Spectrum of Engineering Sciences
ISSN (e) 3007-3138 (p) 3007-312X
Volume 3, Issue 11, 2025

DESIGN AND DEVELOPMENT OF SOLAR FOOD DEHYDRATOR USING QUALITY FUNCTION DEPLOYMENT

Sana Ullah[*1]**, Hamid Ullah**[2]**, Asad Ullah**[3]

[1,2]*Department of Mechanical Engineering, University of Engineering and Technology, Peshawar 25120, Pakistan*
[3]*Department of Mechanical Engineering, University of Engineering and Technology, Mardan 23200, Pakistan*

[*1]sanaullah.uet31@gmail.com

DOI: https://doi.org/10.5281/zenodo.18051164

Keywords
Solar Food Dehydrator, Quality Function Deployment (QFD), Customer Needs, Technical Requirements, House of Quality (HoQ), Concept Generation, Concept Selection.

Article History
Received: 26 September 2025
Accepted: 22 October 2025
Published: 03 November 2025

Copyright @Author

Corresponding Author: *
Sana Ullah

Abstract
Post-harvest losses of fruits in Pakistan remain significantly high due to a lack of efficient and affordable preservation technologies. This paper presents the complete design and development of a hybrid IoT-enabled solar food dehydrator using the Quality Function Deployment (QFD) methodology. Customer needs (Voice of the Customer) and their relative importance are identified through customer surveys. Customer needs are converted into prioritized technical specifications. A relationship matrix is developed between customer needs and technical specification via the House of Quality (HoQ). That is followed by the concept generation, concept selection, where a detailed new model for the solar food dehydrator is presented. A solar dehydrator optimized for user, which reduces postharvest losses, increases dry efficiency, and provides a top solution for small farmers and rural families are the outcomes of this model.

1. Introduction

Quality Function Deployment (QFD) refers to a methodical process used to convert the Voice of the Customer (VOC) into precise technical requirements throughout all phases of product development [1]. It is the customer focused quality management instrument applied to achieve maximum customer satisfaction taking into account the correlations between customer requirements and engineering characteristics. The main tool it offers is the House of Quality (HoQ) which is a matrix-based approach to prioritization of design features according to their importance to the customer, thus making engineering activities to be concentrated on those elements that are the most important to the user [2]. Although QFD has been quite effective in other industry such as the automotive and consumer electronics sectors [1], its application in agricultural technology especially in designing the suitable post-harvest technology such as solar dryers has been limited and represents a great opportunity [3, 4]. Advanced versions, such as interval-grey-probability QFD technique proposed by Cheng et al. [3], which adds more functionality in accepting vague and uncertain information as in customer feedbacks.

Food security remains a global obstacle, particularly in developing countries such as Pakistan, where agriculture is a cornerstone of the economy and career. Post-harvest loss, estimated by Food and Agriculture Organization (FAO) to reach 40-50 % of perishable fruit and vegetables in some regions, is a key issue for food security [5]. The situation is not only a massive loss of the valued nutritional resources, but also a very big financial burden to the people who depend on such crops to earn their living. In Pakistan, especially mango, tomato, banana and peach are highly prone to spoilage due to their high moisture content. Therefore, they require

access to affordable and effective preservation systems especially in the rural regions.
Dehydrating, the process to remove moisture content from foods to prevent microbial growth. It is one of the oldest and most successful food preservation method known to humankind. For generations, the primary method was open sun drying, where the foods were simply laid out on the ground, mat, or roof. While low cost, such method is plagued by severe disadvantages, which are extensive documented in reviews like in Udomkun et.al. [6] and Nair et al. [7]. These limitations include contamination from dust, insects, birds, and other animals, which make the products unhygienic and unsuitable for market use. The process also suffers from unpredictability and slowness, as it relies entirely on favorable conditions, often extend drying periods significantly, therefore exposing the product to spoilage. Additionally, uneven drying occur due to lack of uniformity in the sunlight and wind exposure, causes some portions being over dried whereas others are undried. Lastly, nutrient degradation, vitamins and pigments break down under prolonged exposure to direct ultraviolet radiations and high temperatures, lowering the nutritional and commercial value of the end product.
The production of solar dehydrators came up to address these issues by establishing a controlled, hygienic environment that utilizes solar energy more effectively. The technologies range from simple direct dehydrator to more complex indirect and mixed-mode technologies. The recent reviews, including the patent landscape analysis by Abas and Nyuk [8] and the innovation landscape study by Udomkun et al. [6], show a significant evaluation in this field. There is a tendency towards hybrid systems (e.g., solar-biomass, solar-electric) to operate all-year-round [3, 9], Integration of Internet of Things (IoT) to monitor and control in real-time are underway [7, 10], as revealed in research on optimized drying of certain crops (e.g., tomatoes) [4] and mangoes [11].
However, there still exists a critical gap between technological innovation and the widespread user adoption. Most of the solar dryer designs are technically oriented with less emphasis to the end-user needs, wants, and socio-economic limitation [6, 8]. This often results in systems that technically good systems, but practically not appropriate. They could be prohibitively costly, too complicated to use and maintain, not durable to local conditions, or ill adapted to the variety of crops a farmer might require to dry. This disconnect is one of the main reason why most good projects fail to achieve a significant impact on the ground.
Therefore, this research is very relevant since it tackles a topical problem in the country related to food and economic security directly by offering a sustainable solution to food preservation. It is novel and not over studied since it does not just intend to create another solar dehydrator, but it integrates the robust, user-driven QFD methodology with the current technological development in the hybridization technology, day night operational and Integration of Internet of Things (IoT) to create a product that fully addresses the needs of Pakistani farmers and rural households. This will make sure that the final design is efficient and acceptable as well as usable and affordable by the target market.
As an outcome of making the product user-need based at the beginning of its development, this paper seeks to come up with a solar dehydrator which has high adoption potential, which will make its contribution to reducing post-harvest losses, maximizing the income of farmers, and enhancing food security in Pakistan.

2. Methodology

A survey questionnaire was prepared to get a feedback from the solar dehydrator users in Pakistan about the preferences of a new design of solar food dehydrators. In total, the questionnaire comprised of eighteen (18) questions; ten (10) multiple-choice, one (1) ranking, and seven (7) open-ended questions. It was spread over the Internet, and the survey link was shared through social networks such as Facebook and WhatsApp. A total of 57 customers responded to the survey out of 70 targeted users of solar food dehydrators. The data obtained were assessed to determine the needs of the customers and then each need was rated on a scale of 1-5 with 1 denoting the least important needs and 5 denoting the most important needs. These customer needs, along with their relative importance and the corresponding technical requirements were used to create the House of Quality (HoQ) of the solar food dehydrator. The outcomes from the HoQ guided the concept generation stage, which was succeeded by concept selection. 3D solidworks model of the enhanced solar dehydrator design was created and finally the 3D model was fabricated.

3. Mission Statement

A Mission Statement provides the core function and purpose of the product, identify its primary and secondary target markets and finally defines the product objectives and assumptions. In the case of the solar food dehydrator, the mission statement correlates with the solution to the problems of food preservation in the area by providing an energy-efficient, hybrid-powered, and IoT-enabled drying device. Table 1 contains the mission statement of the solar food dehydrator.

Table 1: Mission statement for the Solar Food Dehydrator

Product Description	Solar Dehydrator with basic and advanced Features
Key main objectives	• Target at least 40% reduction in post-harvest losses in selected fruits • Achieving energy efficiency improvement over traditional dryers • Temperature and Humidity Monitoring • All weather working Facility • Affordable cost for small-scale farmers and home users
Primary Market	• Smallholder farmers • Rural households involved in fruit and vegetable drying • Agricultural cooperatives
Secondary Market	• Local fruit vendors and small-scale food processors • NGOs and public health nutrition programs • Emergency food preservation operations in remote areas
Product Assumptions	• Works in both sunny and cloudy conditions (hybrid power) • Food-safe materials for drying trays and chamber surfaces • Smart controls for real-time temperature and humidity display • Modular design for flexibility in fruit size and type • Minimal maintenance with durable components
Stakeholders	• End users (farmers, processors, households) • Engineering design and prototyping team • Fabrication workshop or local manufacturers • Government/agricultural support programs • Distributors and NGOs promoting sustainable Agri-tech solutions

4. Identifying Customer Needs and establishing their Relative Importance

The aim of this phase is to determine customer needs and requirements and to effectively communicate to the product design and development team. The essence of this strategy is to create a good flow of quality information between the product developers and the targeted customers. It is founded on the fact that the designers of the product directly interact with the customers and also experience the use environment of the product. The information collected based on the survey questionnaire distributed is compiled into the voice of customer (VOC), which is then converted into a specific customer needs. These voice of customer (VOC) can also be termed as customer wants, preferences, choices, wishes, expectations and requirements. These customer needs are represented as "WHATs" in the House of Quality (HoQ) matrix, which is the basis and the most vital stage of the QFD process. Once the customer needs have been identified, their relative importance was determined to calculate the weighted average of the relationship matrix in the HoQ. Table 2 shows the customer needs and their relative importance value as obtained through customer feedback and were rated on a scale of 1 to 5.

5. Defining Technical Requirements

The next stage in the QFD process is to identify a list of relevant technical requirements, which can meet the identified customer needs. Such requirements transform customer needs into quantifiable terms with specifications on how the design will react to each need. The technical requirements should be measurable so as to make sure that needs of the customers are met appropriately. Every need of the customer is linked to at least one technical requirement. Technical requirements can also be called engineering characteristics, quality attributes, design specifications and voice of the company. The technical requirements (HOWs) that will respond to the identified customer needs are listed in Table 3.

Table 2: Customer Needs and their relative importance

No.	Customer Needs	Relative Importance (1–5)
1	The dehydrator dry multiple fruits at a time.	3.9
2	The dehydrator operate under various weather conditions.	5
3	The dehydrator dry fruits quickly.	4.9
4	The dehydrator provide safe drying operation for fruits.	4.7
5	The dehydrator allow users to monitor and control Temperature and Humidity.	4.5
6	The dehydrator provide heat control.	4.9
7	The dehydrator operate on hybrid energy.	4.3
8	The dehydrator support smart connectivity features.	4

Table 3: Target Specs, Final Specs, their units and values

Specs No.	Need No.	Target Specs	Final Specs	Units	Value
1	1,3,4	Multiple trays	Adjustable multiple trays	list	3
2	2,4,7	DC heater	DC heater power	watt	<200
3	2,4,7	AC heater	AC heater power	watt	<400
4	2,4	Battery	Li-ion battery	kwh	>1.2
5	3,7	Uniform airflow	Axial airflow	m/s	<1.5
6	3,7	Exhaust fan	Exhaust airflow	m^3/h	<80
7	4	Corrosion resistant chamber	Stainless steel 304 mesh trays	mm	1.2
8	5,6,8	Temperature sensor	SHT21 temperature sensor	°C	±0.5
9	5,6,8	Humidity sensor	DHT22 humidity sensor	%RH	±2
10	5,6	Real-time display of T&H	LCD T&H display	inch	<3.5

11	4,6	Low thermal conductivity insulation	Glass wool insulation	W/m·K	<0.04
12	4,6	low-noise servo motor	DC servo motor	watt	<60
13	2,3,4,7	AC + DC switching	AC + DC hybrid switching	watt	>1000
14	5,8	Real-time PID control	ESP8266 microcontroller	MHz	240
15	8	Remote data storage & logging	Cloud data logging	min	<1
16	5,8	Remote monitoring & alerts	Android app with live T&H	°C&%RH	list

6. Building House of Quality for solar dehydrator

A House of Quality (HoQ) is built using the above data (customer needs, their relative importance, and technical requirements). It is one of the most important elements of the QFD methodology, that can be used as a framework to assess the effectiveness of the technical requirements in meeting the customer needs [12]. Figure 1 represents the HoQ. The customer needs (WHATs) are presented in the third column of the left, and the technical requirements (HOWs) are located in the second row of the top. The second column shows the relative importance of each customer need. The succeeding cells indicate the relationships amongst the customer needs and the technical requirements which may be from no relationship to weak, medium, and strong relationship. They have weights of 0, 1, 5 and 10 respectively. The blank cells mean no relationship. This interrelationship matrix is aimed at converting customer needs to technical requirements. It operates as a two-dimensional grid which connects all customer requirements with associated technical requirement. After the analysis, the top six prioritized features were obtained as follows: Temperature and humidity sensor for monitoring and control, dual input power to operate in all seasons, insulation material for precise control of heat, forced convection air flow and exhaust fans, microcontroller based IoT, DC and AC heaters for function in all weather conditions. The roof of HoQ is the correlations between the technical requirements themselves. The plus (+) sign represents positive correlation, meaning that improving a particular technical requirement enhances another technical requirement of the corresponding cells, and the minus (-) sign represents negative correlation, implying that improving a particular technical requirement causes deterioration in the technical requirement of the corresponding cells. Figure 1 also indicates the symbols associated with the interrelationship analysis and correlation analysis.

7. Ranking of technical requirements

This phase represents the final element of the House of Quality (HoQ). It is derived from the weighted average of the technical requirements calculated within the interrelationship matrix of the HoQ. This section summarizes the key conclusions drawn from the data presented throughout the entire matrix, providing a clear overview of how each technical requirement contributes to meeting customer needs. It assigns a priority score to each technical requirement and ranks them accordingly. The ranking of these technical requirements is displayed within the HoQ matrix.

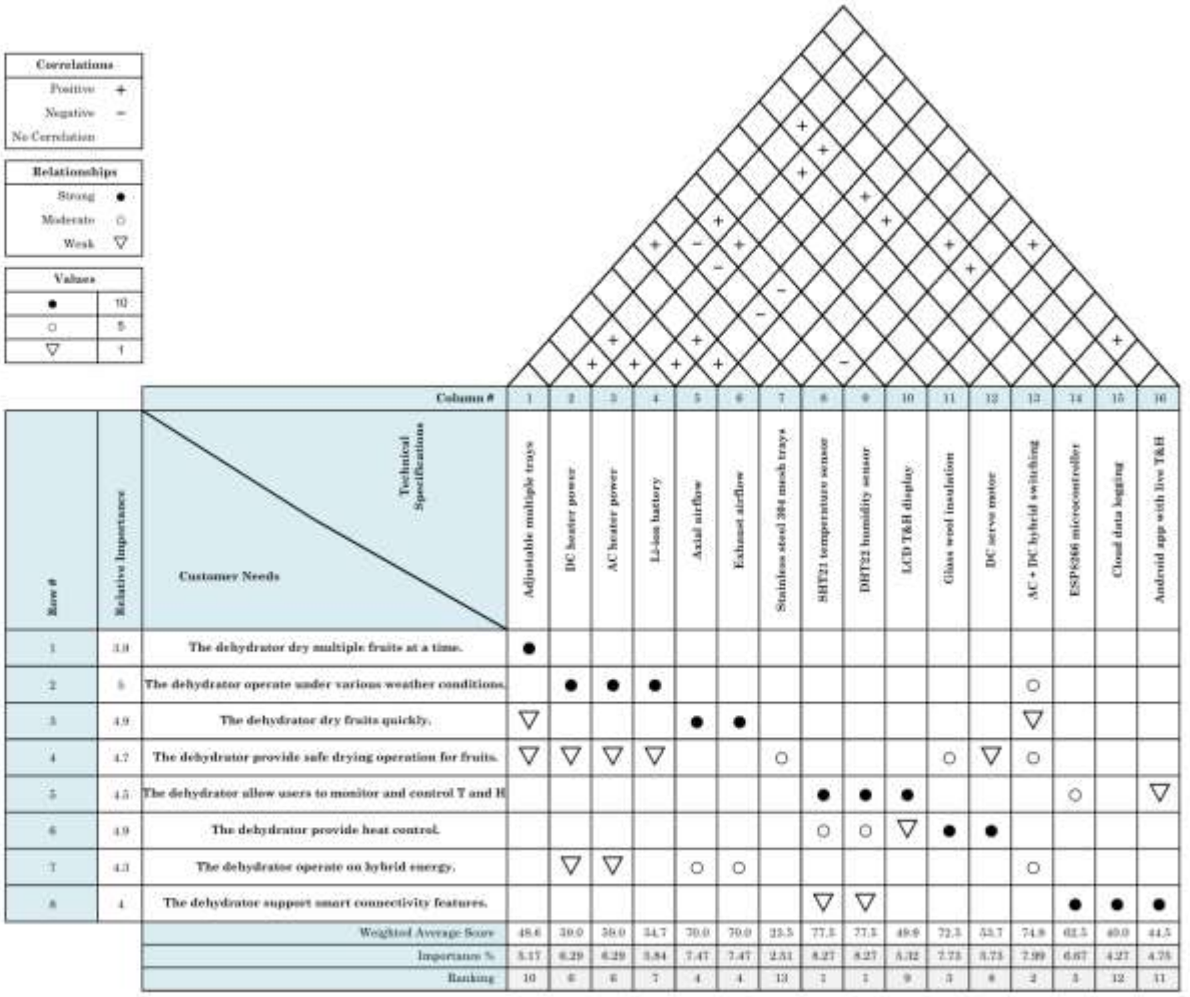

Figure 1: House of Quality

8. Outcome from House of Quality

By summing the weighted scores across all customer needs, the technical requirements were systematically ranked according to their relative importance. The results show that the highest priority is given to the integration SHT21 temperature and DHT22 humidity sensors to enable accurate monitoring and control of the drying process. This is followed by the provision AC+DC hybrid switching to ensure reliable operation under all seasonal and weather conditions. The selection of high-performance insulation materials also emerged as a requirement for achieving precise heat control and improving energy efficiency. Furthermore, the incorporation of a forced-convection axial airflow system with exhaust fans is essential to enhance heat and mass transfer during drying. The analysis also highlights the importance of ESP8266 microcontroller-based IoT system for intelligent control and monitoring. In addition, the use of both DC and AC heating elements is prioritized to support all-season operation while maintaining safe and high-quality food drying. Finally, the ability to accommodate and process multiple types of food was identified as an important technical requirement, contributing to the overall versatility of the system.

9. Concept generation

Solar food dehydrator concepts are generated using the input from the HOQ. Three concepts of the improved solar food dehydrator are generated. Based on the input from end users of solar food dehydrator, features such as *function reliably in all weather conditions, operate on hybrid energy, precise heat control, IoT integration, temperature and humidity monitoring and control* are included in the concepts. **Concept A** shown in Figure 2 has the features of small flat-plate solar collector, forced convection air flow with exhaust blower, microcontroller with cloud connectivity for IoT features, alternate frame for battery and wires, exhaust fan on the top and no wheels for portability.

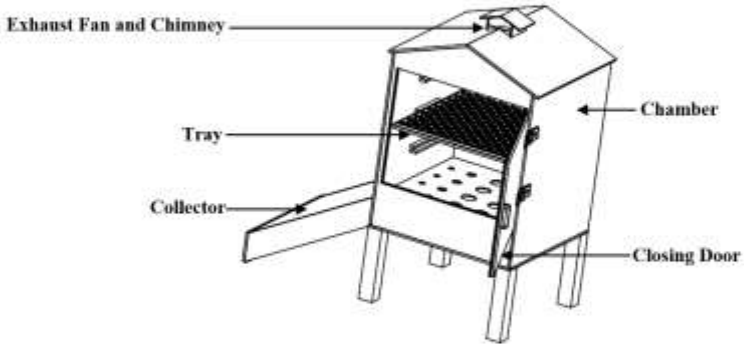

Figure 2: Concept A

Concept B shown in Figure 3 has the features of a long flat-plate solar collector, forced convection air flow with exhaust blower, microcontroller with cloud connectivity for IoT features, multiple trays, alternate frame for battery and wires, blower inside the chamber, single exhaust fan on the top with different design and no wheels for portability.

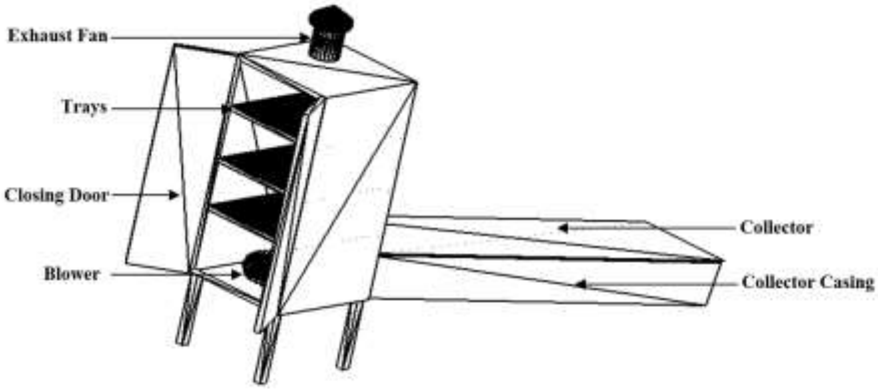

Figure 3: Concept B

Concept C shown in Figure 4 has the features of includes a flat-plate solar collector, forced convection air flow with multiple exhaust fans, microcontroller with cloud connectivity for IoT features, multiple trays, same frame for battery (Down the Chamber), multiple blowers in entrance of solar collector, multiple exhaust fans on the upper side of the chamber and wheels for portability.

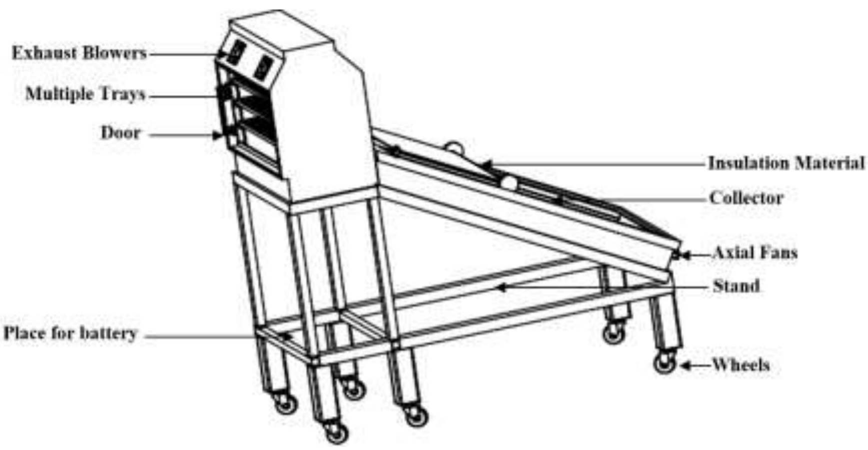

Figure 4: Concept C

9. Concept Selection

The final concept was chosen based on the Pugh concept evaluation criteria outlined in Table 4. In which all criteria are equally weighted. The alternative concepts are scored relative to the reference concept. Instead of point scoring, +, 0, - are used for "better than", "same as" and "worse than" the reference. The total score is determined by counting the number of +, -, and 0 for each concept [13]. According to the results of the evaluation matrix, Concept C emerged as the most suitable option. This selected concept was then modeled using solidworks 2024. The material specifications of the finalized concept are detailed in Table 5. The 3D modeled concept is then fabricated as shown in Figure 5 and 6.

Table 4: Evaluation Matrix for Concept Selection

Criteria	Concepts		
	A (Datum)	B	C
Drying Efficiency		+	+
Cost		-	-
Easy to Manufacture		-	0
Durability		0	+
Safety		0	0
User Friendliness		0	+
Portability		+	+
Sum of "+"		2	4
Sum of "-"		2	1
Sum of "0"		3	2
Net Score		0	3
Ranking		2	1

Table 5: Material Specification of the Concept Selected

Components	Material	Justification
Structural Material	Shutter Board	Because of its low thermal conductivity
Solar Collector	Mild Steel	Because of its good thermal conductivity
Cover	5mm Transparent Glass	To maximize the transmission of solar radiation
Trays	Stainless Steel 2mm thick	To ensure food safety and corrosion resistance
Frame/Stand	Steel	Because of its high structural strength and rigidity

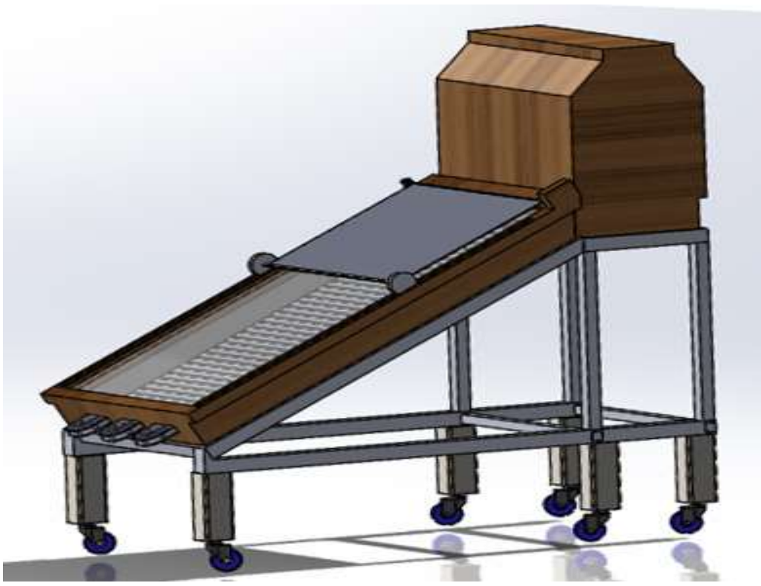

Figure 5: 3D Model of Solar Food Dehydrator

Figure 6: Fabricated Model of Solar Food Dehydrator

10. Discussion and Conclusion

The Solar Food Dehydrator was designed and developed using the Quality Function Deployment (QFD) approach. Customer requirements, or the Voice of the Customer (VOC), were gathered through survey and then translated into specific customer needs. These needs, along with their relative importance, were identified and used to construct the House of Quality (HoQ) for the product. Based on this analysis, the final design specifications of the mobile phone were determined.

The features of final product included a modular, hybrid solar food dehydrator capable of drying multiple fruit types in all-weather conditions efficiently. So, the farmers can preserve food throughout the year, regardless of season and weather variations. The system provides precise control of the collector's heat, ensuring optimal drying conditions which improve food quality by preventing nutrient loss, over drying and preserving the color, flavor and texture of the dried foods. It operates on both AC and DC power sources offering greater energy flexibility and making it suitable for use in rural off-grid areas as well as in urban settings with stable electricity. The model also incorporates basic IoT capabilities of real-time tracking of temperature and humidity. This will allow the users to monitor and manage the drying process without being physically present, and this will also ensuring good quality of the products. Compared to traditional open sun drying and other types of solar dryers, this system significantly reduces drying time which enhance total drying efficiency. As a results, this system will enable farmers and other processors to dry more amounts of foods within a shorter period, making the process more cost-effective, sustainable and reliable for post-harvest preservation.

In conclusion, QFD is an extremely logical tool of creating new products that meet the needs of customers. It is also a useful planning tool on how to enhance the current products with consideration to the customer feedback incorporated into the design process. It is also worth noticing that the survey questionnaire in the study was sent among a number of food dehydrator users in Pakistan. To conduct a research, in the future, a more representative sample of users of solar food dehydrators can be used to obtain more comprehensive information. Also, some other data collection techniques like one-on-one interviews, focus groups, and observation of product usage may be used to get a more detailed feedback on customers.

11. REFERENCES

"H. Ullah and A. Ali, “Design and Development of Mobile Phone Using Quality Function Deployment,” Int. J. Eng. Mater. Manuf., vol. 2, issue no. 1, pp. 1–10, Mar. 2017, doi: 10.26776/ijemm.02.01.2017.01.".

"L.-X. Mao, J. Lan, A. Chen, H. Shi, and H.-C. Liu, “New Approach for Quality Function Deployment Based on Linguistic Distribution Assessments and CRITIC Method,” Mathematics, vol. 13, issue no. 2, pp. 240–256, Jan. 2025, doi: 10.3390/math13020240.".

"Y. Cheng, X. Liu, Y. Zhou, Q. Zhang, and L. Wan, “An improved interval-grey-probability QFD method for prioritizing engineering characteristics under vague environment,” Qual. Reliab. Eng. Int., vol. 41, issue no. 1, pp. 564–588, Feb. 2025, doi: 10.1002/qre.3674".

"A. E. Elwakeel, A. A. Tayoush Oraiath, M. A. Gameh, A. S. Eissa, S. F. Mahmoud, M. H. Eid, A. Moussa, M. B. Mostafa, M. F. Taha, S. A. T. Abulmeaty and A. A. Tantawy, “Quality evaluation of dried tomato fruit and optimization of drying conditions using a modified solar dryer integrated with an automatic solar collector tracker,” Sci. Rep., vol. 15, issue no. 1, article no. 7659, Mar. 2025, doi: 10.1038/s41598-0".

"FAO, Ed., Moving forward on food loss and waste reduction. in The state of food and agriculture, no. 2019. Rome: Food and Agriculture Organization of the United Nations, 2019".

"P. Udomkun, M. Sartas, S. Romuli, T. Wossen, S. Schock , E. Njukwe, B. Mahayothee, B. Vanlauwe and J. Müller, “Review of solar dryers for agricultural products in Asia and Africa: An innovation landscape approach,” J. Environ. Manage., vol. 268, article no. 110730, Aug. 2020, doi: 10.1016/j.jenvman.2020.110730".

"J. N. Nair, V. D. Raju, and T. Nagadurga, “Solar dryers for Food Preservation: An In-Depth Review of Design, Fabrication and Barriers,” Food Eng. Rev., vol. 17, issue no. 1, pp. 104–126, Mar. 2025, doi: 10.1007/s12393-024-09389-z".

"P. E. Abas and F. K. Nyuk, “Patent landscape review on solar food dryer: technology updates,” Int. J. Ambient Energy, vol. 46, issue no 1, article no. 2503274, Dec. 2025, doi: 10.1080/01430750.2025.2503274.".

"S. Edakkoth and K. K. V. V., “A Review on Hybrid Solar-Biomass Dryer for food processing integrated with Sun Tracking System,” Proceedings of the International Conference on Systems, Energy and Environment 2022 (ICSEE 2022), doi: 10.2139/ssrn.4294987.".

"C. N. Sakhale, S. A. Dhale, A. V. Harde, S. D. Shelare, S. Sharma, A. Kumar, S. Kumar, Y. S. Bisht, M. Abbas, “Designing and analyses of mathematical models for sustainable agriculture in India: comparative study on the universal desiccant solar dryer and trapezoidal vertical solar dryer,” Environ. Dev. and Sustain., vol. 27, no. 1, pp. 1–34, Jan. 2025, doi: 10.1007/s106".

"M. C. García-Muñoz, Y. Romero-Barrera, L. F. Amortegui-Sánchez, E. Villagrán, J. J. Espitia-González, and K. J. Pedroza-Berrío, “Solar Dehydration of Mangoes as an Alternative for System Sustainability, Food and Nutritional Security, and Energy Transition", Sustainability, vol. 17, issue no. 12, article no. 5313, Jun. 2025, doi: 10.3390/su17125313".

"J. Righter, N. Washuta, and D. Ragan, “Application of a House of Quality Intervention in an Engineering Capstone Design Course,” in 2025 ASEE Southeast Conference Proceedings, Mississippi State University, Mississippi: ASEE Conferences, Mar. 2025, article no. 45840".

"K. T. Ulrich and S. D. Eppinger, "Product Design and Development Fifth Edition," 2011, Publisher: McGraw-Hill, ISBN: 0071232737".