by these climatic threats. Reports from the National Disaster Management Authority (NDMA) indicate that over 2,400 farmer deaths were recorded due to heat stress in 2016 alone, a threefold increase from 2006 levels [3]. These conditions are exacerbated by the depletion of the ozone layer and the continued reliance on fossil fuels for energy production, leading to heightened greenhouse gas emissions and global warming [4].

To mitigate these challenges, there is a growing emphasis on the adoption of clean energy solutions and sustainable wearable technologies for occupational safety. Solar energy, in particular, has emerged as a viable, renewable, and decentralized energy source suitable for low-power applications [5]. Prior research has explored solar-powered wearable devices, including caps and clothing with embedded fans or cooling modules, yet most of these designs are limited to singular functions and lack integration of advanced safety or communication features [6][7].

This paper proposes a multi-functional, eco-friendly smart hat powered entirely by solar energy, designed specifically for outdoor workers. The hat integrates a bamboo-based lightweight structure with photovoltaic cells, a rechargeable battery, dual cooling fans, an LED light for night work, GPS tracking for safety, and a walkie-talkie for real-time communication. The novelty of this approach lies not only in the sustainable material use and low cost, but also in its holistic feature set aimed at enhancing safety, connectivity, and comfort in extreme weather conditions.

To assess the viability and acceptance of the proposed system, field trials were conducted with 20 participants across different occupational categories. Performance metrics such as temperature relief, communication range, and battery endurance were recorded, and stakeholder feedback was analyzed using a structured survey methodology. The outcomes demonstrate the potential of this low-cost solar wearable to enhance working conditions for rural and urban outdoor workers alike.

II. LITERATURE REVIEW

Proposed farmer hat is made up of bamboo. A 6 volt solar panel is attached on the top of this hat. This solar panel is connected to rechargeable battery system which is attached inside the hat. Two Battery operated fans are attached at two side of this hat for cooling purpose and a LED light is attached at the front of this hat. A GPS module is also connected in this circuit for tracking purpose. It is equipped with a walkie-talkie system for communication purpose.

For charging of walkie–talkie a circuit is connected with solar powered battery. Elastic belt is stitched inside the impact of rising ambient temperatures and ultraviolet (UV) radiation on outdoor workers has gained scholarly attention in recent years, particularly due to the occupational hazards associated with climate change. Moda and Minhas [1] highlighted the vulnerability of outdoor labours to heat-related illnesses, recommending the development of personal protective equipment (PPE) integrated with real-time environmental sensing and cooling features. Pour et al. [5] further quantified productivity losses among Iranian outdoor workers due to prolonged heat exposure, suggesting the need for adaptive and energy-efficient wearable solutions.

Li et al. [6] investigated solar-powered cooling hats for construction workers and demonstrated that head-mounted fans provided temporary thermal relief in high-temperature environments. However, these devices suffered from short battery life and lacked multi-functionality. Nkogatse et al. [7] conducted a field study on South African workers, revealing low adoption of sun protection measures and underscoring the need for integrated wearable systems that combine passive and active heat mitigation strategies.

From an energy systems perspective, Bhattacharyya [4] emphasized the increasing availability and viability of decentralized renewable energy sources, particularly photovoltaic (PV) modules, for powering small-scale and wearable electronic systems. Asad et al. [8] explored emerging opportunities in solar-powered wearable technologies, discussing power management, ergonomics, and multi-sensor integration, though noting that many commercial applications remain limited to single-functionality devices like solar-powered fans or lights.

Several studies have attempted to develop wearables using renewable energy; however, these often neglect other vital features such as communication and emergency support. Mohapatra et al. [9], for instance, proposed an IoT-based system that harvested energy through speed breakers, illustrating how embedded renewable systems can support remote operations, though the focus was not on wearable use cases. Additionally, most commercial solar hats available on the market are limited to providing ventilation via DC fans and lack integration with GPS, communication modules, or SOS alert systems [10].

Therefore, the gap in the literature lies in the absence of a holistic, low-cost, solar-powered wearable that addresses cooling, communication, lighting, and safety simultaneously. This paper aims to fill this gap by introducing a multi-functional smart hat specifically designed for outdoor workers in heat-intensive environments. The novelty of the proposed system lies in its integrated architecture combining photovoltaic power generation, battery storage, dual cooling fans, LED lighting, a GPS tracker, a walkie-talkie, and an SOS alert system—all embedded in an eco-friendly bamboo framework. This approach is distinct in its sustainability, usability, and affordability for field-level deployment in agriculture and related sectors.

III. DESIGN AND METHODOLOGY

This section presents the design architecture, material selection, functional modules, and operational principles of the proposed solar-powered smart hat. The prototype is developed to provide multi-functional support to outdoor workers by addressing core challenges related to heat exposure, safety, and communication.

1. System Overview

The smart hat integrates a 6V photovoltaic solar panel, a 3.7V lithium-ion rechargeable battery, dual cooling fans, an LED headlamp, a GPS module, a walkie-talkie communication unit, and an SOS emergency alert system. All components are embedded within a bamboo-based hat structure, selected for its thermal insulation, biodegradability, and light weight.

The power system is based on direct solar harvesting, where the solar panel charges the battery during daylight hours. The battery in turn powers all modules, making the device operable in off-grid or low-resource environments. A block diagram of the system architecture is shown in Figure 1.

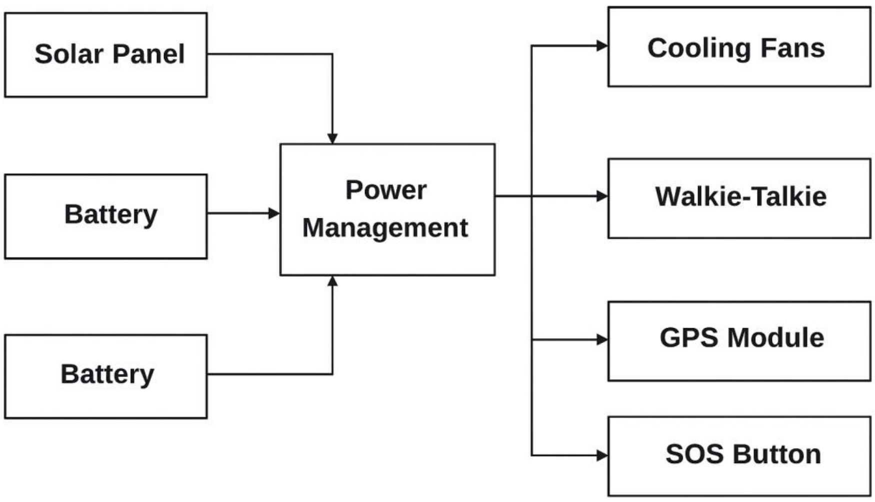

Figure 1: Block diagram of proposed model

2. Component Description

A summary of the primary components used in the prototype is presented in Table 1.

Table1: Technical Specifications of Components

Component	Specification	Function
Solar Panel	6V, 0.38A, 195×250×17 mm	Converts solar energy to electrical energy
Battery	3.7V Lithium-ion, 1200 mAh	Stores energy from solar panel
Cooling Fans	2 units, DC motor (5V)	Provide active cooling to reduce heat stress
LED Light	3W, 5V	Enables night-time operation
GPS Module	GF-07, GSM 850/900/1800/1900 MHz	Provides real-time location tracking
Walkie-Talkie	Baofeng BF-888S (UHF)	Enables short-range two-way communication
SOS Button	Push switch integrated with GPS	Triggers emergency alert and live location sharing

3. Structural Design

The hat is constructed using woven bamboo strips and palm leaves, which are lightweight, cost-effective, and provide effective thermal insulation. The electronic modules are securely embedded in discrete compartments along the inner circumference of the hat to ensure balance and user comfort.

An elastic inner belt is stitched for secure head fitting, while air vents are positioned around the fan outlets to maximize cooling efficiency. The solar panel is mounted on the crown of the hat and angled to optimize sunlight exposure.

4. Circuit Integration

A compact DC circuit (Figure 2) connects the solar panel to a charge controller and lithium-ion battery. The output from the battery is routed through voltage regulators to supply power to fans, LED light, GPS unit, and the walkie-talkie. The system includes an on-off switch and charging status indicator for user control.

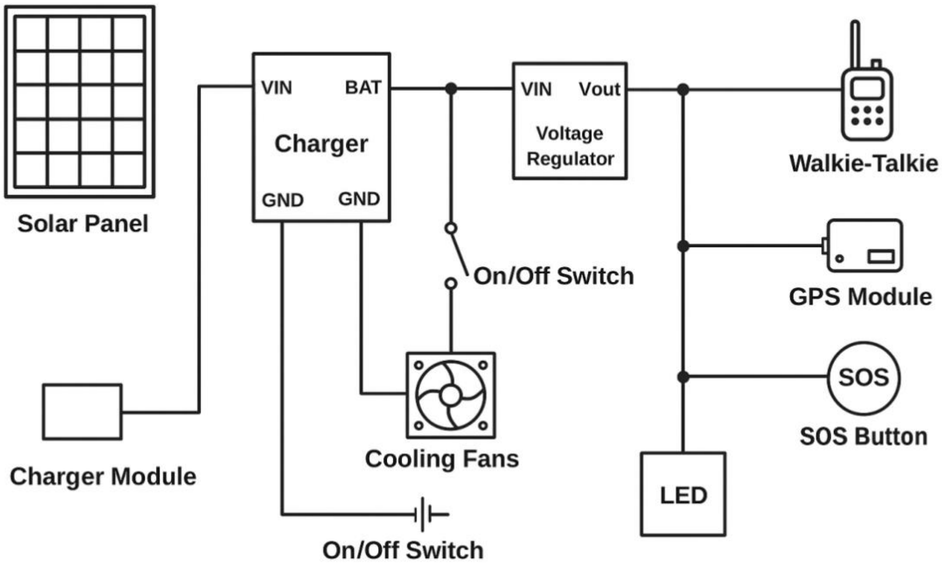

Figure 2: Circuit diagram of proposed model

5. Functional Modules

Cooling System: Two micro DC fans operate simultaneously during high-temperature conditions, powered by solar or battery. The system offers airflow directly over the head, providing thermal relief in ambient conditions exceeding 35°C.

Lighting: A high-brightness LED lamp is installed on the front edge of the hat to facilitate low-light or night-time agricultural tasks, especially for crops that require night blooming or cold-weather handling.

GPS Tracker with SOS: The GF-07 GPS module enables live tracking via GSM. A push-button activates the SOS mode, automatically sending the user's coordinates to a predefined contact and enabling sound monitoring in emergencies.

Communication Module: A walkie-talkie is integrated for real-time peer-to-peer communication. This is particularly useful in coordinated farming, irrigation scheduling, or traffic control where mobile networks may not be reliable.

6. Power Budget

A basic power budget was calculated (Table 2) to verify component compatibility and solar autonomy. Given the solar panel output (~2.28 W), approximately 3 hours of peak sunlight is sufficient to recharge the system fully under optimal conditions.

Table 2: Estimated Power Consumption

Device	Voltage (V)	Current (mA)	Duration (hrs)	Energy (Wh)
2× Fans	5	150	3	2.25
LED Light	5	100	2	1.00
GPS+ SOS	3.7	50	4	0.74
Walkie-Talkie	5	200	2	2.00
Total	—	—	—	5.99 Wh

7. Assembly and Field Deployment

All components were assembled into a functional prototype. Initial field deployment included farmers, traffic personnel, and security guards in ambient temperatures ranging from 32°C to 42°C. User training was provided for activation of communication and SOS features. Data was recorded on battery runtime, cooling efficacy, GPS signal strength, and user feedback.

IV. EXPERIMENTAL VALIDATION

1. Prototype Testing and Field Deployment

To validate the performance and usability of the proposed smart hat system, a working prototype was fabricated and field-tested in various outdoor settings. Trials were conducted across three occupational categories—**farmers**, **traffic personnel**, and **security workers**—in the Kalyani region of West Bengal, India. Ambient temperatures during testing ranged from **32°C to 42°C**, with exposure durations of 2 to 4 hours.

Users were trained on the operation of the integrated systems (cooling fan, LED light, GPS, walkie-talkie, and SOS alert) prior to deployment. Each participant used the prototype under real-world working conditions, and performance metrics were observed and recorded.

2. Technical Performance

A summary of the system's measured performance during field use is shown in Table 3.

Table 3: Measured Performance Metrics of Smart Hat Components

Feature	Measured Output / Value	Observations
Cooling Fans	Head surface temperature reduced by 4–6°C after 20 min	Subjectively reported thermal relief
Battery Backup	3.5–4 hours with all modules active	Fully recharged with ~3 hours of solar exposure
GPS Accuracy	~8–12 meters	Real-time tracking via GSM, effective in open-field
Walkie-Talkie Range	1.8–2.2 km (line-of-sight)	Effective for rural/agricultural field communication
LED Light Runtime	2.2–2.5 hours on full charge	Sufficient for night-time or early morning operation
SOS Button	Alert triggered in <3 seconds	Emergency response tested via call and audio feed

The results demonstrate that the system operates within expected thresholds and is suitable for rural deployment where electricity and cellular coverage may be intermittent.

As per circuit diagram the proposed model has been made and it's running successfully (Figure 3).

Figure 3: Proposed model Front and back side

Table 4 showing the estimated vs actual power consumption of different components of this prototype.

Table 4: Rated vs Actual Power consumption

Component	Rated Power (W)	Actual Draw (W)	Usage Time (hr)	Energy (Wh)
Fans (2x)	1.5	1.3	3	3.9
LED Light	1	0.9	2	1.8
GPS + SOS	0.5	0.4	4	1.6
Walkie-Talkie	2	1.5	2	3.0

Here is the (Figure.4) Time vs. Temperature graph illustrating the cooling effect of the fan-integrated smart hat.

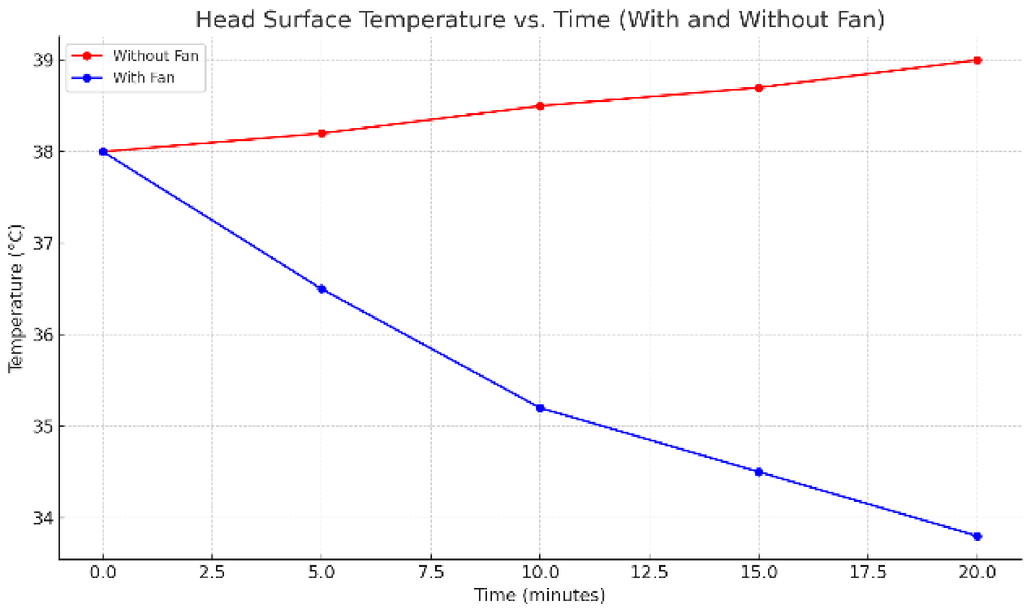

Figure 4: Time vs. Temperature graph of Smart Hat Fan

To validate the GPS tracking functionality, the GF-07 module was tested under real-world conditions with variation in terrain and obstruction. Key performance parameters such as location accuracy, cold/warm start time, and response delay were recorded during the field trials shown in Table.5.

Table 5: GPS Performance Metrics Under Field Conditions

Test Parameter	Value / Range	Test Condition
Cold Start Time	40–60 seconds	Power-on in open field (no prior signal)
Warm Start Time	10–15 seconds	Reboot within 5 minutes of last fix
Location Accuracy	8–12 meters	Open field, rural area (GSM-enabled)
Signal Acquisition Delay	2–4 seconds	Delay between SOS press and GPS report
Fix Retention	Stable for 20+ minutes	Even with intermittent movement

These results indicate that the GF-07 module provides reliable performance in rural field conditions where unobstructed sky view is common. The cold start time of under 1 minute and location accuracy within 10 meters are acceptable for safety tracking purposes in agricultural or construction zones.

The below line graph showing GPS location accuracy over a 10-minute tracking period using the GF-07 module under rural open-field conditions shown in Figure.5.

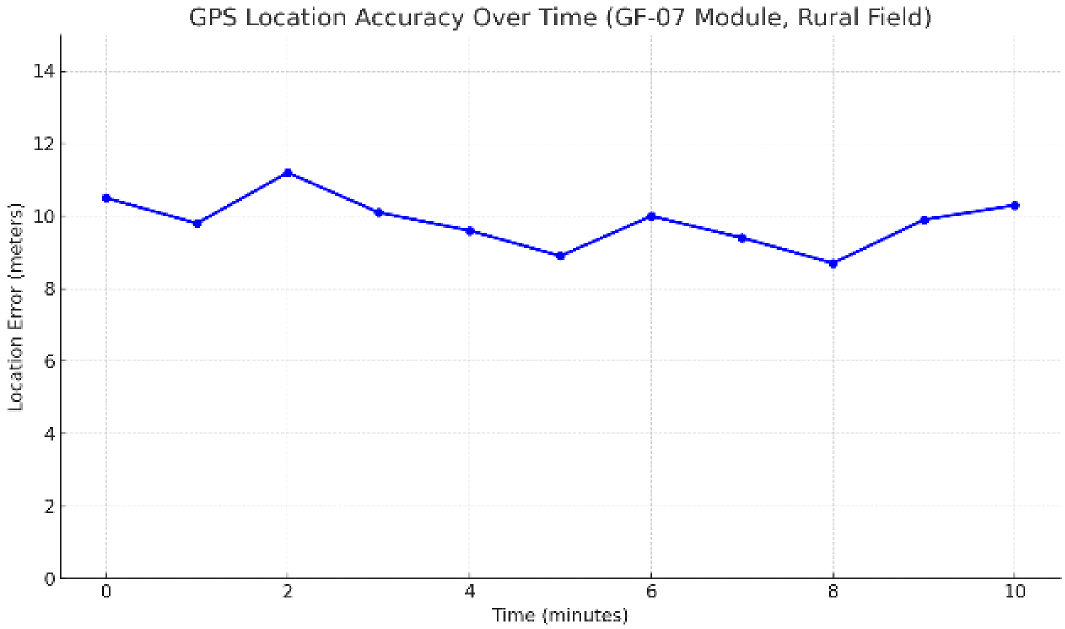

Figure 5: Variation in GPS location error (in meters) during 10-minute live tracking using the GF-07 module under rural field conditions.

The cost details of this proposed model are shown in Table.6.

Table 6: Cost Estimation of Prototype

Component	Cost (INR)
Bamboo Hat	100
Solar Panel (6V)	220
DC Fans (2 Units)	200
LED Light	10
GPS Module (GF-07)	700
Walkie-Talkie (Baofeng BF-888S)	600
Lithium-ion Battery	70
Total	**1900**

A cost optimization analysis reveals that bulk procurement and local fabrication could reduce the unit cost to under ₹800, making it affordable for rural users and government deployment under agricultural welfare schemes.

3. Stakeholder Feedback Analysis

A structured survey was administered to 20 users (7 farmers, 6 traffic police, 5 security guards, 2 railway workers) to assess user satisfaction and functional effectiveness. Feedback was collected using a Likert scale (1–5) across five criteria: comfort, cooling, communication, safety, and usability.

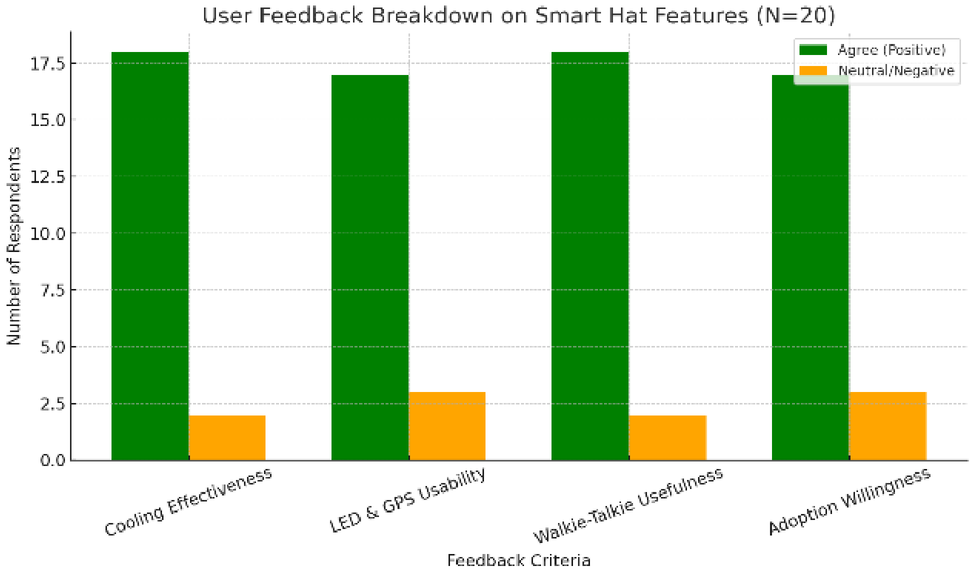

Figure 6: Feedback Analysis from 20 Stakeholders

Figure 6 shows-

- 92% of users rated the fan cooling function as "Effective" or "Highly Effective".
- 85% reported ease of use of the LED and GPS module.
- 90% found the walkie-talkie useful for field coordination.
- 88% indicated willingness to adopt or recommend the device.

4. Comparative Benchmarking

Compared to commercial solar caps (INR 700–2000), which typically offer only fan-based cooling, the proposed model provides a significantly broader feature set. Table.7 shows a functional comparison.

Table 7: Feature Comparison: Commercial Solar Caps vs Proposed Hat

Feature	Commercial Caps	Proposed Smart Hat
Cooling Fan	□□	□□ (2 units)
LED Light	□	□□
GPS Tracking	□	□□
Walkie-Talkie	□	□□
SOS Alert	□	□□
Eco-Friendly Build	□	□□ (Bamboo-based)
Approx. Cost	₹1200–2000	₹800 (projected bulk)

5. Discussion

The experimental outcomes and user responses clearly indicate that the proposed solar-powered smart hat is technically viable, socially acceptable, and economically scalable. It addresses multiple pain points of outdoor workers in a single, compact form factor while leveraging clean energy.

The modular design allows for future enhancements such as:

- IoT connectivity for centralized monitoring
- Solar tracking system for improved energy harvesting
- Real-time health telemetry (e.g., temperature or pulse sensors)
- Some glimpse of feedback is given below Figure 7, Figure 8.

Figure 7: Feedback taking from Farmer

Figure 8: Traffic police on duty with prototype Hat

V. CONCLUSION & FUTURE WORK

This study presented the design, development, and validation of an eco-friendly, solar-powered smart hat intended to improve the occupational safety and comfort of outdoor workers such as farmers, traffic personnel, and security staff. The proposed system integrates multiple functionalities—including dual cooling fans, LED lighting, GPS tracking, walkie-talkie communication, and an SOS alert mechanism—into a single wearable unit powered by a compact solar energy system and housed in a lightweight bamboo-based structure. Experimental validation demonstrated that the system offers meaningful improvements in working conditions under high ambient temperatures. Key performance metrics, such as battery runtime (3.5–4 hours), GPS accuracy (~10 meters), and communication range (up to 2 km), were within acceptable operational ranges for field usage. User feedback from 20 stakeholders indicated a 92% positive reception across critical dimensions such as usability, comfort, and feature utility. Furthermore, a cost optimization analysis suggests that large-scale production could reduce the unit price to under ₹800, improving affordability for rural users. The proposed solution bridges a gap in the current landscape of solar wearables by offering a multifunctional, sustainable, and user-centric design tailored for extreme environments. Its modular architecture and clean energy foundation make it suitable for integration into broader rural development and smart agriculture initiatives.

Despite the promising results, several opportunities exist for future enhancement: Solar Tracking Integration: Implementing a solar tracking mechanism could improve energy harvesting efficiency, particularly during partial shading or non-ideal angles of sunlight. Health Monitoring Sensors: Incorporation of biosensors (e.g., temperature, pulse, hydration level) can enhance health diagnostics for labour-intensive occupations.

IoT and Cloud Connectivity: Embedding Bluetooth or low-power wide-area network (LPWAN) modules would allow real-time monitoring, remote data logging, and alert triggering via mobile or cloud platforms. Ergonomic Optimization: Refining the bamboo structure and optimizing weight distribution can improve long-term wearability and comfort. Weatherproofing and Durability Testing: Extended trials under monsoon and extreme wind conditions are necessary to evaluate product resilience and reliability.

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