ENERGY ELEMENTS

Scientific and Technological Journal for Researchers and Engineers

Issue 1, 2026

Energy. Chemistry. Ecology. IT

ISSN: 3093-9399

ENERGY ELEMENTS

Scientific and Technological Journal for Researchers and Engineers

ELEMENTS is a journal that unites the key components of progress: science, technology, energy, and ecology. Each article in the publication is a distinct “element” contributing to the creation of a sustainable and innovative future.

Sections of the Journal

Coverage of the latest research and technologies in traditional and renewable energy, energy efficiency, and sustainable energy supply

Publication of materials on fundamental and applied research in chemistry and technologies aimed at advancing science and industry

Articles devoted to environmental sustainability, environmental protection, and innovative approaches to sustainable development technologies

Publication of research in digital technologies, programming, artificial intelligence, and their applications in science and industry

Publication Frequency: Quarterly (with special issues)
Language of Publication: English
Distribution Format: Electronic (online)
Date of First Issue: 2026
Address: 25, Istiqbal street, Tashkent, Uzbekistan, 100047

Registered with the Inspectorate for Supervision in the Field of Informatization and Telecommunications under the Ministry of Digital Technologies of the Republic of Uzbekistan. Certificate of Registration No. 1712647, issued on July 15, 2026.

Contacts

www.elementsjournal.uz
+998900668557
info@elementsjournal.uz
@elementsjournal
Energy Elements Journal
@elements_journal

Energy. Chemistry. Ecology. IT

ENERGY ELEMENTS

Scientific and Technological Journal for Researchers and Engineers

Table of Contents

I Energy Perspectives

II Applied Chemistry

III Green Solutions

IV IT and Digital Transformation

5
Editorial Board

I

6
Analysis of Sulfur Impact on the Oxidation of Petroleum Residues
Saydakhmedov Elyorbek Egamberdiyevich

13
Ultra-Deep Geothermal Drilling: Tapping the Earth's Core for Energy
Review by ELEMENTS

II

15
Effect of Impregnating Agents on The Porosity and Sorption Capacity of Carbon Blocks
Mussatay Yessengeldi Amangeldiyuly

23
An Appropriate Method for Processing Low-Quality Fluorite Concentrate and Fluorine-Containing Waste of Aluminum Production
Rajabov Shukhrat Kholmurodovich

32
Artificial Intelligence in Chemistry: A New Catalyst for Progress
Review by ELEMENTS

III

33
Integrating Lean Management Practices for Enhancing Sustainability in Solar Energy Sector
Muhammad Usman Ali, Yasir Muhammad, Ehtasham Mustafa, Shahzad Akbar

Energy. Chemistry. Ecology. IT

July 2026 3

ENERGY ELEMENTS

Scientific and Technological Journal for Researchers and Engineers

Table of Contents

I Energy Perspectives

II Applied Chemistry

III Green Solutions

IV IT and Digital Transformation

IV

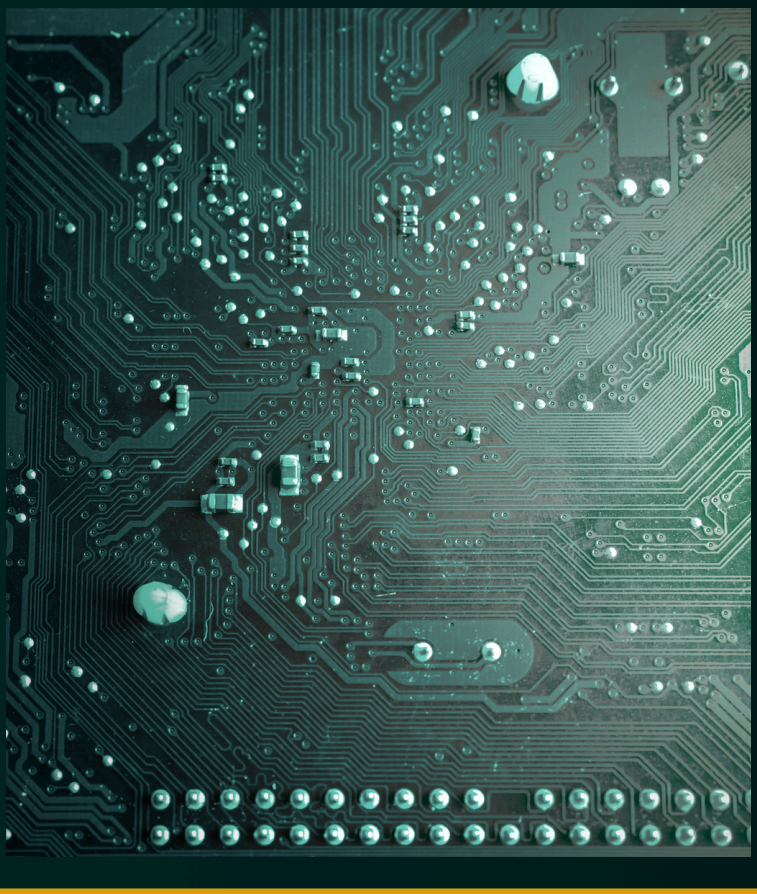
59
Exploring the Uncertainties and Ambiguities in Accepting Wind Power Projects: Evidence From Pakistan
Faiz Jalil, Rafiq Mansoor

74
Agrivoltaics: A Dual-Use Solution for Food and Energy
Review by ELEMENTS

76
Multi-Modal Ensemble Learning Architecture for Labor Market's Digital Transformation
Assylbek Gizatov, Nurtas Zhaksybayev, Alibi Jangeldin

91
Advancing Sustainable Construction Management through BIM Practices and Their Impact on MEP Project Efficiency
Muhammad Usman Ali, Javed Ahmad Khan Tipu, Eman N. Shaqour, Faiz Jalil, Malik Imran Mujeeb, Usman Aftab

119
Artificial Intelligence in Orbit: The Φsat-2 Mission and the Transformation of Satellite Technologies
Review by ELEMENTS



July 2026 4

Energy. Chemistry. Ecology. IT

ENERGY ELEMENTS
Scientific and Technological Journal for Researchers and Engineers

Editorial Board

Igamberdi Saydakmedov
DSc, Professor
Honored Worker of Industry of the Republic of Uzbekistan, Tashkent Institute of Chemical Technology, Tashkent, Uzbekistan
Editor-in-Chief

Vugar Abdullaev
DSc, Associate Professor
Oil Gas Scientific Research Project Institute, SOCAR, Baku, Azerbaijan
Deputy Editor-in-Chief

Zoyakhon Saydakhmedova
DSc
JSC "Uzbekneftegaz", Tashkent, Uzbekistan
Editorial Board Member

Zakirkhodja Tadjikhodjaev
DSc, Professor
Tashkent Chemical-Technological Institute, Tashkent, Uzbekistan
Editorial Board Member

Gensheng Li
PhD, Professor
China University of Petroleum, Beijing, China
Editorial Board Member

Vladimir Vishnyakov
DSc, Professor
University of Huddersfield, Huddersfield, United Kingdom
Editorial Board Member

Fikret Aliyev
DSc, Professor
Institute of Applied Mathematics, Baku State University, Baku, Azerbaijan
Editorial Board Member

Shie-Ming Peng
PhD, Distinguished Chair Professor
National Taiwan University, Taipei, Taiwan, China
Editorial Board Member

Vagif Guliyev
DSc, Professor
Institute of Applied Mathematics, Baku State University, Baku, Azerbaijan
Editorial Board Member

Wen-Zhen Wang
PhD, Professor
Xi'an University of Petroleum, Shaanxi Province, China
Editorial Board Member

Fahraddin Kadirov
DSc, Professor
Institute of Oil and Gas, Ministry of Science and Education of Azerbaijan, Baku
Editorial Board Member

ENERGY ELEMENTS

ENERGY PERSPECTIVES

SECTION 1

Issue 1, 2026 | TABLE OF CONTENTS

Strengthening the energy sector through knowledge, technology, and vision.

— Energy ELEMENTS

P 7

ANALYSIS OF SULFUR IMPACT ON THE OXIDATION OF PETROLEUM RESIDUES

Saydakhmedov Elyorbek Egamberdiyevich

www.elementsjournal.uz @elements_journal info@elementsjournal.uz

ANALYSIS OF SULFUR IMPACT ON THE OXIDATION OF PETROLEUM RESIDUES

Saydakhmedov Elyorbek Egamberdiyevich
DSc, professor, Deputy Chairman of the Board, JSC «O'ZLITINEFTGAZ», Tashkent, Uzbekistan
e-mail: e.saydakhmedov@liting.uz

Abstract

This study investigates the effect of introducing elemental sulfur into the oxidation feedstock during the production of oxidized petroleum bitumen. Vacuum residue from fuel oil distillation and granular sulfur were used as the base materials. Oxidation experiments were carried out at 230 °C with controlled air flow, varying the sulfur concentration from 0 % to 5 %. The results showed that introducing sulfur in optimal amounts (up to 2 %) significantly improves the physical and mechanical properties of the resulting sulfur–bitumen binders — increasing penetration and ductility and lowering brittleness temperature — compared to conventional oxidized bitumen. Higher sulfur concentrations (> 5 %) lead to process inefficiency and deterioration of binder properties. The findings confirm that sulfur additives can be effectively used to intensify the oxidation process, enhance product quality, and optimize production parameters for bitumen manufacturing.

Keywords

oil bitumen, sulfur, needle penetration, tar, oxidation process, softening point

1. Introduction

The existing technology for the production of oxidized bitumen, due to the often changing composition of petroleum feedstock for processing and the unstable quality of the feedstock for the oxidation process, causes difficulties in obtaining bitumen of the required quality. Therefore, directional regulation of the properties of the prepared raw materials for the oxidation process is an urgent task.

Modern trends in the development of science and technology associate the solution of this problem with the development of effective methods for influencing the properties of the initial raw materials used in the production of commercial petroleum bitumen, optimizing the technological parameters of the process for their production and adjusting the properties of oxidized bitumen in various ways [1]. In the production of oxidized bitumen, an effective way

of such exposure is to control the properties of the oxidation feedstock using various additives.

We have studied elemental sulfur as such an additive, which is available in huge quantities at oil refineries and gas refineries as by-products. Her choice is because the use of elemental sulfur as a modifier to oil bitumen is currently expanding in the world in order to improve their physical and mechanical properties [2]. The role of elemental sulfur is to change the structure of petroleum bitumen due to reaction reactions with unsaturated components and compounds of petroleum bitumen with the formation of sulfur-containing compounds and supramolecular structures [3]. This circumstance should certainly affect the results of the oxidation of raw materials with the addition of sulfur.

2. Methodology

The vacuum distillation tar of fuel oil of the Ferghana Oil Refinery was chosen as the object of study, the main physicochemical properties of which are presented in *Table 1*. Granular sulfur was used as elemental sulfur, obtained as a by-product in a process unit for hydrodesulfurization of a fraction of diesel fuel (*Table 2*).

Samples of tar with the addition of sulfur in an amount of up to 5% to the tar were prepared as raw materials.

The prepared tar and sulfur samples were oxidized in a 5-liter laboratory unit equipped with a source for air circulation, a thermometer, and a refrigerator for cooling condensate vapor. The charge of oxidation feed was 2 kg.

Oxidation was carried out at a temperature of 230 °C with constant air circulation in the amount of 3 l/min per 1 kg of raw material until the softening point was reached to values that meet the requirements of the current standard.

Table 1. Basic physical and chemical properties of tar

№	Properties	Values
1.	Density , kg/m^3	984
2.	Conventional viscosity at 80°C, sec	16
3.	Flash point, °C	250
4.	Sulfur content,% wt.	2,77
5.	Softening temperature, °C	21
6.	Coking ability , %	7,83
7.	The composition,% wt.	
	oils, including:	60,6
	paraffin-naphthenic hydrocarbons	22,2
	aromatic hydrocarbons	32,7
	resin	37,5
	asphaltenes	6,7

Table 2. Main characteristics of technical sulfur

№	Properties	Temperature °C	
		20	150
1.	Density , kg/m^3	2050	1760
2.	Color	yellow	yellow
3.	Compressive strength, MPa	12 - 22	-
4.	Melting point, °C	119	-
5.	Viscosity, Pa·s	-	0,1
6.	Boiling point, °C	444,8	-
7.	Heat capacity, kJ / kg	0,7	1,84
8.	The degree of purity, %	99,9	

The properties of petroleum bitumen were determined according to the methods adopted for testing viscous road bitumen. The main indicators of the process and physico-mechanical properties of the obtained oxidized bitumen are presented in *Table 3*.

3. Result

It can be seen from the table that the addition of sulfur to the oxidation feedstock, the tar of vacuum distillation of fuel oil, leads to a change in the basic properties of the obtained oxidized bitumen. The resulting oxidized bitumen undergoes mixed changes. At certain optimal sulfur concentrations in the oxidation feedstock, the obtained bitumen possesses higher physical-mechanical and rheological properties compared to bitumen obtained by oxidation of tar only.

Table 3. Key indicators of tar oxidation with the addition of elemental sulfur

№	Indicators	GOST 22245-90 for BND 60/90	Tar sulfur content				
			0	0,5	1	2	5
1.	Needle penetration depth, 0,1 mm: at 25°C at 0°C	61-90 no less 20	81 23	83 24	88 25	84 20	78 18
2.	Elongation, sm: at 25 °C at 0 °C	no less 55 no less 3,5	58 4,2	62 4,5	64 4,3	59 3,8	51 3,4
3.	Softening point, °C	no less 47	49	49,5	49	49	49,5
4.	Fragility temperature, °C	not higher -15	-17	-20	-21	-17	-14
5.	Ductility interval, °C	-	66	69,5	70	66	63,5
6.	Structure coefficient	-	1,14	1,12	1,09	1,12	1,24
7.	Change in softening temperature after heating, °C	no more than 5	3	2	2	2	3
8.	Sulfur content,%wt.	-	2,2	2,7	3,2	4,2	6,9
9.	Oxidation time, hour	-	10	8	8	8	9
10.	The sum of gases and losses, %	-	2,8	2,5	2,3	3,1	3,8

A study of the basic standard properties of oxidized sulfur-bitumen binders showed that the addition of sulfur to the oxidation feedstock within 1% determines the production of bitumen with improved characteristics. The elongation of bitumen increases from 58 to 64 cm, the penetration of oxidized bitumen increases to 88 units, then drops to 78, that is, the hardness of bitumen increases. The brittleness temperature of oxidized bitumen showed an extreme change in the amount of sulfur - first the temperature decreases, and then when the sulfur content is more than 2% it rises to minus 14 ° C.

When the sulfur concentration in the tar is 5% or more, such indicators of bitumen as penetration, ductility, and the brittleness temperature of the oxidized product do not meet the requirements of the current standard.

In addition, at a sulfur concentration of more than 5%, coke is formed on the walls of the reactor, which indicates a decrease in the efficiency of the process. Obviously, the use of sulfur as an additive to oxidation feedstock leads to an increase in the degree of aromaticity of reaction products, an increase in the number of resins and asphaltenes in the reaction mixture, the subsequent interaction of which with sulfur leads to the formation of carbonaceous formations on the walls of the reactor.

The softening point after warming, which characterizes the heat resistance of oxidized bitumen from the addition of sulfur, decreases slightly. This can be explained by the oxidizing effect of sulfur, which, when entering into a dehydrogenation reaction with hydrocarbons, replaces hydrogen atoms and promotes the growth of molecular weight. Dehydrogenated chains undergo cyclization, resulting in an increase in the number of structure-forming complexes such as asphaltenes and other high molecular weight compounds. This, in turn, is accompanied by a change in the group composition of tar: the content of resins and asphaltenes increases, while the content of paraffin-naphthenic hydrocarbons decreases.

It should be noted that the introduction of technical sulfur in the oxidation tar in an amount of up to 2% wt. allowed to significantly intensify the process of its oxidation. At the same time, the duration of tar oxidation at an optimum sulfur content is reduced by 20%. This is important in the direction of reducing the economic constraints of bitumen producing enterprises and increasing the resources of the initial raw materials for the production of oil bitumen with controlled quality characteristics.

4. Conclusion

Thus, the involvement of sulfur in the composition of the oxidation feedstock in the production of oxidized bitumen can be considered one of the most effective technological approaches to intensifying the oxidation process. The introduction of elemental sulfur at optimal concentrations not only accelerates the reaction and improves process efficiency but also leads to the formation of sulfur–bitumen binders with enhanced physical and mechanical characteristics compared to conventional oxidized bitumen obtained from petroleum residues without additives. These improvements include increased ductility and penetration, better structural stability, and a lower brittleness temperature, which are critical for ensuring the operational reliability of bituminous materials in road construction.

Furthermore, this method of feedstock activation contributes to reducing the duration of the oxidation stage and increasing the yield of high-quality product, thereby optimizing resource utilization at refineries. In addition to technological advantages, the use of elemental sulfur — a widely available by-product of oil and gas processing — provides an economically viable and environmentally beneficial solution. Consequently, sulfur modification of oxidation feedstock represents a promising direction for expanding production capacity, improving product quality, and supporting sustainable development in the bitumen industry.

References:

1. Kutyin, Yu.A. Bitumen technologies and quality of bitumen / Yu.A. Kutyin, E.G. Telyashev, G.N. Viktorova // Chemistry and technology of fuels and oils. - 2006. - No. 2. - P. 10-12.

2. Ludwig, A.C. Plasticited Suhlfur Asphalt Replacements / A.C. Ludwig // Industrial and Engineering Chemistry Product Research and Development, 1982. - V.21. – P. 65-68.

3. Groshin, A.P. The structure and properties of the modified sulfur binder / A.P. Groshin, Y.V. Korolev, Y.G. Kalinkin // Construction Materials – 2005. - № 7. - P. 6-9.

MINI-REVIEW BY ELEMENTS

Ultra-Deep Geothermal Drilling: Tapping the Earth's Core for Energy

The global energy sector is rapidly shifting toward decarbonization and seeking sources that can deliver **stable baseload power, low emissions, and global scalability**. One of the most promising solutions emerging on the horizon is **ultra-deep geothermal energy** — a technology that enables access to the Earth's thermal resources at depths of up to 20 km, where temperatures can reach 400–500 °C [1, 2].

The key technological breakthrough lies in the **drilling method**. Instead of conventional mechanical drill bits, **millimeter-wave (mmWave) drilling** uses gyrotrons to vaporize rock without physical contact. This allows operators to penetrate hard basaltic and granitic formations faster and more efficiently, significantly reducing equipment wear and overcoming the depth limitations of traditional geothermal systems [3].

One of the most notable players in this field, **Quaise Energy**, announced **its first successful field tests** of mmWave drilling to a depth of around 100 meters in 2025 [4]. This marks an important transition from laboratory-scale demonstrations to early industrial deployment. The development is also supported by major research and governmental organizations, including **ARPA-E** and the **MIT Energy Initiative**, which are building technology roadmaps and deployment strategies for the coming decade [2, 3].

The **advantages of superhot geothermal energy** include:

- stable baseload power generation independent of weather conditions,
- compact land footprint,
- minimal carbon emissions,
- the potential to repurpose existing coal and gas power plants into geothermal facilities.

However, the technology is still in its demonstration phase. Key challenges remain, including material durability under extreme temperatures, casing integrity, efficient removal of drilling byproducts, and the high cost of early pilot wells [2, 4, 5]. Nevertheless, according to leading research institutions, solutions like ultra-deep geothermal drilling have the potential to **significantly strengthen the resilience of the global energy system** in the long term [1–5].

[1] CATF. Superhot Rock Geothermal, 2021–2025.

[2] ARPA-E. Superhot Rock Energy Technology Roadmap, 2025.

[3] MIT Energy Initiative. Superhot Geothermal Systems, 2023.

[4] Quaise Energy. Field Test Reports and Press Releases, 2025.

[5] Houston Chronicle; WSJ. Quaise Demonstration Milestones, 2025.

ENERGY ELEMENTS

APPLIED CHEMISTRY

SECTION 2

Issue 1, 2026 | TABLE OF CONTENTS

Transforming raw materials into solutions for a sustainable future.

— Energy ELEMENTS

P 15

EFFECT OF IMPREGNATING AGENTS ON THE POROSITY AND SORPTION CAPACITY OF CARBON BLOCKS

Y.A. Mussatay

P 23

AN APPROPRIATE METHOD FOR PROCESSING LOW-QUALITY FLUORITE CONCENTRATE AND FLUORINE-CONTAINING WASTE OF ALUMINUM PRODUCTION

Rajabov Shukhrat Kholmurodovich

www.elementsjournal.uz @elements_journal info@elementsjournal.uz

EFFECT OF IMPREGNATING AGENTS ON THE POROSITY AND SORPTION CAPACITY OF CARBON BLOCKS

Mussatay Yessengeldi Amangeldiyuly
Al-Farabi Kazakh National University, Almaty, Kazakhstan
e-mail: esenshon104@mail.ru

Abstract

This study presents the results of thermochemical synthesis and functional modification of carbon–silicon sorbents derived from rice husks, intended for use as filtering materials with antiseptic properties. Carbonization was carried out in an inert gas atmosphere at temperatures ranging from 600 to 900 °C, followed by activation in a flow of carbon dioxide or water vapor. The resulting porous structures were characterized by a high specific surface area (up to 550 m^2/g) and a considerable micropore volume. Molecular iodine, chlorhexidine gluconate, and tannin were employed as impregnating agents. Experimental data confirmed the ability of the sorbent to absorb iodine vapors from both gaseous and liquid phases, with a saturation capacity of up to 259 mg/g. The influence of impregnation on the textural properties of the material was investigated: an increase in specific surface area and pore volume was observed upon the introduction of active components. BET analysis demonstrated a total micropore surface area of up to 551 m^2/g, confirming the efficiency of the modification for air purification purposes. The developed filtering monoblocks are promising for application in air disinfection systems within enclosed and sanitation-sensitive environments.

Keywords

Carbon–silicon sorbents, carbonization, activation, iodine, antiseptic activity, porous structure, filtering materials, rice husk, adsorption

1. Introduction

In the modern world, where air quality is becoming increasingly problematic due to urban development, industrial emissions, and other factors, ventilation systems play a key role in ensuring clean and healthy air. Atmospheric pollution poses serious threats to human health and contributes to the emergence of various respiratory diseases.

Carbon–silicon filters represent a class of materials capable not only of capturing the finest particulate pollutants but also of effectively neutralizing bacteria and viruses owing to their antibacterial properties. Bactericidal carbon–silicon filters hold the potential to

revolutionize ventilation systems by providing not only clean but also safe air for residents and workers in indoor environments.

Contaminated air contains a wide range of solid particles, harmful chemical gases, as well as bacteria, viruses, and other hazardous impurities. The impact of these pollutants on human health and ecosystems has been extensively studied, with evidence confirming their contribution to numerous diseases and increased premature mortality rates. Atmospheric air may contain a wide spectrum of hazardous gaseous impurities, including sulfur and nitrogen compounds (such as sulfur dioxide, SO_2; sulfate anions, SO_4^{2-}; nitrate anions, NO_3^-), carbon oxides (e.g., carbon monoxide, CO), formaldehyde (HCHO), and various volatile organic compounds (VOCs). In recent years, growing concern has also been raised about the spread of bacteria and viruses transmitted through airborne pathways. Consequently, the development of effective and safe air filters has become increasingly urgent [1–4].

Carbon–silicon filters are mainly produced from rice husk. To date, the production of sorbents from rice-processing waste has been developed primarily within the framework of husk utilization. Since rice floral bracts (husks) and straw contain significant amounts of amorphous silicon dioxide, these residues can serve as sources for various silicon-containing sorbents (such as diatomites, tripoli, and opoka) or for pyrogenic silica. According to the literature [5], defatted rice bran is capable of removing chromium, copper, and zinc ions from solutions, whereas rice husk can remove strontium, cadmium, nickel, lead, zinc, chromium, cobalt, and aluminum ions.

Sorbents derived from rice husk possess a unique ability to effectively adsorb radionuclides and heavy metals. In [6], sorption of rare earth metals from model solutions was also tested. In recent years, sorbents obtained from agricultural waste after physico-chemical processing have been proposed for use as oil sorbents. In particular, rice husk has attracted considerable attention as an oil sorbent [7]. The effectiveness of sorbents already developed from plant-based raw materials has proven to be fairly high.

Gas filtration and ventilation systems [8] represent an innovative solution in the field of exhaust gas treatment, ensuring efficient purification of air from harmful substances and pollutants. These systems are equipped with specialized filters designed to capture and neutralize various types of gases, including toxic and odorous components, thereby making the air safer and more suitable for breathing.

2. Methods and Materials

The synthesis process begins with carbonization, i.e., the thermal decomposition of the raw material (pyrolysis) at 600–900 °C in an inert argon atmosphere. This stage aims to remove volatile components, increase the carbon and silicon content, and form a material with a well-developed porous structure and high specific surface area. Subsequently, activation of the carbon material is carried out using oxidizing gases such as carbon dioxide or water vapor at temperatures ranging from 600 to 1000 °C. This process facilitates the removal of amorphous carbon and enhances the porous structure, resulting in improved physicochemical properties.

Carbonization and activation were performed in a muffle furnace at temperatures from 300 to 900 °C for 30–120 minutes in a carbon dioxide atmosphere without air access. *Figure 1* presents the experimental setup with a capacity of 5 kg/h, providing sequential moisture removal, depolymerization, and partial decomposition of the raw material within the temperature range of 650–800 °C. At temperatures up to 270 °C, dehydration occurs, while within 600–850 °C, processes of decarboxylation and the formation of pyrolysis tars are observed, accompanied by dehydration and decarbonylation [9–10].

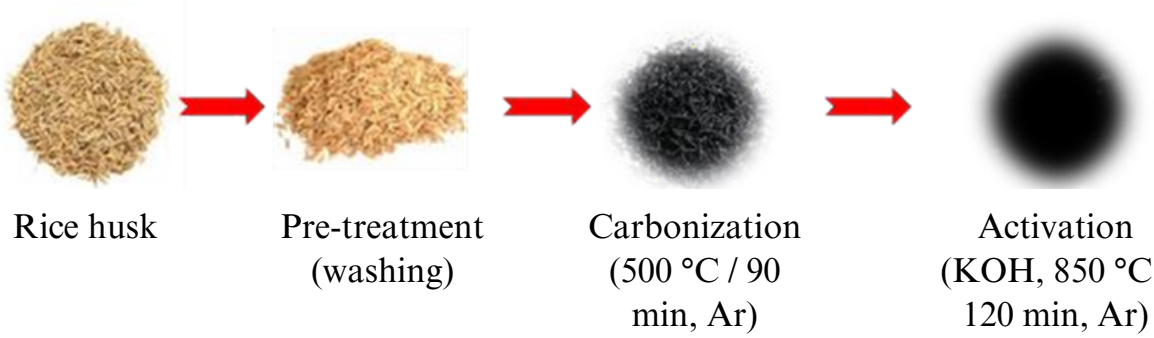


Figure 1. Schematic of the thermochemical process for obtaining carbon materials from rice husk

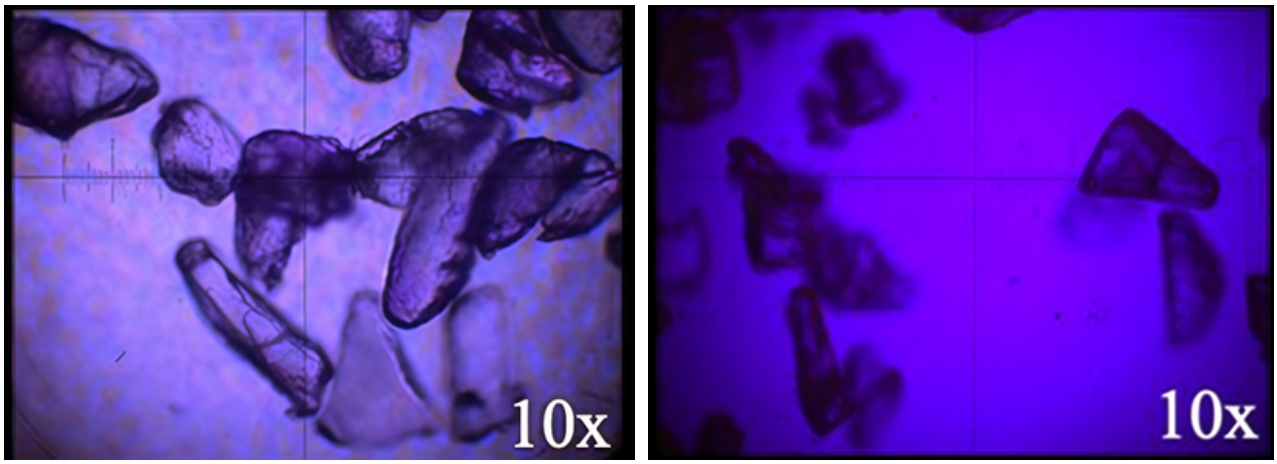


Figure 2. Optical microscopy results at 10× magnification

The schematic of the thermochemical production of carbon materials from rice husk is shown in *Figure 1* [11] and reflects the sequence of the main process stages. The raw material — rice husk — is preliminarily treated with a potassium hydroxide solution to remove mineral impurities, followed by dehydration in a fume hood. Subsequently, carbonization is carried out in a muffle furnace, leading to the formation of a porous carbon structure.

The study of the microstructural surface of carbonized rice husk makes it possible to determine its functional properties when used in pyrotechnic compositions. One of the most effective methods for analyzing surface structure is optical microscopy (OM). This method allows for quantitative morphological analysis and the measurement of linear parameters of the surface microstructure of solid materials.

The structure of the carbonized material was examined using optical microscopy at ×10 magnification. The micrographs revealed a heterogeneous surface with elements of a porous structure. Areas with varying carbon material density were observed, indicating incomplete carbonization in certain zones. Optical analysis also identified microcracks and channel-like formations, which are characteristic of plant-derived carbons.

3. Experimental Section

3.1 Impregnating Agents in Carbon Blocks

The range of substances with antiseptic properties that can be employed as impregnating agents is quite broad. However, their intrinsic characteristics impose limitations on their use in air purification applications. One of the most widely used substances in practice is iodine. Iodine and its compounds have been applied as antiseptics for more than 150 years and are well-established agents. An iodine solution is rightly considered one of the most common antiseptics in everyday life. Nevertheless, the use of iodine-based preparations for air disinfection has not been reported in the literature.

The problem of air purification can be addressed by passing an airflow through channel filters impregnated with iodine. Activated carbon can serve as a suitable material for the fabrication of such filters, as its pores are capable of retaining solutions of antiseptic agents. Preliminary studies revealed bactericidal activity in samples of activated carbon with different iodine adsorption levels (*Table 1*).

Table 1. Iodine sorption from the gas phase at 25 °C

Initial mass of sorbent, g	Mass of sorbent + I_2, g					
	10 days	20 days	30 days	40 days	50 days	60 days
10,03	15,6	17,5	18,85	19,44	19,44	19,53
10	15,56	17,54	18,91	19,33	19,43	19,52
10,05	15,49	17,56	18,93	19,35	19,45	19,49

To investigate the feasibility of using channel filters made of carbon–silicon carbonized rice husk for air disinfection, the sorption of iodine vapors from the gas phase was studied.

The experiment was based on the sublimation properties of iodine. At 25 °C, the vapor pressure of iodine above its crystals in a closed volume is 41.2 Pa. Sorption of iodine vapors, carried out in a hermetically sealed desiccator, was performed on a carbon sorbent in the form of a multichannel monoblock. The sorbent exhibited a developed surface area ranging from 250 to 550 m²/g. Sorption was continued until complete saturation of the sorbent with molecular iodine (*Figure 3*).

Figure 3 shows the dependence of sorbent saturation with iodine on time, obtained at a temperature of 25 °C and an iodine vapor pressure of 41.2 Pa. Saturation is expressed in milligrams of adsorbed iodine per gram of sorbent.

As can be seen from *Figure 3*, complete saturation of the sorbent is achieved after 400 hours (16–17 days) and amounts to 259 mg/g.

To determine the maximum sorption capacity of the sorbent under static conditions, a Petri dish containing iodine crystals was placed in a tightly sealed desiccator. Alongside, a glass beaker containing a sorbent sample of fixed mass was also placed inside the desiccator.

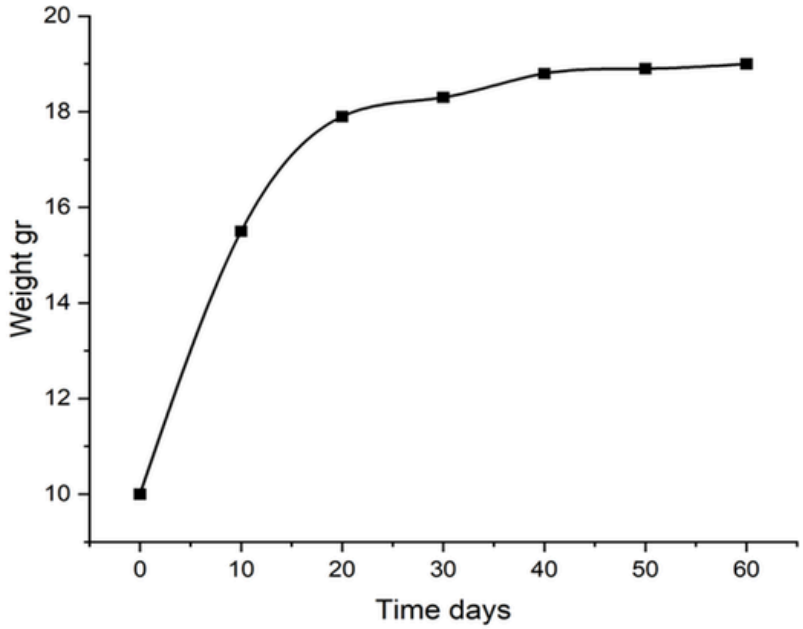


Figure 3. Dependence of sorbent saturation with iodine on time

The sorption of molecular iodine from aqueous solutions was also studied. This investigation was carried out since impregnation of the block material with aqueous iodine solutions was considered as an alternative approach. The solubility of iodine in water at 25 °C is 340 mg/L. To examine the sorption activity of the sorbent with respect to molecular iodine dissolved in water, a series of standard iodine solutions with concentrations ranging from 50 to 340 mg/L was prepared. The concentrations of the prepared solutions were verified by titration with 0.01 M sodium thiosulfate solution in the presence of starch as an indicator.

Subsequently, 100 mL of each solution was transferred into 250 mL conical flasks, brought into contact with 1 g of sorbent, and after sorption equilibrium was established, the residual iodine content in the solutions was determined by titration under the same conditions. Based on the results obtained, the mass of adsorbed iodine and the degree of its removal from the solutions were calculated.

To determine the maximum sorption capacity of the aluminosilicate sorbent with respect to molecular iodine, potassium iodide solutions were used, in which the solubility of iodine is significantly higher. Sorption was carried out from solutions with different iodine

significantly higher. Sorption was carried out from solutions with different iodine concentrations.

Based on the titration data obtained, the adsorption of iodine per 1 g of sorbent was calculated, and the Langmuir adsorption isotherm was derived as the dependence of adsorption on the equilibrium iodine concentration in the solution after sorption equilibrium was established (*Figure 4*).

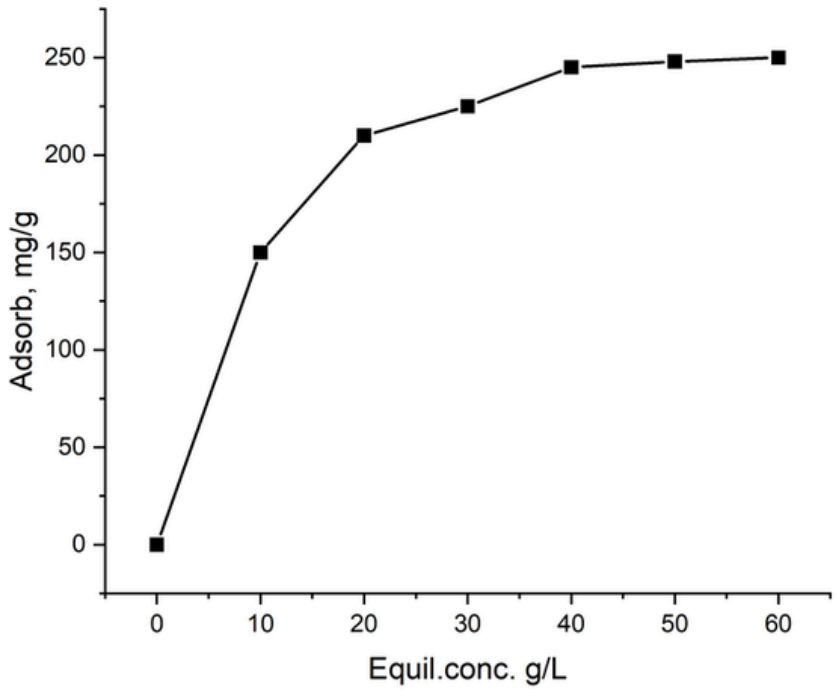


Figure 4. Iodine adsorption isotherm from aqueous solutions

Chlorhexidine gluconate solution and tannin powder were selected as impregnating agents. The effect of the carbonization process on the specific surface area and specific pore volume of the initial sorbent was investigated. It was established that carbonization enables the production of stronger carbon sorbents with a high specific surface area.

Measurements of the specific surface area and pore size of impregnated carbon–silicon sorbents were carried out. The study of the influence of impregnating agents on the sorption characteristics of the carbon–silicon sorbent showed that increasing the concentration of chlorhexidine and tannin led to an increase in both the specific surface area and the specific pore volume of the sorbents. It was established that impregnation of the carbon sorbent resulted in an increase in specific surface area from 320 m^2/g to 350 m^2/g and in specific pore volume from 0.1256 cm^3/g to 0.1399 cm^3/g.

To obtain information about the porous structure of the filter block material, the method of low-temperature nitrogen adsorption was employed. The study was carried out on a 3H-2000PS instrument after preliminary conditioning of the samples at 200 °C under a residual pressure of less than 0.001 mmHg. Nitrogen adsorption isotherms were measured at 77 K within a relative pressure range of 0.005 to 0.991, followed by standard analysis using the Brunauer–Emmett–Teller (BET) method. The parameters determined included the total pore volume (V_Σ), micropore volume ($V\mu$), and average pore diameter (Davg, accounting for both micro- and mesopores). The capability of this method to determine pore size distribution is limited to the micro- and mesopore regions. The measurement error for this method is estimated at 10%. The total surface area of micro- and mesopores was found to be 551 m^2/g.

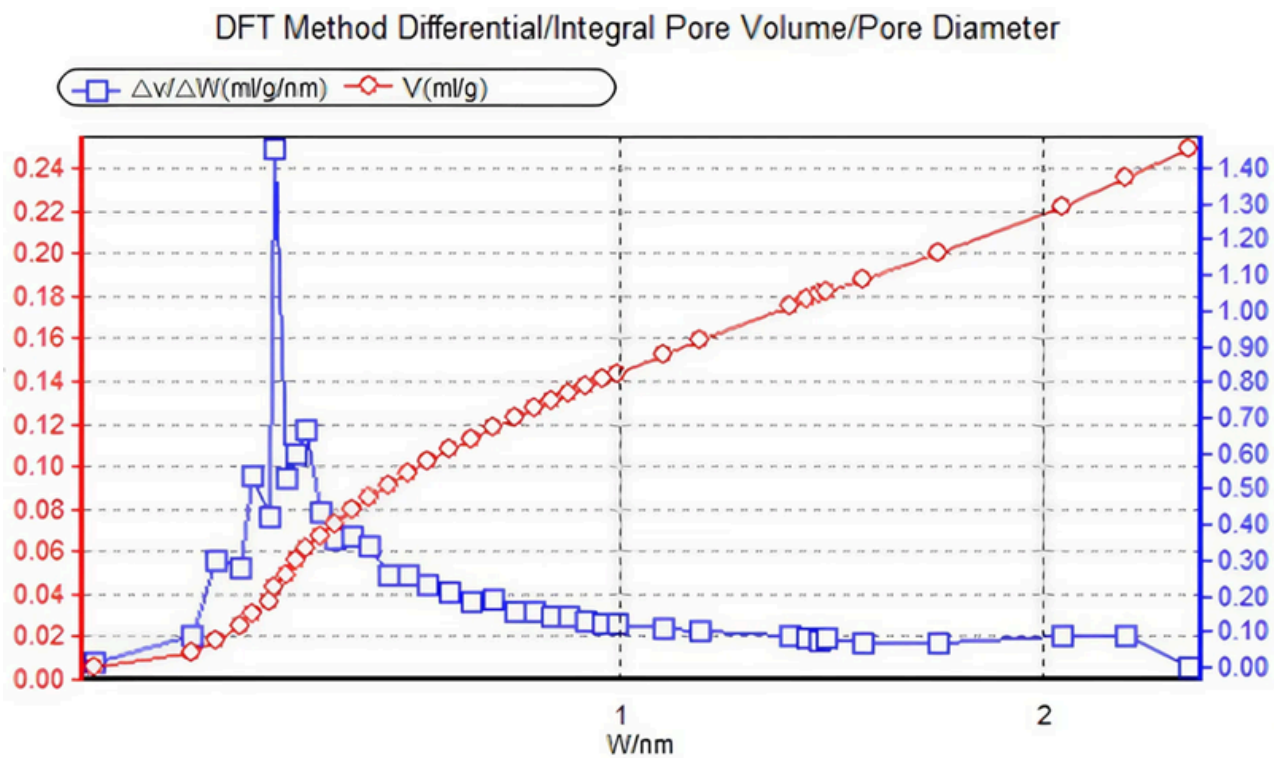


Figure 5. Adsorption isotherm of the monoblock sample obtained by the differential–integral method

According to the measurement results, the micropore volume (≤1.69 nm) was 0.2007 mL/g. The total pore volume (≤2.54 nm) was 0.2492 mL/g. The volume of all pores, including macropores, was measured using the water impregnation method. Although this method is not considered standard, it most closely corresponds to the conditions of the intended application of the filters. The prepared filters were weighed, immersed in water, and then subjected to vacuum to ensure complete impregnation. The total pore volume was determined to be 0.545 mL/g. Thus, upon impregnation, the filter is capable of retaining an amount of dissolved impregnating agent equivalent to its own mass.

4. Conclusion

As a result of the present work, a technology for producing carbon–silicon sorbents from rice husk with subsequent impregnation by antiseptic agents has been developed and tested. It was established that the combination of carbonization and activation processes enables the formation of a material with a high specific surface area and a well-developed porous structure, suitable for capturing and retaining antiseptic substances. Impregnation of the sorbents with iodine, chlorhexidine, and tannin led to an increase in sorption capacity and improvement of the textural characteristics of the material.

The fabricated filtering monoblocks demonstrated a high capacity for absorbing iodine vapors from both gaseous and liquid phases, confirming their potential for application in air purification systems with antiseptic properties. The results presented here may be utilized in the development of effective filtering elements for medical, sanitary, and military applications.

References:

[1] Vallero D. A. (2007) Fundamentals of Air Pollution. Elsevier. https://doi.org/10.1016/B978-0-12-373615-4.X5000-6

[2] Tsoli S., Ploubidis G. B., Kalantzi O. I. (2019) Particulate air pollution and birth weight: A systematic literature review. Atmospheric Pollution Research 10(3):707–717. https://doi.org/10.1016/j.apr.2019.01.016

[3] Park D. H., Joe Y. H., ..., Hwang J. (2020) Determination of air filter anti-viral efficiency against an airborne infectious virus. Journal of Hazardous Materials 402:122640. https://doi.org/10.1016/j.jhazmat.2020.122640

[4] Roy A., Mishra C., ..., Solanki N. (2018) A review of general and modern methods of air purification. Journal of Thermal Engineering 4(5):1801–1815. https://doi.org/10.18186/THERMAL.529054

[5] Krigmont H. V. (2023) Development of the disinfecting air filter. Lecture Notes in Electrical Engineering 991:351–358. https://doi.org/10.1007/978-3-031-34526-539

[6] Chen S. L., Chang S. W., ..., Chen H. L. (2021) Possible warming effect of fine particulate matter in the atmosphere. Communications Earth & Environment 2(1):1–8. https://doi.org/10.1038/s43247-021-00278-5

[7] Sun B., Lin J., ..., Sun D. (2022) In situ biosynthesis of biodegradable functional bacterial cellulose for high-efficiency particulate air filtration. ACS Sustainable Chemistry & Engineering 10(1):419–428. https://doi.org/10.1021/acssuschemeng.1c07532

[8] Al-Attabi, R.; Morsi, Y.; Schütz, J.A.; Cornu, D.; Maghe, M.; Dumée, L.F. Flexible and reusable carbon nano-fibre membranes for airborne contaminants capture. Sci. Total Environ. 2021, 754, 142231. https://doi.org/10.1016/j.scitotenv.2020.142231

[9] Christopherson D. A., Yao W. C., Sedaghat A. R. (2020) High-efficiency particulate air filters in the era of COVID-19: Function and efficacy. Otolaryngology - Head and Neck Surgery 163(1):3–9. https://doi.org/10.1177/0194599820941838

[10] Lim T. H., Yeo S. Y., Lee S. H. (2018) Multidirectional evaluations of a carbon air filter to verify their lifespan and various performances. Journal of Aerosol Science 123:38–45. https://doi.org/10.1016/j.jaerosci.2018.09.009

[11] Gao Y., Tian E., ..., Mo J. (2022) Utilizing electrostatic effect in fibrous filters for efficient airborne particles removal: Principles, fabrication, and material properties. Applied Materials Today 27:101369. https://doi.org/10.1016/j.apmt.2022.101369

AN APPROPRIATE METHOD FOR PROCESSING LOW-QUALITY FLUORITE CONCENTRATE AND FLUORINE-CONTAINING WASTE OF ALUMINUM PRODUCTION

Rajabov Shukhrat Kholmurodovich
PhD, Associate Professor, Department of Chemical Production Technology, Faculty of Chemistry, Tajik National University, Dushanbe, Tajikistan
e-mail: R.Shuhrat.Kh@mail.ru

Abstract

The technology of reception cryolite and fluoride of aluminum from alumina-, fluorine containing aluminum production wastes. In the present article technology of reception cryolite and fluoride of aluminum from alumina and fluorine containing wastes of aluminum production is descried. The physical and chemical analysis is carried out optimum condition of process passing and defined compositions of raw materials and products.

Keywords

aluminum production, alumina and fluorine containing wastes, aluminum manufacture, acidic decomposition, fluoric acid, criolite and aluminum fluoride production.

1. Introduction

The primary consumption of extracted fluorspar, a natural mineral of fluorite, is in the production of fluorine compounds used for primary aluminum manufacturing. Modern methods for processing fluorine-bearing ores are based on the beneficiation of fluorite ores by flotation techniques, followed by decomposition with concentrated sulfuric acid [1, 2]. For the production of technical hydrofluoric acid, fluorspar with a CaF_2 content of not less than 92% is typically used, while the production of anhydrous hydrogen fluoride requires concentrate containing 96–97% of the main component.

In recent years, due to the growing demand for fluorine salts, the reserves of fluorite ore have become noticeably depleted. Moreover, in the aluminum industry, valuable fluorine-containing secondary raw materials accumulate, including gas-cleaning sludge, spent electrolyzer linings, and other by-products. The processing of these materials would not only reduce environmental impact but also enhance the efficiency of aluminum production by lowering emission-related costs.

The primary consumption of extracted fluorspar, a natural mineral of fluorite, is in the production of fluorine compounds used for primary aluminum manufacturing. Modern methods for processing fluorine-bearing ores are based on the beneficiation of fluorite ores by flotation techniques, followed by decomposition with concentrated sulfuric acid [1, 2]. For the production of technical hydrofluoric acid, fluorspar with a CaF_2 content of not less than 92% is typically used, while the production of anhydrous hydrogen fluoride requires concentrate containing 96–97% of the main component.

In recent years, due to the growing demand for fluorine salts, the reserves of fluorite ore have become noticeably depleted. Moreover, in the aluminum industry, valuable fluorine-containing secondary raw materials accumulate, including gas-cleaning sludge, spent electrolyzer linings, and other by-products. The processing of these materials would not only reduce environmental impact but also enhance the efficiency of aluminum production by lowering emission-related costs.

In previous studies, the sulfuric acid decomposition of solid alumina–fluorine-containing aluminum production wastes was investigated, and a technology for producing hydrofluoric acid from these wastes was developed [3–6].

Objects of the Study

At present, a plant for the production of cryolite and aluminum fluoride is operating in Yavan, Republic of Tajikistan (LLC TALCO Chemical), using fluorite concentrate supplied by LLC TALCO Fluorite as fluorine-containing raw material, in accordance with GOST 29220-91.

The process flow diagram of the plant provides for the implementation of a technology for producing hydrofluoric acid directly from fluorine-containing aluminum production wastes. Partial substitution of fluorite concentrate with such wastes not only reduces the production cost but also improves the environmental situation in the region. Due to the insufficient amount of calcium fluoride required for HF production, it is considered reasonable to carry out the sulfuric acid decomposition of fluorine- and alumina-containing wastes (washed sludge — sodium sulfates and carbonates) from the aluminum plant of State Unitary Enterprise TALCO in a mixture with fluorite concentrate from LLC TALCO Fluorite. The chemical composition of these materials, determined by standard chemical analysis, is presented in *Table 1*.

Table 1. Chemical composition of the batch materials used

Name	Component content, wt.%								
	Al_2O_3	Na_3AlF_6	NaF	MgF_2	C	Fe_2O_3	SiO_2	CaF_2	$CaCO_3$
Washed gas-cleaning sludge from the TALCO aluminum plant (State Unitary Enterprise)	9-15	20-27	1-3	0,6-0,9	16-30	1,0-1,6	0,3-0,6	0,7-1,0	-
Fluorite concentrate from LLC TALCO Fluorite	0,25	-	-	-	-	0,25	0,5	97,0	2,0

To determine the mineralogical composition of the raw materials used, X-ray phase analysis was carried out on a DRON-2.0 diffractometer with Cu_α radiation. The analysis results are presented in *Figure 1*.

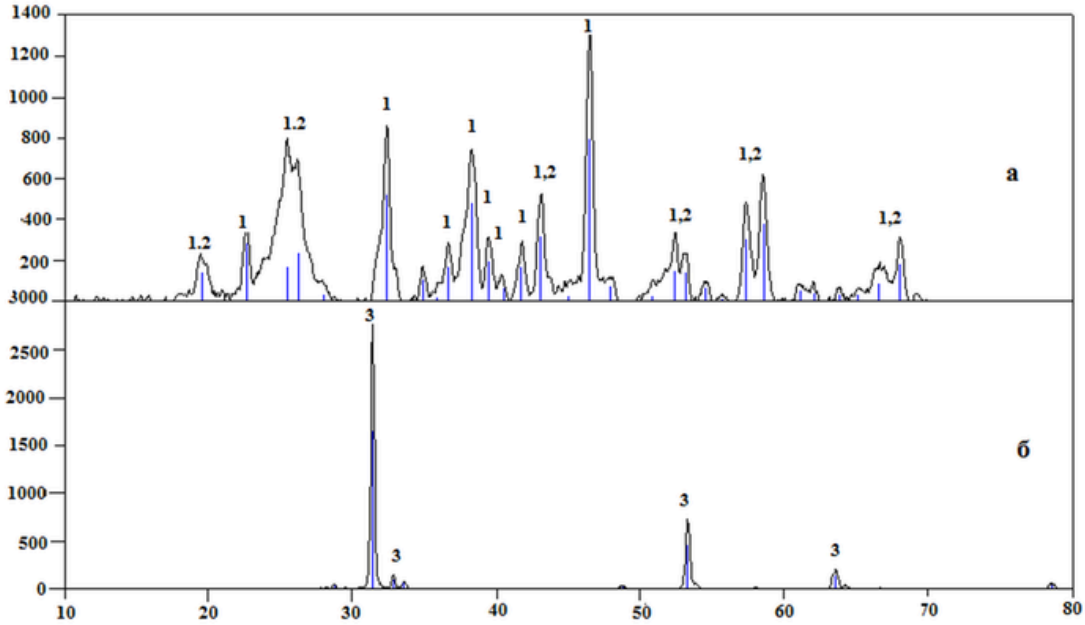


Fig. 1. X-ray diffraction patterns: (a) washed gas-cleaning sludge from the TALCO aluminum plant (State Unitary Enterprise) and (b) fluorite concentrate from LLC TALCO Fluorite. 1 – Na_3AlF_6 (cryolite); 2 – Al_2O_3; 3 – CaF_2 (fluorite).

Experimental Procedure for Acid Decomposition

The method for producing hydrogen fluoride is based on the decomposition of fluorine-containing wastes mixed with fluorite concentrate using sulfuric acid, according to the following reaction equations [1–8]:

$$2Na_3AlF_6+6H_2SO_4=3Na_2SO_4+Al_2(SO_4)_3+12HF, \quad (1)$$

$$Al_2O_3+3H_2SO_4=Al_2(SO_4)_3+3H_2O, \quad (2)$$

$$Fe_2O_3+3H_2SO_4=Fe_2(SO_4)_3+3H_2O, \quad (3)$$

$$2NaF+H_2SO_4=Na_2SO_4+2HF, \quad (4)$$

$$2AlF_3+3H_2SO_4=Al_2(SO_4)_3+6HF, \quad (5)$$

$$CaF_2+H_2SO_4=CaSO_4+2HF, \quad (6)$$

$$MgF_2+H_2SO_4=MgSO_4+2HF, \quad (7)$$

$$CaCO_3+H_2SO_4=CaSO_4+H_2O+CO_2. \quad (8)$$

The laboratory setup for acid decomposition of the charge, consisting of fluorine- and alumina-containing washed sludge from aluminum production and fluorite concentrate (*Figure 2*), is a sealed cylindrical steel vessel with a capacity of 800 mL. The vessel is internally lined with carbon–graphite material and equipped with a screw cap, which is internally lined with fluoroplastic.

To remove the product gas from the reactor, a fluoroplastic gas outlet tube is used, with one end immersed in a polyethylene vessel containing distilled water. As the gas passes through the water, gaseous HF is absorbed, forming hydrofluoric acid.

The presence of SiO_2 in the composition of the technogenic raw material leads to the formation of H_2SiF_6, which contaminates the hydrofluoric acid. To remove silica impurities, a certain amount of soda is added to the solution. As a result of the reaction

$$H_2SiF_6 + Na_2CO_3 = Na_2SiF_6 \downarrow + CO_2 + H_2O \quad (9)$$

an insoluble sodium fluorosilicate is formed, which can further react with an excess of soda to yield sodium fluoride, silica, and carbon dioxide:

$$Na_2SiF_6 + 2Na_2CO_3 = 6NaF + SiO_2 \downarrow + 2CO_2. \quad (10)$$

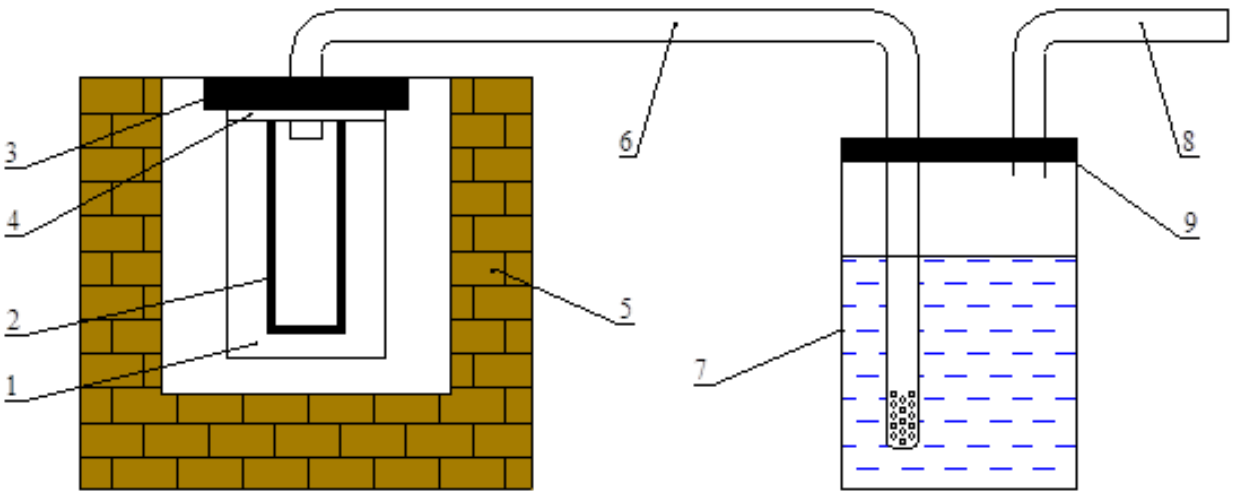


Figure 2. Schematic of the laboratory setup for acid decomposition of fluorine–alumina-containing technogenic raw material:

1 – steel vessel; 4 – fluoroplastic lining; 7 – polyethylene vessel with water;
2 – carbon lining; 5 – shaft muffle furnace; 8 – polyethylene tube for exhaust gas release;
3 – steel lid; 6 – fluoroplastic gas outlet tube; 9 – polyethylene stopper.

The purified hydrofluoric acid, containing only minor amounts of H_2SiF_6 and H_2SO_4, is directed to the production of cryolite in accordance with GOST 10561-80 or aluminum fluoride in accordance with GOST 19181-78.

A series of studies was carried out on the processing of technogenic raw materials from the aluminum plant by sulfuric acid decomposition of a charge consisting of fluorite and fluorine–alumina-containing technogenic materials in various mass ratios, with the aim of reducing the environmental burden in the vicinity of primary aluminum production facilities.

Table 2 presents the values of fluorine recovery into solution at different mass ratios of the components, depending on process parameters such as temperature, duration, sulfuric acid concentration, and solid-to-liquid ratio (S:L).

Table 2. Dependence of fluorine recovery from the charge under various parameters of acid decomposition

No.	Mass ratio of fluorite to technogenic raw material	Solid-to-liquid ratio (S:L)	Process duration, min	Temperature, °C	H_2SO_4 concentration, wt.%	Fluorine recovery, %
1	10:90	1,0:1,5	20	260-280	90-92	64,7
2	20:80	1,0:1,5	20	260-280	90-92	76,8
3	30:70	1,0:1,5	20	260-280	90-92	81,7
4	40:60	1,0:1,5	20	260-280	90-92	86,3
5	50:50	1,0:1,5	20	260-280	90-92	91,3
6	60:40	1,0:1,5	20	260-280	90-92	93,9
7	70:30	1,0:1,5	20	260-280	90-92	94,2
8	80:20	1,0:1,5	20	260-280	90-92	94,8
9	90:10	1,0:1,5	20	260-280	90-92	95,1
10	60:40	1,0:1,5	20	260-280	90-92	93,9
11	60:40	1,0:1,0	20	260-280	90-92	93,9
12	60:40	1,0:0,8	20	260-280	90-92	87,3
13	60:40	1,0:1,0	15	260-280	90-92	84,4
14	60:40	1,0:1,0	20	260-280	90-92	93,9
15	60:40	1,0:1,0	25	260-280	90-92	91,2
16	60:40	1,0:1,0	30	260-280	90-92	87,4
17	60:40	1,0:1,0	20	160-180	90-92	61,0
18	60:40	1,0:1,0	20	200	90-92	74,2
19	60:40	1,0:1,0	20	240-260	90-92	93,9опт
20	60:40	1,0:1,0	20	260-280	90-92	93,9
21	60:40	1,0:1,0	20	240-260	80	85,2
22	60:40	1,0:1,0	20	240-260	70	71,9

As can be seen from the data in *Table 2*, the optimal parameters for fluorine recovery, ensuring subsequent production of hydrofluoric acid from the proposed raw material mixture, are as follows: mass ratio of fluorite to technogenic raw material = 60:40; temperature = 240–260 °C; sulfuric acid concentration = 90–92 wt.%; solid-to-liquid ratio (S:L) = 1:1; and process duration = 20 min. Under these conditions, the degree of fluorine recovery from the charge reaches its maximum value of 93.9%.

The cake obtained after sulfuric acid decomposition consists mainly of aluminum, sodium, iron, and calcium sulfates, along with carbon. To extract the most valuable component—aluminum sulfate—the cake was subjected to aqueous treatment under the following conditions: solid-to-liquid ratio (S:L) = 1:5, temperature = 95 °C, and process duration = 30 min. Under these conditions, the degree of aluminum sulfate recovery (calculated as Al_2O_3) reached 97.7% (*Table 3*).

Table 3. Values of the main parameters of the aqueous leaching process

No.	Solid-to-liquid ratio (S:L)	Temperature, °C	Duration, min	Sulfate content in solution, g/dm³			Al_2O_3 recovery, %
				$Al_2(SO_4)_3$	$Fe_2(SO_4)_3$	Na_2SO_4	
1	1:1	95	30	0,80	0,13	3,10	24,0
2	1:2	95	30	1,68	0,21	4,90	51,0
3	1:3	95	30	2,57	0,38	7,10	78,0
4	1:4	95	30	3,07	0,46	8,51	93,1
5	1:5	95	30	3,22	0,58	10,10	97,7
6	1:6	95	30	3,22	0,58	10,10	97,7
7	1:5	50	30	1,61	0,43	4,20	49,0
8	1:5	75	30	2,41	0,53	6,50	73,2
9	1:5	95	30	3,22	0,58	10,10	97,7
10	1:5	95	20	2,89	0,54	9,95	87,9
11	1:5	95	30	3,22	0,58	10,10	97,7опт
12	1:5	95	40	3,22	0,58	10,10	97,7

To extract aluminum hydroxide, the sulfate solution was treated with a sodium carbonate solution. As a result of the reactions

$$Al_2(SO_4)_3 + 3Na_2CO_3 + H_2O = 2Al(OH)_3\downarrow + Na_2SO_4 + 3CO_2 \quad (11)$$

and

$$Fe_2(SO_4)_3 + 3Na_2CO_3 + 3H_2O = 2Fe(OH)_3\downarrow + 3Na_2SO_4 + 3CO_2, \quad (12)$$

aluminum and iron ions are precipitated in the form of hydroxides.

Table 4 presents the results on the precipitation degree of aluminum and iron hydroxides from sulfate solutions after treatment with a Na_2CO_3 solution.

As can be seen from *Table 4*, the most favorable conditions for the precipitation of aluminum hydroxide are: solution volume ratio = 0.4:1.0; sodium carbonate concentration = 1 g-eq/L; temperature = 25 °C; and process duration = 15 min. Under these conditions, the precipitation degree of aluminum hydroxide reaches 97.4%, while that of iron hydroxide reaches 98.8%.

The resulting precipitate of aluminum and iron hydroxides was dried at 100–120 °C to constant weight. Subsequently, in order to separate aluminum hydroxide (by obtaining sodium aluminate) from iron hydroxide, the material was treated for 5–15 min with sodium hydroxide solutions of varying concentrations and volume ratios at temperatures ranging

from 25 to 60 °C.

Table 4. Values of the main parameters of the precipitation process of aluminum and iron hydroxides from sulfate solutions

No.	Volume ratio of soda solution to sulfate solution	Concentration of soda solution, g-eq/L	Temperature, °C	Duration, min	Precipitation degree, %	
					$Al_2(SO_4)_3$	$Fe_2(SO_4)_3$
1	0,2:1,0	1	25	15	64,6	71,2
2	0,3:1,0	1	25	15	82,3	89,0
3	0,35:1,0	1	25	15	92,1	94,1
4	0,4:1,0	1	25	15	97,9	98,3
5	0,5:1,0	1	25	15	98,6	98,5
6	0,4:1,0	0,7	25	15	91,0	88,3
7	0,4:1,0	0,8	25	15	94,3	94,7
8	0,4:1,0	1	25	15	97,4	98,3
9	0,4:1,0	1,2	25	15	98,7	98,8
10	0,4:1,0	1	25	15	97,4	98,3
11	0,4:1,0	1	40	15	97,4	98,8
12	0,4:1,0	1	60	15	94,2	98,8
13	0,4:1,0	1	25	10	91,2	93,0
14	0,4:1,0	1	25	15	97,4опт	98,3
15	0,4:1,0	1	25	20	97,4	98,8

Table 5. Aluminum recovery from the hydroxide precipitate during alkaline treatment of sulfate solution

No.	Solid-to-liquid ratio (S:L)	NaOH concentration, g/dm³	Temperature, °C	Duration, min	Al_2O_3 recovery, %
1	2:10	100	25	15	54,0
2	2:15	100	25	15	68,0
3	2:20	100	25	15	86,0
4	2:30	100	25	15	86,1
5	2:35	100	25	15	86,1
6	2:20	80	25	15	83,7
7	2:20	100	25	15	86,0
8	2:20	120	25	15	86,4
9	2:20	100	30	15	93,7
10	2:20	100	40	15	97,2
11	2:20	100	60	15	97,2
12	2:20	100	40	5	93,1
13		100	40	10	97,2опт
14	2:20	100	40	15	97,2

As shown in *Table 5*, the optimal parameters for the process are: solid-to-liquid ratio = 2:20 (2 g precipitate: 20 mL solution), NaOH concentration = 100 g/dm³, temperature = 40 °C, and process duration = 10 min. Under these conditions, the degree of aluminum recovery from the cake into solution (calculated as aluminum oxide) reaches 97.2%.

When treating the mixture of aluminum and iron hydroxide precipitates with sodium hydroxide solution, the following reaction may occur.

$$Al(OH)_3+NaOH = NaAl(OH)_4 \quad (13)$$

The sodium aluminate solution was carbonized with gaseous CO_2 in order to obtain aluminum hydroxide. As shown in *Table 6*, the most efficient conditions for carbonization of the sodium aluminate solution are: temperature = 20 °C, CO_2 flow rate = 2 L/min, and process duration = 3 min. Under these conditions, the precipitation degree of aluminum hydroxide reaches 97.3%.

Table 6. Values of the main parameters of the carbonization process of sodium aluminate solution (per 100 mL of solution)

No.	Sodium aluminate content in solution, g/dm³	Duration, min	Temperature, °C	CO_2 flow rate, L/min	Precipitation degree of aluminum hydroxide, %
1	10,9	1	20	2	69,5
2	10,9	2	20	2	89,5
3	10,9	3	20	2	97,3
4	10,9	4	20	2	97,3
5	10,9	5	20	2	93,4
6	10,9	3	20	2	97,3
7	10,9	3	40	2	88,0
8	10,9	3	60	2	81,7
9	10,9	3	20	1,5	73,9
10	10,9	3	20	2	97,3опт
11	10,9	3	20	3	97,3

4. Conclusion

As a result of the experiments, the optimal conditions for sulfuric acid decomposition of a mixture of aluminum production gas-cleaning sludge and fluorite concentrate (containing 97.0 wt.% CaF_2) were determined: mass ratio of fluorite to technogenic raw material = 60:40; temperature = 240–260 °C; sulfuric acid concentration = 90–92 wt.%; solid-to-liquid ratio (S:L) = 1:1; and process duration = 20 min. Under these conditions, the degree of fluorine recovery from the charge reaches 93.9%. The remaining mixture of sulfates can be selectively separated to obtain individual chemical compounds that may be utilized in various industries [8].

The method developed on the basis of this research can be implemented without significant modifications using the existing equipment at LLC TALCO Chemical.

References:

[1] Fatyanov, A.V., Leonov, S.B., Katashin, L.V. State of fluorite ore beneficiation. Moscow: Tsvetmetinformatsiya, 1972. 65 p.

[2] Zaitsev, V.A., Novikov, A.A., Rodin, V.I. Production of fluorine compounds from phosphate raw materials. Moscow: Khimiya, 1982. 248 p.

[3] Kabirov, Sh.O., Safiev, Kh.S., Sirochov, N.M., Azizov, B.S., Mirpochaev, Kh.A., Ruziev, D.R., Mukhamediev, N.P., Boboev, Kh.E., Radzhabova, Sh.Kh. Method for complex processing of solid fluorine-containing aluminum production wastes. Patent No. 515 RT (Minor Patent). Dushanbe, 2012.

[4] Safiev, Kh., Kabirov, Sh.O., Azizov, B.S., Mirpochaev, Kh.A., Ruziev, D.R., Boboev, Kh.E., Radzhabov, Sh.Kh. Technology for producing cryolite and aluminum fluoride from alumina- and fluorine-containing aluminum production wastes. Doklady Akademii Nauk RT, Vol. 54, No. 10, 2011, pp. 845–850.

[5] Radzhabov, Sh.Kh., Ruziev, D.R., Boboev, Kh.E., Azizov, B.S., Safiev, Kh. Thermodynamic analysis of the sulfuric acid decomposition process of fluorine- and alumina-containing aluminum production wastes. Bulletin of the National University. Series of Natural Sciences, Dushanbe, 2012, No. 1/2 (81), pp. 131–134.

[6] Radzhabov, Sh.Kh., Ruziev, D.R., Boboev, Kh.E., Azizov, B.S., Safiev, Kh. Kinetics of the sulfuric acid decomposition process of solid fluorine-containing aluminum production wastes. Doklady Akademii Nauk RT, Vol. 56, No. 1, 2013, pp. 44–47.

[7] Radzhabov, Sh.Kh., Shoev, I.S., Mukhamediev, N.P., Ruziev, D.R., Safiev, A.Kh., Boboev, Kh.E., Mirpochaev, Kh.A., Safiev, Kh. Comprehensive processing of fluorine- and alumina-containing aluminum production wastes. Doklady Akademii Nauk RT, Vol. 57, No. 1, 2014, pp. 51–56.

[8] Volkova, M.F., Prokhorov, A.G., et al. On the issue of reduction and rational use of sludge wastes from sodium sulfide production. Proceedings of the Ural Research Chemical Institute (UNIKHIM), 1984, Issue 57, pp. 99–102.

MINI-REVIEW BY ELEMENTS

Artificial Intelligence in Chemistry: A New Catalyst for Progress

In 2025, artificial intelligence (AI) consolidated its role as a driver of discovery in chemistry. Beyond data processing and property prediction, **domain-adapted large language models (LLMs)** now assist with reaction reasoning, synthesis planning, and even experiment optimization.

A prominent example is **Chemma**, a domain-specific LLM for organic synthesis. Trained on 1.28 million reaction Q&A pairs, Chemma demonstrates state-of-the-art performance in single-step retrosynthesis and yield prediction and, when coupled to Bayesian optimization, accelerates condition discovery in real laboratory campaigns [1].

Another line of progress is **hierarchical agent** systems such as **ChemHAS**, which stack specialized AI agents and tools. This architecture reduces tool-prediction errors and improves text-based molecular design, property and reaction prediction across multiple chemistry benchmarks, outperforming strong general and domain baselines [2].

Concurrently, surveys map how AI is **reframing catalyst discovery**, from classical ML to LLM-enabled workflows that integrate literature mining, mechanistic priors, and autonomous experimentation—especially relevant for green chemistry and sustainable synthesis [3].

Yet open challenges remain: data quality and coverage, tool reliability, model interpretability, and the risk of spurious "hallucinations." A 2025 **Nature Computational Science** study systematically probes the limitations of multimodal models for chemistry and materials and underscores the need for careful validation and standardized benchmarks [4].

AI is transitioning from a supportive tool to a **co-pilot** in chemical research—most effective when paired with transparent pipelines, high-quality data, and human-in-the-loop verification.

[1] Zhang, Y., et al. Chemma: Large Language Models for Organic Synthesis. arXiv preprint arXiv:2504.18340 (2025)

[2] Li, Z., Zhang, B., et al. ChemHAS: Hierarchical Agent Stacking for Chemistry. arXiv preprint arXiv:2505.21569 (2025).

[3] Xu, Y., et al. AI-Empowered Catalyst Discovery: From Machine Learning to Large Language Models. arXiv preprint arXiv:2502.13626 (2025).

[4] Alampara, N., et al. Probing the limitations of multimodal language models for chemistry and materials research. Nature Computational Science (2025).

ENERGY ELEMENTS

GREEN SOLUTIONS

SECTION 3

Issue 1, 2026 | TABLE OF CONTENTS

Every time you choose to conserve resources, you cast a vote for the future.

— Energy ELEMENTS

P 33

INTEGRATING LEAN MANAGEMENT PRACTICES FOR ENHANCING SUSTAINABILITY IN SOLAR ENERGY SECTOR

Muhammad Usman Ali, Engr. Dr. Yasir Muhammad, Engr. Dr. Ehtasham Mustafa, Shahzad Akbar

P 59

EXPLORING THE UNCERTAINTIES AND AMBIGUITIES IN ACCEPTING WIND POWER PROJECTS: EVIDENCE FROM PAKISTAN

Faiz Jalil, Dr Rafiq Mansoor

www.elementsjournal.uz @elements_journal info@elementsjournal.uz

INTEGRATING LEAN MANAGEMENT PRACTICES FOR ENHANCING SUSTAINABILITY IN SOLAR ENERGY SECTOR

Muhammad Usman Ali
PhD Scholar, Department of Mechanical Engineering, International Islamic University, Islamabad, Pakistan
e-mail: muhammad.phdem24@iiu.edu.pk | ORCID: 0009-0000-4089-8992

Engr. Dr. Yasir Muhammad
Associate Professor, Department of Electrical Engineering, COMSATS University Islamabad, Attock Campus, Pakistan
e-mail: yasir.ee@ciit-attock.edu.pk

Engr. Dr. Ehtasham Mustafa
Assistant Professor, Department of Electrical Engineering, Faculty of Engineering & Technology, Gomal University, Dera Ismail Khan, Pakistan
e-mail: ehtashammustafa@gu.edu.pk

Shahzad Akbar
PhD Scholar, Department of Mechanical Engineering, International Islamic University, Islamabad, Pakistan
e-mail: muhammad.phdese3@iiu.edu.pk

Abstract

The solar energy sector is swiftly advancing to address increasing energy demands and diminish reliance on fossil fuels. Nonetheless, inefficiencies, resource wastage, and elevated operational expenses persist in obstructing sustainable development. This study seeks to establish a strategy framework for attaining sustainability in Pakistan's solar business by implementing Lean Management practices. Lean approaches, recognized for improving operational efficiency through waste reduction and value maximization, possess significant potential to revolutionize solar project management in the local context. The study also reveals the obstacles that impede the adoption of Lean practices. The study utilizes a mixed-methods approach, commencing with an extensive literature analysis to delineate the conceptual connection between Lean concepts and sustainability features. Primary data were obtained through standardized questionnaires administered to key stakeholders, such as managers, engineers, and sustainability officers inside Pakistan's solar energy companies. The aims were to: (1) investigate stakeholder awareness and views of Lean and sustainability; (2) evaluate the correlation between Lean practices; and (3) utilize these findings to develop a feasible framework for Lean integration. Research demonstrates a robust acknowledgment among professionals on the significance of Lean principles in advancing sustainability within the solar sector. The utilization of methodologies such as Value Stream Mapping (VSM), Just-in-Time (JIT) inventory management, and continuous improvement (Kaizen) demonstrated substantial beneficial associations with diminished project delays, cost reductions, and improved collaboration. The study pointed out the barriers and, in this regard, the suggested framework integrates Lean practices with the operational realities of

solar installation in Pakistan, offering a blueprint to enhance productivity, minimize waste, and promote national sustainability objectives. The study underscores the significance of company culture, leadership dedication, and governmental assistance in enabling Lean transformation. Training programs and stakeholder participation are recognized as essential facilitators for successful adoption, in addition to improve performance, promote sustainability, and facilitate the overall shift to clean energy.

Keywords

Lean Management (LM); Solar Energy; Sustainability; Renewable Energy; Waste Reduction; Project Efficiency; Operational Performance; Lean Management Practices (LMP), Lean tools

1. Introduction

The rapid expansion of the solar energy sector necessitates novel approaches to address inefficiencies in construction methods and project implementation. In Pakistan, solar construction projects frequently experience delays, budget overruns, and resource inefficiencies due to dependence on conventional methods. This research advocates for the incorporation of Lean methodologies focused on waste minimization and value enhancement as a remedy for these systemic issues. Through the implementation of lean methods, solar companies can optimize operations and enhance project timeframes. It promotes ongoing enhancement, effective communication, and optimal resource usage. This study examines the influence of Lean methods on improving operational and sustainability results in Pakistan's solar construction industry. The research provides a framework to assist organizations in adopting Lean methodologies for enhanced project delivery and enduring sustainability [1]. This study emphasizes the critical necessity for enhanced efficiency in the solar business and presents Lean methods as a viable option. It analyses how Lean methodologies can optimize project results by reducing waste and refining procedures. The research advocates for a culture of continual improvement through best practices and case insights. Ultimately, it enhances efficiency and sustainability in the growth of renewable energy.

In recent years, escalating environmental and social concerns have necessitated that firms implement more responsible and sustainable operational procedures. This transition has compelled both industry and academia to investigate effective methods for incorporating sustainability into fundamental processes. The worldwide importance of sustainability was prominently highlighted in the 1987 report by the United Nations' World Commission on Environment and Development, entitled "Our Common Future". This seminal statement emphasized the interconnection of society, natural resources, and the environment, promoting long-term planning and systemic transformation to guarantee sustainable development for future generations [2]. Sustainable development is defined as fulfilling existing demands without jeopardizing the capacity of future generations to satisfy their own needs. This notion underscores a balanced strategy that integrates economic development, environmental conservation, and social fairness to guarantee sustainable well-being and resource accessibility for present and future generations [3]. The notion of "lean," initially presented by Toyota Motor Corporation in the 1950s, has undergone considerable evolution in tandem with progress in operations management. This evolution transpired in two

principal phases. The initial phase, extending into the early 1990s, emphasized constant quality enhancement. By the late 1990s, lean methodologies broadened to include quality, cost, and delivery efficiency. The second phase arose in the 2000s, as increasing interest in sustainability began to transform operational goals, redirecting lean's emphasis toward providing more customer value. During this period, researchers increasingly examined the alignment and integration of traditional lean concepts with sustainability aims, acknowledging the potential for synergy between efficiency-driven processes and ecologically and socially responsible practices [4].

The increasing emphasis on sustainability and intensified focus on environmental enhancement have established environmental sustainability as a primary goal in corporate initiatives. This transition highlights the necessity of integrating sustainability initiatives with conventional organizational objectives, including the improvement of profitability and operational efficiency [5]. Green industrialization, seen as a crucial strategy for attaining sustainable development within the industrial sector, fosters expansion without augmenting the use of natural resources. The system prioritizes efficiency and environmental stewardship. Lean management closely adheres to this principle, promoting minimal waste and efficient resource use in production and operational operations [2]. Simultaneously, academic study has progressively investigated the potential correlation between lean adoption and ecologically friendly production results. This junction has led to the emergence of the "lean–green manufacturing" paradigm, which amalgamates lean concepts focused on fulfilling consumer demand with environmentally sustainable methods designed to reduce ecological effect. Despite its increasing significance, lean-green manufacturing is an evolving field, devoid of a broadly accepted definition or organized research methodology. Lean is fundamentally acknowledged as a methodical approach for ongoing process enhancement [4]. The lean methodology emphasizes the identification and eradication of waste while promoting ongoing enhancement. In the context of renewable energy product

manufacturing, lean approaches can markedly decrease operational expenses, improve capital efficiency, shorten lead times, and facilitate the industry's continuous growth. By optimizing processes and enhancing value, lean promotes more efficient resource utilization, so bolstering the competitiveness and sustainability of renewable energy industries [6]. Certain experts assert that lean firms can improve their environmental performance, as lean and green techniques possess intrinsic common goals. Both methodologies prioritize the eradication of waste and the enhancement of process efficiency. By addressing analogous inefficiencies, lean approaches might unintentionally advance environmental objectives, harmonizing operational excellence with sustainability results [7]. Non-electricity industries are advancing at a sluggish rate, with energy efficiency enhancements achieving merely 1.5% last year, which is less than half of the 3.2% aim required to fulfill global sustainability objectives. In emerging nations, such as Pakistan, energy costs have escalated significantly due to a global demand for natural gas, with increases soaring up to 1,900%. Notwithstanding these expenses, access to natural gas is constrained, leading to prevalent "brownouts" and energy deficits. Simultaneously, investment in fossil fuel production persists in its expansion, while numerous measures designed to eliminate coal have either stagnated or been overturned, presenting a significant obstacle to the shift to greener energy systems [8].

Access to energy from all sources must be the utmost priority for everyone. This must encompass equal access to natural resources and a funding mechanism to mitigate elevated energy prices for the most impacted nations. This study aims to point out the barriers, highlight the benefits and establish a complete framework that facilitates solar energy companies in Pakistan in adopting Lean practices as a strategic approach to attain sustainability. *Figure 1* illustrates the primary aim is to improve the sustainability performance of these companies by assessing the awareness and comprehension of key decision-makers concerning the adoption of Lean methods and seeks to integrate Lean thinking with sustainable growth in Pakistan's solar energy sector.

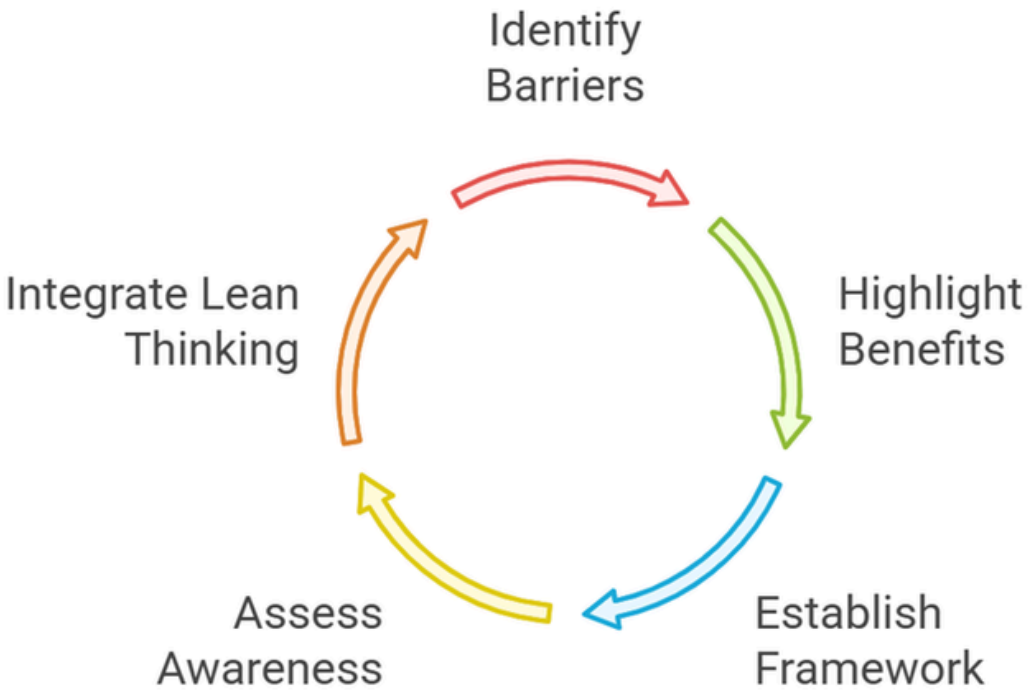


Fig. 1. Cycle of Lean Integration for Sustainability (source: the authors)

2. Literature Review

2.1. Overview of Lean Practices in Construction

Lean Construction (LC) originated in the early 1990s when Koskela proposed a lean production system to tackle construction difficulties using the framework of Transformation, Flow, and Value (TFV). Identifying substantial waste in the construction sector, critical components of lean production, including Just in Time, Total Quality Management, and Kanban, were deemed vital for enhancing construction efficiency [9]. The objective of the LC concept was to optimize workflow, effectively satisfy customer needs, and reduce waste from construction processes and materials. Although LC was initially inspired by lean production, its definition has since expanded and developed in response to the growing interest and adoption of the concept [10]. LC is a new way to manage production that brings together different theories, principles, and techniques in a way that reduces waste, maximizes value, meets customer needs, and smooths out differences in workflow and activities that don't add value in a collaborative, respectful, and people-centred environment [11]. At the heart of these definitions is the fundamental nature of LC as an innovative production management philosophy that directly contests the conventional trade-off among quality, cost, and time [9]. Lean approaches are being used in renewable energy building to improve efficiency and minimize waste. Their integration facilitates prompt delivery, resource optimization, and sustainability across project phases [12]. Lean construction concepts prioritize the delivery of optimal value while minimizing waste, hence enhancing project performance considerably. Their application augments efficiency, diminishes operating expenses, and elevates client happiness. These benefits are especially critical for the solar energy sector, where timely and cost-effective execution is essential [13]. The application of lean principles in engineering and construction has shown great promise for enhancing productivity and reducing environmental impact. According to a thorough analysis, the most important Lean principle is waste reduction. Case studies have shown that by efficiently applying Lean approaches, material waste may be reduced by 15% to 30% [14].

2.2. Application of Lean in Solar Sector

Research on solar photovoltaic (PV) installations indicates that the application of Lean methodologies, such as Value Stream Mapping (VSM) and the Last Planner System, can decrease project length by as much as 25%. These findings underscore Lean's efficacy in enhancing stakeholder cooperation and maximizing resource utilization. These results validate the efficacy of Lean approaches in expediting solar project implementation and enhancing sustainability [12]. Research indicates that the implementation of Lean methodologies in solar photovoltaic (PV) projects, including Value Stream Mapping (VSM), Just-in-Time (JIT), 5S, and the Last Planner System, has resulted in quantifiable enhancements in performance indicators. The implementation of VSM in solar farm development decreased non-value-adding operations by more than 30%, resulting in expedited project delivery [15]. The Last Planner System has demonstrated efficacy in enhancing workflow dependability and minimizing time overruns in solar installation projects [16]. Lean practices have gained traction in Pakistan and other developing countries to mitigate challenges related to material waste, ineffective site management, and coordination failures among stakeholders [4]. With interdisciplinary teams and improved supply chain responsiveness, Lean Construction concepts contributed to the reduction of

project delays in solar infrastructure projects. In addition, Lean techniques contribute to sustainable development by reducing the carbon footprint of construction activities and optimizing the use of resources, which is in line with the United Nations' Sustainable Development Goal 7 [17]. Nonetheless, obstacles remain in the use of Lean principles within the solar industry. These factors encompass resistance to change, insufficient formal training, and a poor understanding of Lean advantages among middle management. Successful Lean implementation in renewable energy building projects necessitates robust leadership commitment, process standardization, and a culture of continuous learning [18]. Ultimately, solar companies may help achieve sustainability goals in the areas of both the environment and society by implementing Lean management practices. Solar companies, especially those in developing nations like Pakistan, can speed up the shift to renewable energy sources and overcome operational hurdles with the use of a framework that combines Lean technologies with sustainability indicators.

2.3.Impact on Waste Reduction and Sustainability

A substantial body of work highlights the influence of Lean methods on waste minimization and sustainability in solar construction [12]. By implementing lean approaches, material waste during solar panel installations can be efficiently minimized by as much as 30%. The research contends that Lean does more than just boost efficiency; it also helps bring sustainability objectives into harmony by lessening the impact that solar installations have on the environment [13].

Sustainable development necessitates the conservation of natural capital, which regulations stipulate must include renewable natural capital [19]. Two distinct principles of sustainable development pertinent to the stewardship of renewable resources. Initially, harvest rates must match regeneration rates, a concept known as sustainable yield. Natural capital should be recognized as possessing regenerative and assimilative capacities, and neglecting to preserve these capacities constitutes capital consumption, which is unsustainable. Natural and artificial capital can be sustained at multiple levels. Secondly, waste emission rates must correspond to the intrinsic absorption capacity of the ecosystems receiving the waste. Natural capital serves as a supplementary source of raw materials and energy alongside artificial capital [20]. Governments formulate long-term visions for sustainable national infrastructure systems, alongside adaptable strategies to illustrate their objectives [21]. Similarly, it was investigated how infrastructure systems serve as the backbone of every society by offering basic services such as water, energy, waste management and natural resources [22]. Consequently, sustainability and environmental consciousness should commence with the selection and use of eco-friendly materials that provide advantageous characteristics compared to traditional construction materials.

2.4. Challenges to Lean Implementation

Considering the benefits, numerous studies have identified challenges such as organizational opposition, inadequate managerial support, and insufficient employee training to the effective application of Lean practices in solar building. [12] [23].

Solar PV technology has advanced dramatically, as can be seen in research by [19], In recent years, it has, however, proven inadequate and necessitates additional investigation. The low conversion efficiency of solar PV technology relative to conventional systems remains the primary technological obstacle in the advancement of solar energy systems. A further limitation is the incapacity of solar facilities to promptly adjust to load demand. This issue is absent in conventional power plants, leading to enhanced efficiency [24]. Multiple studies illustrate various technological challenges in solar energy generation, including the intermittent nature of solar radiation, which hinders the photovoltaic system's capacity to satisfy consumer demand, and discrepancies between standard and real-time conditions that impact performance. When a component malfunctions, the solar photovoltaic system often becomes nonfunctional until the component is substituted [19]. Despite numerous studies endorsing the significance of lean methodologies for enhancing operational flow, challenges persist in its implementation. The primary drawbacks are its inadequacy in addressing variance and the absence of acknowledgment of human factors, alongside the operational emphasis limited to the workplace floor [4]. Numerous issues are indicated by grievances from trade unions and the escalation of employee duties within corporations, without a corresponding increase in compensation. These issues stem from a misconception regarding the mechanism of lean principles are especially pronounced in small and medium enterprises [25]. The issues stem not from lean itself, but from the necessity to comprehend its functionality. The effective deployment of lean is predominantly contingent upon the senior management's comprehension of its operational processes and the appropriate implementation strategies. Also, there is a necessity for a mutual understanding between senior management and employees to collaboratively foster an image of integrated application, with the imperative to cultivate long-term employees and leaders [26].

2.5. Sustainable Solar Energy through Lean Practices

The concept of lean gained prominence through the publication of “The Machine That

Changed the World." The lean idea is characterized by various definitions, since it continues to evolve [27]. The use of lean practices is prevalent method of continuous improvement that has transformed global manufacturing methods, practices, and principles [4]. Also, it centres on a mindset of ongoing performance enhancement through systematic waste elimination on the production floor [4]. A literature review concurred that the primary principles of lean are Value, Value Stream, Flow, Pull, and Perfection, the principles were introduced to tackle the numerous issues that emerged within and among business divisions due to discrepancies in corporate culture and management philosophies [28]. Lean approaches promote sustainability across three interconnected dimensions: environmental, economic, and social. Lean tools, like Value Stream Mapping (VSM) and Just-In-Time (JIT), mitigate material waste and energy consumption by optimizing operations and enhancing workflow efficiency. Ballard and Howell (2003) asserted that the Last Planner System improves planning precision and mitigates delays in construction projects, resulting in more efficient resource utilization and diminished environmental effect [16]. In solar photovoltaic (PV) installations, researchers have documented a 25% decrease in project duration and substantial cost reductions achieved using Lean practices [29], [18]. These enhancements not only diminish greenhouse gas emissions linked to construction but also decrease the lifespan expenses of solar infrastructure.

Economically, Lean management facilitates solar companies in enhancing profit margins by decreasing inventory expenses, augmenting labour productivity, and eliminating rework. Just-In-Time (JIT) and Kanban systems, when utilized in solar component procurement and installation, guarantee the delivery of only essential components at the required time, hence minimizing storage expenses and mitigating damage hazards. Lean principles improve customer happiness and financial performance by closely aligning production with demand, a characteristic especially beneficial in dynamic industries such as solar energy [30]. Socially, Lean fosters employee empowerment by systematic problem-solving, clear communication, and ongoing education. Methods like Kaizen events and Gemba walks promote inclusive decision-making and enhance employee engagement, resulting in increased job satisfaction and diminished occupational risks particularly pertinent on labour-intensive solar installation sites [31].

Numerous academics assert that lean is intrinsically connected to sustainability, as lean facilitates key objectives of sustainability, including cost reduction, emission minimization, economic value creation, and improvement in assessing the work environment [4].

Developing countries have implementation hurdles despite these benefits. Lack of understanding, training, cultural aversion to change, and fragmented supply networks are issues. In Pakistan, Lean is still seen as a production strategy, not a project management

philosophy. *Figure 2* illustrates Lean practices to enhance solar energy projects. This strategy focuses on two primary domains: Efficiency Enhancement, utilizing techniques such as Value Stream Mapping (VSM), Just-In-Time (JIT), and the Last Planner System; and Waste Mitigation, emphasizing the reduction of material waste and environmental sustainability. The implementation of lean principles in solar construction seeks to attain substantial sustainability objectives, encompassing emissions reduction, cost minimization, and workforce empowerment. Nonetheless, the implementation encounters significant challenges, including insufficient training, poor leadership support, and technical constraints.

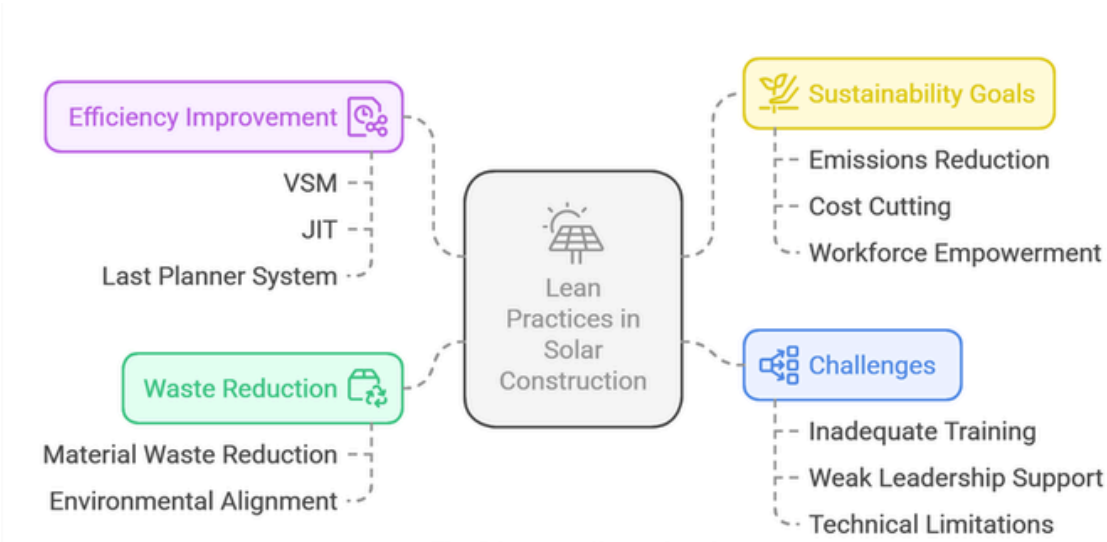


Fig. 2. Lean Practices in Solar Construction (source: the authors)

3. Research Methodology

A mixed-methods strategy was utilized, combining qualitative and quantitative techniques to investigate the research, as previously implemented such as [12] [14]. This method facilitates a thorough comprehension of the problems and efficacy of Lean practices in solar projects through the triangulation of data from experts. To formulate semi-structured questions for surveys and interviews, the Delphi approach was employed in accordance with prior studies such as [32], [33], [34]. Brainstorming sessions were conducted with experts from the solar energy industry, academic scholars, professional peers, and relevant engineering professionals to gather diverse perspectives. A questionnaire was then distributed to 150 targeted stakeholders using purposive sampling techniques, as recommended by [1], resulting in 115 valid responses. Furthermore, comprehensive interviews were carried out with 50 chosen specialists to obtain a more profound understanding of the perceived advantages, current challenges, and the kind of institutional and policy support necessary to improve sustainability in the solar energy sector. Survey data was evaluated with SPSS statistical software as conducted by [12] [35], [36], to find trends, correlations, and patterns associated with Lean implementation in solar development. Participants were thoroughly briefed on the study's goal and scope before their involvement, and their informed consent was secured to guarantee voluntary participation. All data obtained from surveys and interviews were managed with stringent secrecy as shown in *Figure 3*. Personal identifiers were eliminated to preserve anonymity, and the material was

utilized exclusively for scholarly and analytical purposes within the scope of this research.

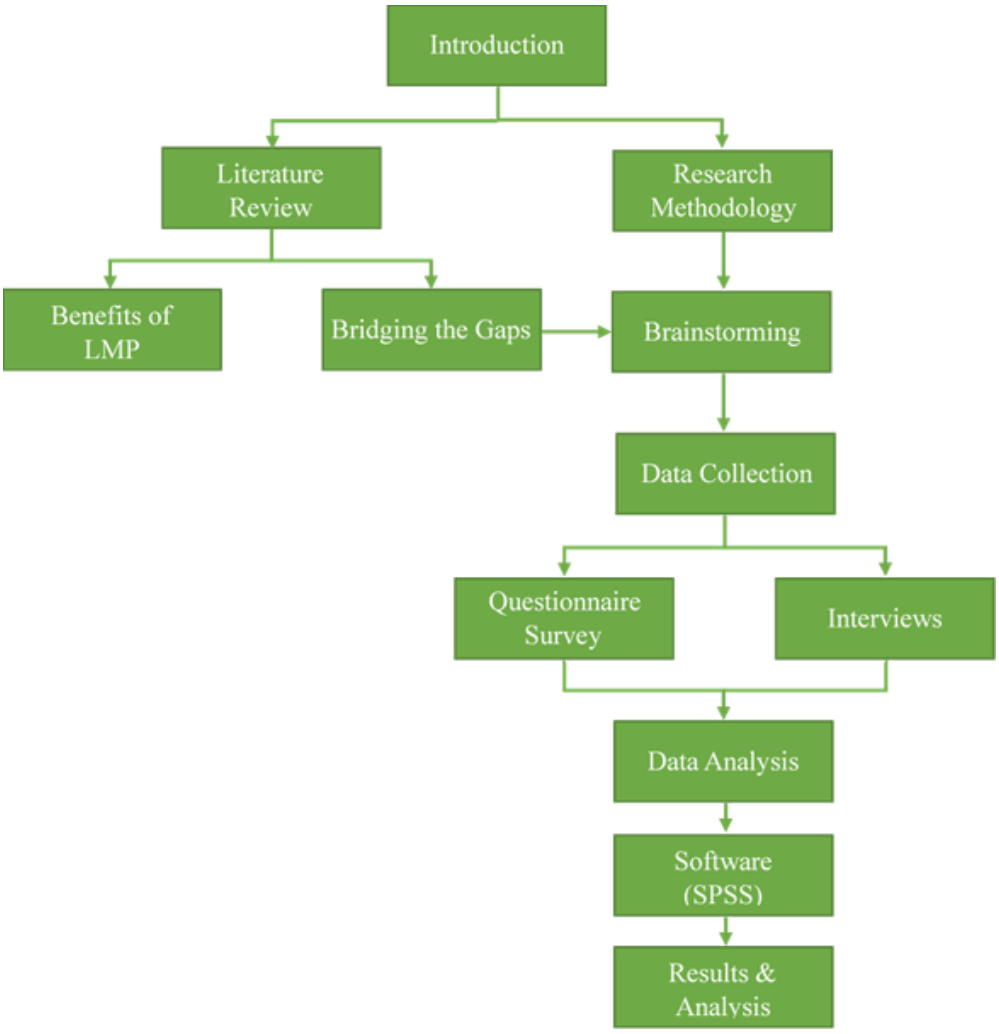


Fig. 3.Flowchart for Research Methodology

4. Results & Analysis

4.1. Respondent's Profile

Figure 4 offers essential information into the professional backgrounds of respondents involved in the study on Lean Management methods and sustainability within the solar energy sector. It underscores the variety in positions, expertise levels, and project types, hence augmenting the validity and representativeness of the research findings. Within the Role in Organization category, the data indicates that Site Engineers constitute the predominant group at 30.5%, highlighting their substantial participation in on-site project execution. Quality/Operations Managers and Design Engineers account for 25.3% and 24.2%, respectively, indicating a significant presence of professionals tasked with maintaining process efficiency and design coherence—both integral to Lean methodologies. Project Managers, responsible for planning and coordination, constitute 20.0%, providing strategic insights into implementation issues and overarching decision-making.

Most respondents (32.6%) indicated having 6–10 years of experience, demonstrating a

sophisticated comprehension of the construction sector and operational methodologies. Individuals with fewer than 2 years of experience constitute 27.4%, contributing novel insights, whilst those with 2–5 years and over 10 years of experience are evenly represented at 20.0% each. This broad spectrum facilitates a thorough comprehension of Lean adoption from both novice and experienced experts.

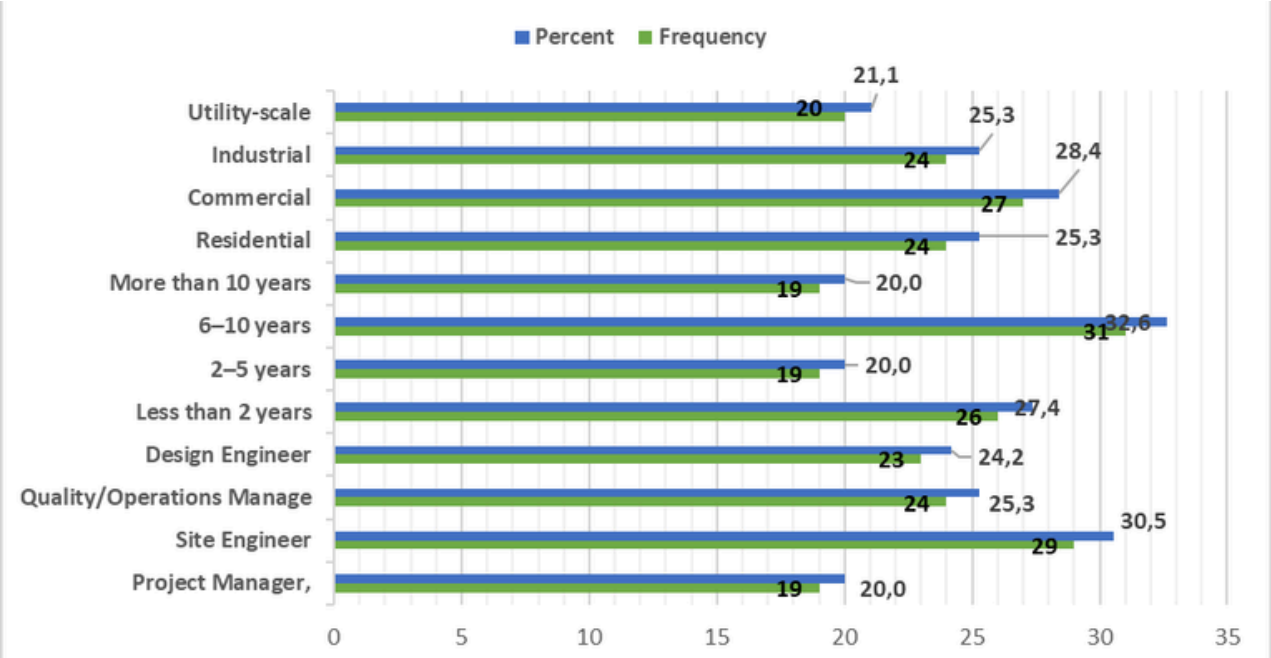


Fig. 4. Respondents Profile

Concerning Types of Projects, Commercial projects constitute 28.4%, closely followed by Residential and Industrial projects, each at 25.3% Utility-scale projects constitute 21.1%, reflecting the involvement of specialists engaged in extensive solar infrastructure development. This distribution across several project types guarantees that the data encompasses a comprehensive perspective on Lean techniques and sustainability initiatives across all scopes and difficulties of solar energy deployment. The table illustrates a comprehensive respondent profile, enhancing the robustness and generalizability of the study findings to diverse solar building situations in developing nations such as Pakistan.

4.2.Benefits & Sustainability Achieved in dimensions by Using Lean Tools

The *Table 1* delineates the contributions of several Lean Management Practices (LMP) to project advantages and sustainability aspects within the solar energy sector.

Value Stream Mapping (VSM) and Just-In-Time (JIT) methodologies provide the most significant influence, particularly in minimizing material waste, enhancing deadlines, and attaining environmental and economic sustainability. 5S demonstrated negligible advantages, with only enhancements in timelines and economic sustainability noted. Kaizen had a moderate impact on all three areas of sustainability. The "All of these" category signifies that employing a mix of LMP strategies substantially aids in attaining all dimensions of sustainability, with 12 responses affirming large advantages. In contrast, individuals not utilizing LMPs or uncertain about their use reported diminished or absent advantages, along with increased occurrences of "none" regarding sustainability outcomes. This underscores the strong association between LMP adoption and improved sustainability in project performance.

Table 1. Benefits and Sustainability Achieved by Adopting LMP

LMP (Tools)	Benefits Achieved							Sustainability Achieved in Dimensions				
	Reduced material waste	Better resource management	Improved project timelines	Reduced costs	Improved team collaboration	Enhanced energy efficiency	None	Environmental	Economic	Social	All of them	None
5S	0	1	5	0	0	0	0	0	6	0	0	0
Kaizen	0	1	1	2	0	0	0	1	1	1	1	0
VSM	5	0	6	1	1	4	0	1	5	5	6	0
JIT	6	1	2	2	0	0	0	8	1	2	0	0
Reducing Rework	1	2	1	0	1	1	0	1	2	1	2	0
All of these	1	5	3	0	3	2	0	0	0	2	12	0
None	1	0	0	7	0	0	14	0	6	4	0	12
Not Sure	0	1	0	9	1	0	4	0	7	4	0	4
Total	**14**	**11**	**18**	**21**	**6**	**7**	**18**	**11**	**28**	**19**	**21**	**16**

A more convenient version of the table is available via the QR code.

The correlation *Table 2* illustrates statistically significant links among the utilization of Lean tools, observed sustainability advantages, and the sustainability aspects affected by Lean practices, derived from a sample size of 95 respondents. The Pearson correlation coefficients indicate positive and relatively strong relationships among all three variables, implying a significant interrelation with Lean adoption in the solar energy sector. The association between "Which Lean tools has your organization utilized?" and "What sustainability benefits have you observed from Lean adoption?" is 0.469, significant at the 0.01 level. This signifies a moderate positive correlation, indicating that firms employing a broader array of Lean technologies are likely to achieve more significant sustainability advantages, including diminished waste, enhanced energy efficiency, and cost reductions.

Table 2. Correlation among LMP, Benefits & Sustainability observed

		Which Lean tools has your organization used?	**What sustainability benefits have you observed through Lean adoption?**	**Which sustainability dimensions are most influenced by Lean practices in your experience?**
Which Lean tools has your organization used?	Pearson Correlation	1	.469**	.377**
	Sig. (2-tailed)		0.000	0.000
	N	95	95	95
What sustainability benefits have you observed through Lean adoption?	Pearson Correlation	.469**	1	.562**
	Sig. (2-tailed)	0.000		0.000
	N	95	95	95
Which sustainability dimensions are most influenced by Lean practices in your experience?	Pearson Correlation	.377**	.562**	1
	Sig. (2-tailed)	0.000	0.000	
	N	95	95	95
**. Correlation is significant at the 0.01 level (2-tailed).				

The association between "Which Lean tools has your organization utilized?" and "Which sustainability dimensions are most impacted by Lean practices?" is 0.377, significant at the 0.01 level. This indicates that with the increased application of Lean technologies, respondents recognize a wider impact on essential sustainability elements (economic, environmental, or social), hence supporting Lean's contribution to comprehensive sustainable development.

The most robust connection identified is 0.562 between sustainability benefits and the sustainability characteristics affected, which is statistically significant. This suggests that an increase in reported sustainability advantages from Lean techniques correlates with a

heightened acknowledgment of its favourable effects across multiple sustainability aspects. These results underscore the efficacy of Lean approaches in improving sustainability in the construction and solar energy industries.

4.3. Key Challenges & Requirement of Government Support

The *Table 3* displays a cross-tabulation of management support, governmental support requirements, and principal hurdles in executing Lean methods within solar projects.
The data indicates that "Cost of implementation" is the primary issue encountered by firms with highly supportive top management (23 replies), suggesting that even robust leadership is impeded by financial limitations in Lean adoption. In contrast, "Lack of awareness/training" is exclusively linked to businesses without managerial support (19 replies), highlighting the essential function of leadership in fostering knowledge and awareness. Both "Resistance to change" and "Inadequate tools or infrastructure" were only reported by respondents from businesses with moderately supportive management, each with 18 replies. This indicates that partial help may be inadequate to surmount technological and cultural obstacles. Most respondents assert that national awareness campaigns (41) and financial incentives or subsidies (35) are essential, particularly in the absence of internal organizational support. The obligatory incorporation of Lean in contracts was endorsed by proponents claiming insufficient awareness and training, underscoring the necessity for regulatory enforcement to promote adoption. The table demonstrates that effective Lean implementation in solar projects relies on a synergy of robust internal management support and certain external government actions.

Table 3. Cross-tabulation among Challenges, Management Role & Government Support

		Is top management supportive of Lean implementation in your organization?				What level of government support is needed to promote Lean adoption?		
		Very supportive	**Somewhat supportive**	**Neutral**	**Not supportive**	**Mandatory inclusion in contracts**	**Financial incentives or subsidies**	**National awareness programs**
What are the key challenges in implementing Lean practices in solar projects? (Select all that apply)	**Lack of awareness/ training**	0	0	0	19	19	0	0
	Resistance to change	0	18	0	0	0	0	18
	Lack of management support	0	0	17	0	0	17	0
	Inadequate tools or infrastructure	0	18	0	0	0	18	0
	Cost of implementation	23	0	0	0	0	0	23
Total		23	36	17	19	19	35	41

The examination of principal challenges uncovers a multifaceted environment wherein internal organizational constraints and external structural deficiencies coalesce to hinder the successful execution of Lean practices in solar initiatives. Among the most notable obstacles identified, implementation costs (n = 23) arise as a pivotal obstacle, particularly in businesses with strong support from senior management. This paradox indicates that although strategic leadership may advocate for Lean ideals, budgetary limitations frequently impede their implementation. It underscores the necessity for specific financial instruments, such as capital subsidies or tax incentives, to transform managerial purpose into tangible results. A significant challenge is the insufficient awareness and training (n = 19), stated solely by respondents from organizations that are unsupportive of Lean adoption. This pattern suggests that in settings with disengaged leadership, employee familiarity with Lean tools and processes is limited. Consequently, a cascading effect ensues in the absence of leadership understanding, operational teams stay untrained, resulting in stagnation of innovation and process enhancement. The resistance to change (n = 18) and insufficient tools or infrastructure (n = 18), both noted under somewhat supportive leadership, underscore structural inflexibility and technological constraints. These comments indicate that little managerial support is inadequate to dismantle established practices or to facilitate the infrastructural enhancements required for Lean implementation. In these instances, organizational inertia, along with obsolete tools, constrains the adaptability and responsiveness of solar companies, particularly in swiftly changing technology environments.

The absence of management support (n = 17), categorized under neutral leadership, indicates a situation where Lean principles may be conceptually grasped but lack the necessary endorsement or resources for execution. This state impedes progress and results in

disjointed or experimental adoption without comprehensive integration. These findings highlight the complex obstacles associated with Lean adoption in the solar business. The text underscores the urgent necessity for a dual-intervention model: one that entails internal organizational transformation, focusing on leadership involvement and capacity enhancement; and the other necessitating external assistance from governmental and industry regulators, encompassing awareness initiatives, obligatory contract stipulations, and infrastructure investment. Neglecting these elements in Lean implementation efforts may result in shallow, fragmented, and ultimately unsustainable outcomes over time. This table provides a detailed analysis of the connections among organizational leadership, governmental support systems, and the primary obstacles faced in the execution of Lean Management Practices (LMP) in the solar energy sector, especially in developing regions like Pakistan. The research indicates a substantial association between the extent of top management support and the characteristics of the issues encountered by firms.

The cost of implementation is a significant barrier (n = 23), mentioned solely by respondents from firms with strong support from senior management for Lean efforts. This observation highlights a conundrum in which the strategic support for Lean concepts is present, while financial limitations impede practical implementation. This underscores the need for supplementary external interventions, such as financial incentives, grants, or subsidies, to translate executive purpose into quantifiable results. In contrast, the absence of awareness and training (n = 19) is exclusively reported by firms with unsupportive leadership, highlighting a systemic disjunction between executive priorities and operational preparedness. In these circumstances, a lack of leadership commitment seems to closely correspond with restricted information diffusion and diminished adoption of Lean approaches throughout the workforce. Challenges such as resistance to change (n = 18) and inadequate tools or infrastructure (n = 18), primarily reported under somewhat supportive leadership, underscore the structural rigidity and operational inertia that can obstruct Lean integration, especially in technologically deficient settings. The obstacle of insufficient management support (n = 17) under neutral leadership exemplifies a condition of organizational ambivalence where Lean may be conceptually recognized but is neither advocated nor sufficiently funded, resulting not disjointed or shallow implementation attempts. Stakeholders predominantly advocate for national awareness programs (n = 41) and financial incentives (n = 35) as essential support mechanisms among external enablers. Furthermore, the compulsory incorporation of Lean clauses in contracts (n = 19) is recommended by individuals facing educational and institutional constraints, indicating that regulatory enforcement could be crucial in normalizing Lean techniques throughout the business. The findings underscore that successful Lean adoption in the solar business requires a dual-pronged strategy. Effective and enduring leadership is essential for fostering organizational transformation and cultural preparedness. External political policies, financial frameworks, and awareness campaigns are crucial to alleviate economic and informational obstacles. In the absence of integrative efforts, Lean projects may become fragmented, diminishing their capacity to improve sustainability and performance in the solar energy sector.

4.4. Suggestions by Experts

Figure 5 examines the perspectives of several stakeholders in Pakistan's solar energy sector concerning the most successful strategies to promote the adoption of Lean Management methods. The analysis utilizes replies from 95 experts classified by their respective roles: Project Managers, Site Engineers, Quality/Operations Managers, and Design

Engineers. Each group was instructed to select desired actions from a list comprising certification and training programs, regulatory policy reforms, inclusion in public tenders/contracts, pilot projects and benchmarking, and a comprehensive plan. The findings provide detailed insights into the perspectives of professionals according to their functional roles. A considerable number of Project Managers highlighted the significance of certification and training programs (n=7) as well as pilot projects and benchmarking (n=6). This indicates a strategy perspective that emphasizes capacity-building and performance assessment systems as essential for Lean implementation. Site Engineers, primarily involved in field execution, equally emphasized training (n=9) and pilot projects (n=7) as essential, showing a practical necessity for experiential learning and demonstrable use of Lean principles.

Fig. 5. Suggestions by Experts

Conversely, Quality/Operations Managers shown a pronounced inclination towards an integrated approach, opting for "All of these" (n=9), indicating that no one measure would suffice independently. Their preference for a multi-faceted strategy emphasizes the necessity for coordinated actions across policy, education, procurement, and implementation sectors. Design Engineers, positioned upstream in the construction lifecycle, expressed a preference for pilot projects (n=6) and contractual inclusion (n=5), indicating a necessity for the procedural integration of Lean principles into formal project frameworks. The cross-functional analysis indicates that although training and pilot projects are universally deemed essential, the significance of institutional support via policy reform and contractual mandates is acknowledged—especially by individuals in quality assurance and design development roles. The findings collectively validate the imperative of a hybrid top-down and bottom-up approach for enhancing Lean Management in Pakistan's solar construction industry. This includes the formulation of legislative frameworks, capacity-building programs, and the institutionalization of Lean methodologies inside public procurement and project planning systems. This holistic approach would conform to global best practices and enhance the long-term sustainability and competitiveness of Pakistan's renewable energy sector.

5. Interviews with the Experts

5.1. Understanding and Familiarity with Lean Practices in the Solar Sector

Participants from various positions such as Project Managers, Site Engineers, Quality/Operations Managers, and Design Engineers exhibited differing degrees of knowledge with Lean Management methodologies. Most participants with more than 6 years of experience, especially those engaged in industrial and utility-scale solar projects, demonstrated a robust familiarity with Lean methods like 5S, Kaizen, Value Stream Mapping (VSM), Just-in-Time (JIT), and Reducing Rework (RW). A few of junior professionals (2–5 years of experience) recognized possessing merely a theoretical comprehension, typically acquired throughout their academic education or through minimal practical exposure. All responders acknowledged Lean as a systematic methodology designed to eradicate waste, optimize process flow, and augment project value.

5.2. Observed Benefits from Lean Implementation

Professionals interviewed repeatedly stated that solar construction projects benefited materially from the application of Lean principles. Among the most often mentioned benefits were: (I) Enhanced workflow effectiveness and resource management, especially with the use of VSM and JIT tools. (II) Decrease (25%-30%) in material waste at critical stages of solar panel installation. (III) Improved project schedules; participants reported a 15–20% reduction in the time needed to complete the project. (IV) Improved team coordination, particularly with the Last Planner System and Kaizen. (V) Savings improved inventory control and reduced rework. These advantages were especially noticeable in projects at the utility and industrial scales, when Lean methodologies were used more strictly.

5.3. Sustainability Achieved through Lean Practices

Interviewees firmly linked Lean principles to sustainability outcomes, noting beneficial effects:

5.3.1. Environmental Sustainability: The majority of respondents noted a direct decrease in carbon footprints associated with construction, reduced energy consumption, and material conservation, particularly in areas where Just-in-Time and 5S methodologies were applied.

5.3.2. Economic Sustainability: Almost all participants concurred that Lean enhanced financial performance by reducing costs, preventing rework, and optimizing worker efficiency.

5.3.3. Social Sustainability: Lean methodologies such as Kaizen and Gemba walks were recognized for enhancing worker engagement, job happiness, and safety on solar project sites.

Several professionals indicated that Lean's collaborative and people-centric mindset contributed to improved team morale, a crucial element in maintaining social cohesion at project sites.

5.4. Challenges Faced During Implementation

Participants identified multiple obstacles to the introduction of Lean methodologies in the solar industry:

- The predominant difficulty identified was the absence of formal training and knowledge among field engineers and supervisors.
- Resistance to change, particularly from seasoned personnel familiar with conventional practices, impeded the implementation of Lean.
- Insufficient infrastructure or digital tools to facilitate Lean processes (e.g., VSM software, JIT logistics) were another troublesome.
- The uneven support from top management and the lack of internal policy demands hindered the institutionalization of Lean methods.

In response, several organizations implemented pilot projects or designated Lean champions at the site level to incrementally alter mindsets and evaluate Lean advantages in limited contexts prior to broader implementation.

5.5. Strategies Used to Overcome Challenges on Site

Numerous specialists delineated the proactive strategies they employed to tackle these challenges:

- Workplace training sessions conducted by senior engineers proficient in Lean methodologies.
- Visual management systems and performance dashboards that render Lean adoption quantifiable and transparent.
- Weekly coordination meetings to mitigate miscommunication and encourage a culture of continual improvement.
- Incremental implementation strategies initiating with 5S and progressively including more sophisticated tools such as VSM or JIT.

These localized solutions enhanced stakeholder engagement and enabled teams to develop Lean capabilities organically.

5.6. Suggestions to Top Management and the Government of Pakistan

5.6.1. To Top Management:

- Integrate Lean KPIs into project performance evaluations.
- Allocate resources for Lean-focused training and certifications for personnel.
- Establish Lean policies throughout departments to guarantee consistency and dedication.
- Advocate for success narratives and internal benchmarking to enhance motivation and facilitate adoption.

5.6.2. To the Government of Pakistan:

- Compulsory use of Lean methodologies in public tender papers for solar and infrastructure initiatives.
- Initiate national awareness initiatives cantered on Lean principles for sustainability in construction.
- Offer cash incentives or tax concessions to companies executing certified Lean initiatives.
- Formulate public-private collaborations to initiate Lean implementation frameworks and assess results.

6. Discussion

6.1. Understanding and Familiarity with Lean Practices

The results indicate an increasing but inconsistent comprehension of Lean principles among various jobs in the solar industry. Site engineers and project managers demonstrated moderate to high knowledge with Lean principles, whereas design engineers and younger personnel exhibited confusion or minimal exposure. Interview insights indicated that experience significantly influences awareness; individuals with 6–10 years of field experience demonstrated more familiarity with Lean applications, having observed its effectiveness in reducing delays and optimizing resource management on solar construction sites.

6.2. Perceived Advantages of Lean Implementation

Participants identified numerous advantages associated with Lean adoption, with diminished material waste and enhanced project timeframes being the most mentioned results. Instruments like VSM and JIT facilitated the optimization of procurement and inventory processes, resulting in enhanced operational efficiency. A substantial number of participants recognized the role of Lean methods in improving environmental performance, including energy conservation and diminished carbon footprints.

6.3. Accomplishments in Sustainability

Lean approaches were perceived as positively impacting all three pillars of sustainability. Environmentally, there were reductions in material and energy waste; economically, Lean facilitated cost reduction and enhanced production; and socially, it empowered teams by clarifying responsibilities and improving communication. The implementation of technologies such as Kaizen and the Last Planner System fostered a collaborative culture, resulting in enhanced stakeholder alignment and accountability.

6.4. Obstacles in Execution

Notwithstanding these achievements, numerous companies encountered significant implementation obstacles. Resistance to change, especially among senior management, was a prevalent issue. Numerous companies lacked organized training programs or access to Lean-specific resources. Smaller enterprises were particularly hindered by financial and resource constraints. Adequate assistance from senior management and clear regulations from regulatory authorities were consistently seen as obstacles, highlighting the necessity for leadership commitment and strategic vision. *Figure 6* demonstrates an evolving comprehension of lean principles across various professional areas. It illustrates a continuum from little to comprehensive lean understanding. Junior personnel demonstrate uncertainty and limited familiarity with lean principles, whereas design engineers indicate a moderate comprehension. Site Engineers possess moderate to advanced expertise, while Project Managers display expert-level understanding of lean principles. This visual depiction indicates a clear relationship between professional experience, role responsibility, and the extent of lean knowledge inside an organizational framework.

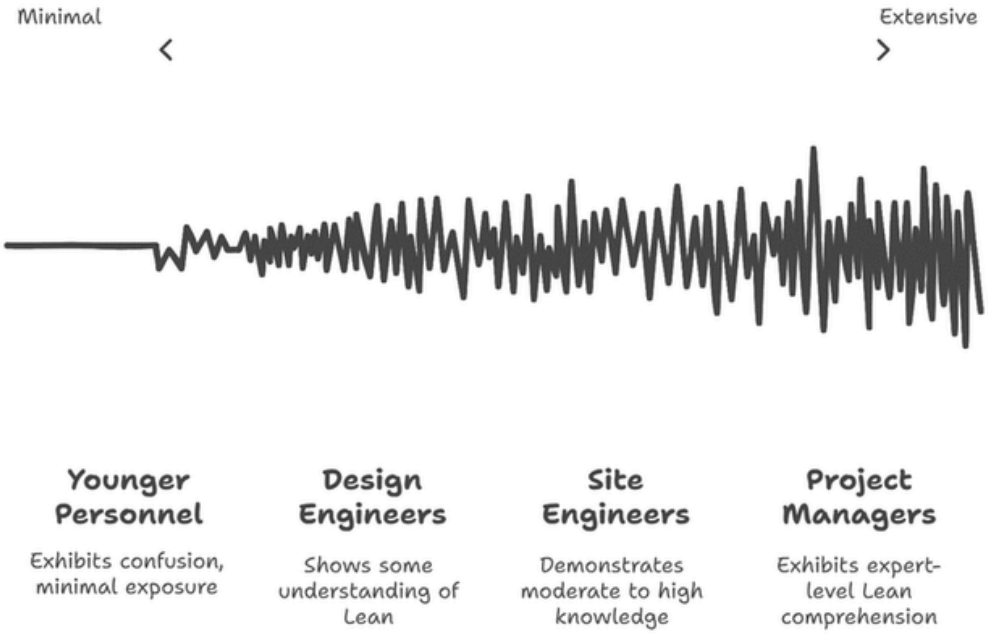


Fig. 6. Lean comprehension varies across roles and experience levels (source: the authors)

7. Conclusion

This study examined the incorporation of Lean Management Practices (LMP) inside Pakistan's solar energy sector to enhance sustainability across environmental, economic, and social aspects. A mixed-methods strategy utilizing a structured questionnaire (n=95) and semi-structured interviews (n=50) was implemented to collect data from professionals such as project managers, engineers, quality managers, and design specialists. The investigation indicated that, although the awareness and utilization of Lean tools like 5S, Kaizen, JIT, and VSM are comparatively low, respondents possess a robust perception of their potential to

enhance efficiency, minimize waste, and optimize project timeframes. Statistical findings validated a substantial association between the implementation of Lean techniques and the observed enhancements in sustainability outcomes, namely in minimizing material waste, augmenting energy efficiency, and refining cost control. Notwithstanding the optimistic perspective, many obstacles remain, such as inadequate awareness and training, reluctance to adapt, insufficient managerial backing, and elevated implementation expenses. Respondents with over 6 years of experience demonstrated greater knowledge with Lean principles and were more inclined to have witnessed concrete sustainability benefits. The study indicates that the implementation of Lean methods provides a strategic avenue for Pakistan's solar energy sector to attain its sustainability objectives, contingent upon the enhancement of organizational and policy-level support mechanisms.

8. Recommendation

This research examines the influence of Lean Management Practices (LMP) on enhancing sustainability within Pakistan's solar energy sector through a mixed-methods approach. A total of 95 survey responses and 50 interviews were obtained from various stakeholders, including project managers, engineers, and quality managers. The results indicate that professionals with more than six years of experience possess greater familiarity with and are more inclined to utilize Lean methods such as 5S, Kaizen, JIT, and VSM. These techniques were linked to diminished material waste, optimized project schedules, cost-effectiveness, improved communication, and greater resource use. Participants confirmed that Lean approaches significantly enhance environmental, economic, and social sustainability by reducing emissions, optimizing costs, and promoting team accountability.

Notwithstanding these advantages, significant obstacles such as aversion to change, inadequate managerial support, insufficient training, and elevated implementation costs impede wider adoption, particularly among smaller enterprises. Interviewees underscored the necessity for technical proficiency, leadership involvement, and cultural transformation to facilitate successful Lean adoption. To surmount these obstacles, stakeholders advocated for structured training, pilot initiatives, and active leadership engagement. They urged national organizations such as AEDB and NEPRA to incorporate Lean criteria into public policy and contracting, while advocating for governmental support through incentives and awareness initiatives. These solutions are seen as essential for enhancing solar building efficiency and furthering Pakistan's sustainability objectives.

9. Framework

Following comprehensive research and expert recommendations, the framework is presented in *Table 4* below. This framework aims to deliver a systematic and pragmatic guide for the implementation of Lean Management concepts within Pakistan's solar energy sector. Its objective is to optimize project workflows, reduce waste, and improve overall operational efficiency. The framework integrates Lean tools with sustainability objectives to promote environmental, economic, and social benefits. Ultimately, it directs stakeholders in attaining economical, prompt, and sustainable solar project execution.

Table 4. Suggested Framework to Achieve Sustainability in Solar Energy Sector

Framework	Lean Practice/Tool	Purpose	Implementation Strategy	Expected Sustainability Outcome	Responsible Entity
1. Planning & Design	Value Stream Mapping (VSM)	Identify & eliminate non-value-added steps	Train planning teams to map project flows	Reduced material & time waste	Design Engineers, PMs
2. Site Management	5S (Sort, Set, Shine, etc.)	Improve site organization & productivity	Weekly audits, signage, layout planning	Improved workflow & efficiency	Site Engineers
3. Procurement & Logistics	Just-In-Time (JIT)	Reduce inventory cost & overproduction	Partner with suppliers for scheduled delivery	Cost savings, reduced storage waste	Procurement Managers
4. Execution & Monitoring	Kaizen	Continuous improvement	Weekly meetings for team suggestions	Better collaboration, quality enhancement	Quality/Operations Managers
5. Risk Minimization	Reducing Rework	Avoid repetitive work and material waste	Conduct design clash detection, real-time progress reviews	Reduced delays, improved quality	QA/QC Team, Design Engineers
6. Training & Awareness	Certification Programs	Build lean capabilities	Partner with institutions (e.g., NUST, UET, etc.) for modules	Skilled workforce, cultural transformation	HR, AEDB, Academia
7. Policy & Regulation	Inclusion in Public Contracts	Institutionalize Lean in tenders	Require Lean practices in RFPs for public-funded solar projects	National sustainability alignment	NEPRA, AEDB, Govt Bodies
8. Performance Evaluation	KPIs for Lean Performance	Track Lean effectiveness	Define metrics (e.g., % rework reduced, time saved)	Data-driven decisions, accountability	Top Management, PMs
9. Benchmarking	Pilot Projects	Demonstrate success	Select 2–3 solar pilot projects to showcase lean implementation	Replicable model for industry-wide scaling	Industry Consortiums, AEDB
10. Community & Social	Gemba Walks	Observe real-time challenges on-site	Managers participate in daily field checks	Enhanced team morale, better safety	Supervisors, PMs

References:

[1] S. V. A. K. O. G. R. S. J. A. Chinmay Pingulkar, "Enhancing Efficiency in Solar Construction Projects through Lean Methodologies," Journal of Quantum Science and Technology (JQST) , vol. 1, no. 1, Mar. 2024.

[2] K. M. Riva Krut, Sustainable Measures, 1st ed. Routledge, 1999.

[3] L. Andrej Kirn; Fakultet za društvene znanosti, "SUSTAINABLE DEVELOPMENT AND ENVIRONMENTAL VALUES," srce, May 2000, pp. 149–162.

[4] B. Aldewachi and Z. Ayağ, "Achieving sustainability in solar energy firms in Turkey through adopting lean principles," Sustainability (Switzerland), vol. 14, no. 1, Jan. 2022, doi: 10.3390/su14010108.

[5] J. A. Garza-Reyes, "Lean and green-a systematic review of the state of the art literature," J Clean Prod, vol. 102, pp. 18–29, Sep. 2015, doi: 10.1016/j.jclepro.2015.04.064.

[6] L. M. Khodeir and R. Othman, "Examining the interaction between lean and sustainability principles in the management process of AEC industry," Ain Shams Engineering Journal, vol. 9, no. 4, pp. 1627–1634, Dec. 2018, doi: 10.1016/j.asej.2016.12.005.

[7] M. J. Lenoxv. all authors and affiliations ANDREW A. KING, "LEAN AND GREEN? AN EMPIRICAL EXAMINATION OF THE RELATIONSHIP BETWEEN LEAN PRODUCTION AND ENVIRONMENTAL PERFORMANCE," Sage Journals POMS, vol. 10, no. 3, pp. 254–256, 2001.

[8] Naveed Hussain; Fahd Hussain, "Pakistan aims for 60% clean energy by 2030," the Express TRIBUNE, Karachi, Jul. 04, 2025.

[9] M. Aslam, E. Baffoe-Twum, and S. Malik, "Benchmarking lean construction conformance in Pakistan's construction industry," Engineering, Construction and Architectural Management, vol. 31, no. 5, pp. 2077–2100, May 2024, doi: 10.1108/ECAM-11-2023-1125.

[10] A. Mossman, "What is lean construction: Another look - 2018," in IGLC 2018 - Proceedings of the 26th Annual Conference of the International Group for Lean Construction: Evolving Lean Construction Towards Mature Production Management Across Cultures and Frontiers, The International Group for Lean Construction, 2018, pp. 1240–1250. doi: 10.24928/2018/0309.

[11] M. Aslam, Z. Gao, and G. Smith, "Optimizing Construction Design Process Using The Lean Based Approach," 2020. [Online]. Available: www.leanconstructionjournal.orgwww.leanconstructionjournal.org

[12] C. Pingulkar, S. Vadlamani, A. Kumar, O. Goel, R. Agarwal, and S. Jain, "Enhancing Efficiency in Solar Construction Projects through Lean Methodologies," Journal of Quantum Science and Technology (JQST), vol. 1, [Online]. Available: www.jqst.org

[13] M. A. Marhani, A. Jaapar, and N. A. A. Bari, "Lean Construction: Towards Enhancing Sustainable Construction in Malaysia," Procedia Soc Behav Sci, vol. 68, pp. 87–98, Dec. 2012, doi: 10.1016/j.sbspro.2012.12.209.

[14] O. Temitope Ayo-Soyemi Engineering Project Manager, "Sustainable Agile-Lean Transformation in Solar Engineering Practices: Bridging Traditional Project Management and Modern Methodologies," IJEDR2502042 International Journal of Engineering Development and Research, p. 306, 2025, [Online]. Available: www.ijedr.org

[15] D. D. A.-D. F. S. S. D. S. David Oswald, "An industry structured for unsafety? An exploration of the cost-safety conundrum in construction project delivery," science direct, vol. 122, Feb. 2020.

[16] G. Ballard and G. A. Howell, "Lean project management," Building Research and Information, vol. 31, no. 2, pp. 119–133, Mar. 2003, doi: 10.1080/09613210301997.

[17] G. Ballard and I. Tommelein, "Lean management methods for complex projects," Engineering Project Organization Journal, vol. 2, no. 1–2, pp. 85–96, Jun. 2012, doi: 10.1080/21573727.2011.641117.

[18] S. M. A. Lincoln H. Forbes, Modern Construction: Lean Project Delivery and Integrated Practices. CRC Group, 2011.

[19] G. Raina and S. Sinha, "Outlook on the Indian scenario of solar energy strategies: Policies and challenges," Apr. 01, 2019, Elsevier Ltd. doi: 10.1016/j.esr.2019.04.005.

[20] Herman E. Daly, Toward some operational principles of sustainable development. In The Economics of Sustainability, 1st ed. London: Taylor and Franci, 2017.

[21] D. A. M. F. S. H. M. H. H. M. N. O. J. R. G. W. & J. W. H. Scott Thacker, "Infrastructure for sustainable development," Nat Sustain, no. 2, pp. 324–331, Apr. 2019.

[22] N. Kumar Sharma, "Sustainable Building Material for Green Building Construction, Conservation and Refurbishing," International Journal of Advance Science and Technology, vol. 29, no. 10S, pp. 5343–5350, 2020, [Online]. Available: https://www.researchgate.net/publication/342946652

[23] P. Dave and R. Owen,) Implementing lean in construction: Lean construction and BIM [CIRIA Guide C725] CIRIA. 2013. [Online]. Available: www.ciria.org/service/lean

[24] N. S. M. N. Izam, Z. Itam, W. L. Sing, and A. Syamsir, "Sustainable Development Perspectives of Solar Energy Technologies with Focus on Solar Photovoltaic—A Review," Apr. 01, 2022, MDPI. doi: 10.3390/en15082790.

[25] D. H. H. 2, H. H. L. 1 Wen Hui Lee 1, "7 - The renewable energy–environment nexus," The Renewable Energy-Water-Environment Nexus Fundamentals, Technology, and Policy, pp. 177–203, Oct. 2023.

[26] Md. M. A. T. M. V. Hasan, "Leading with Lean: A Review of Literature on Lean Leadership.," International Journal on Leadership, vol. 12, no. 2, 2024.

[27] A. Cherrafi, S. Elfezazi, A. Chiarini, A. Mokhlis, and K. Benhida, "The integration of lean manufacturing, Six Sigma and sustainability: A literature review and future research directions for developing a specific model," J Clean Prod, vol. 139, pp. 828–846, Dec. 2016, doi: 10.1016/j.jclepro.2016.08.101.

[28] M. Khalaf Albezuirat, M. Iqbal Hussain, R. Ahmad, N. Noriman Zulkepli, and M. Khalaf Albzeirat, "Improving the Efficiency of Solar Power Plants Through Smart Lean Manufacturing Assessment," 2020. [Online]. Available: https://www.researchgate.net/publication/342693111

[29] Lauri. Koskela, An exploration towards a production theory and its application to construction. Technical Research Centre of Finland, 2000.

[30] R. Shah and P. T. Ward, "Defining and developing measures of lean production," Journal of Operations Management, vol. 25, no. 4, pp. 785–805, Jun. 2007, doi: 10.1016/j.jom.2007.01.019.

[31] L. F. Alarcón, S. Diethelm, O. Rojo, and R. Calderón, "Assessing the impacts of implementing lean construction," Revista Ingenieria de Construccion, vol. 23, no. 1, pp. 26–33, 2008, doi: 10.4067/s0718-50732008000100003.

[32] F. Hasson, S. Keeney, and H. McKenna, "Research guidelines for the Delphi survey technique," J Adv Nurs, vol. 32, no. 4, pp. 1008–1015, 2000, doi: 10.1046/j.1365-2648.2000.t01-1-01567.x.

[33] T. Grisham, "The Delphi technique: a method for testing complex and multifaceted topics," International Journal of Managing Projects in Business, vol. 2, no. 1, pp. 112–130, Jan. 2009, doi: 10.1108/17538370910930545.

[34] M. Evans, P. Farrell, A. Mashali, and W. Zewein, "Critical success factors for adopting building information modelling (BIM) and lean construction practices on construction mega-projects: a Delphi survey," Journal of Engineering, Design and Technology, vol. 19, no. 2, pp. 537–556, Apr. 2021, doi: 10.1108/JEDT-04-2020-0146.

[35] E. N. Shaqour, "The impact of adopting lean construction in Egypt: Level of knowledge, application, and benefits," Ain Shams Engineering Journal, vol. 13, no. 2, Mar. 2022, doi: 10.1016/j.asej.2021.07.005.

[36] E. N. Shaqour, "The role of implementing BIM applications in enhancing project management knowledge areas in Egypt," Ain Shams Engineering Journal, vol. 13, no. 1, Jan. 2022, doi: 10.1016/j.asej.2021.05.023.

EXPLORING THE UNCERTAINTIES AND AMBIGUITIES IN ACCEPTING WIND POWER PROJECTS: EVIDENCE FROM PAKISTAN

Faiz Jalil
Islamic international university, Islamabad, Pakistan
e-mail: muhammad.phdem24@iiu.edu.pk

Dr Rafiq Mansoor. M Usman
Islamic international university, Islamabad, Pakistan
e-mail: rafiq.mansoor@iiuedu.pk

Abstract

Uncertainties and Ambiguities in Accepting Wind Power Projects considered as a necessary phenomenon in development and the implementation of wind power technologies. It is generally argued that public attitudes need to be changed to change the implementation of possible wind energy technologies. The purpose of this analysis is to explore the perceptual factors pertinent to social acceptance of wind energy technologies with special focus on Sahven Sharif and Sakarand wind farms in interior Sindh province of Pakistan. The respondents were interviewed by using open ended questionnaire and the themes were extracted from the responses followed by the categorization of the factors for the easy conclusion of the study. Results of the study revealed that there were various diverse factors has influential role in societal acceptance of wind power projects includes financial and non-financial determinants. The study also revealed some potential implications for the policy makers in order to uplift the wind power projects that will ultimately contributes in improving the existing energy crisis level of the country.

Keywords

Wind Power, Project Management, Community Acceptance, Uncertainty, Ambiguity, and Decision-Making.

1. Introduction

Modern technologies push the world in a new era of green environment. Now a day's corporate sector emphasizes on the renewable energy sources due to the scarcity of the natural resources [1]. It is technology that brings revolutionary change in the business as well as in the lifestyle of society. In the context of renewable energy sources, wind energy is taken into account one amongst the foremost advanced technologies for the applying of renewable energies that is experiencing the strongest growth. The planning and implementation of wind

technologies needs a powerful socio-economic element [2]. Over the past 20 years, the gap between energy demand and its supply has become more and more apparent, with renewable energies and energy sources recently attracting the eye of policymakers and researchers, with customers [3]. In all above-mentioned cycle acceptance of technology plays a vital role, as those who admired and accepted the new development in technologies considered as developed societies however those who didn't know as under developing societies[4]. Therefore, Technology acceptance has become one in every of the foremost important subject.

Pakistan targeted to obtain the status of the highest number of renewable energy users till 2050 and to reach the aim they adopted the wind power source for 70% reliability. To reach the target, local adoption is an important issue and to synchronize new technology adaptation among local communities [3][5][6]. However, due to lack of education and awareness, implementation of new technologies, political and local base community interference has considered as the main issue in order to make the wind power energy dream into reality in Pakistan [7][8][9][10] The municipalities plans for the development of wind turbines faced a flat growth rich is also endorsed by Pakistan renewable Industry Association[11]. The wind projects in Pakistan with the collaboration of Denmark was launched in 2014 with the aim to support GoP target for renewable energy sources by 2050 as well as to sort out the role for local communities by means of awareness to accept the change in the society and support such projects for their future[12]. Therefore, Wind power projects target of 2050 provide food for thought for the researcher to carry out the research in this direction to analyze the factors involved in hindrance of local acceptance and deployment of wind power.

This thesis is an attempt to explore the social and cultural factors of uncertainties and ambiguities as well as the moving attitudes associated with alternative energy. Despite widespread information of alternative energy developments, previous analysis has not adequately explained the relevant social factors [13][14]. It is suggested, however, that the nature, strength and spatial extent of these effects may vary according to the case the native context and also the price of the country. "Therefore, it will be necessary to look at the species the affected landscape within the project and the way it is perceived by the domestic authorities and also the Sindh. In some geographic areas, the Associate in Nursing Offshore website may be the most popular[15][16] on onshore alternatives, but in different geographical areas found differently [17]. In search of various obstacles to the social acceptance of the wind come some studies found the effects of wind turbines on animals, especially birds[18] and the technological characteristics such as the size of the rotary motor and the noise: factors that occur less important[19].

Problem Statement

The U shape development curve for public attitudes toward different projects has been observed by many previous studies, which covers three dimensions of acceptance i.e. pre-installation, post-installation and during installation of different projects range between low, high streams of acceptance [18][13][19].As the wind power projects are on top priority list in government developmental projects due to its environment friendly nature, but at the same time it is facing some sort of resistance from the local communities as it grasps a huge piece of land as well as due to its huge structure they live in constant fear state because this modern equipment is new to them [20].

Therefore, this study intends to explore and analyze those contextual factors (particularly in the case of Pakistan) involved in hindrance of local acceptance and deployment of wind power projects. The study will additionally focus on the factors which produce a sense of

insecurities in local communities with the aim to find out the factors that could possibly improve the acceptation of the wind power projects in the local communities.

2. Literature Review

2.1 Theoretical Evidence

This research concerns the acceptance model of Davis's theory. The technology acceptance model was developed by Davis (1989) and is one of the most common models of research models for predicting the use and acceptance of data systems and technology users. individual. TAM has been extensively studied and verified by completely different studies that study the behavior of technology acceptance in many information system constructions. In the tam-o'-shanter model, there are 2 observed quality factors and the perceived ease of use is a relevant behavior of computer use [20]. Davis defines perceived quality because it is subjective by the likelihood for potential users that the use of a specific application system can improve a person's professional or personal performance[21]. An easy use (EOU) can be defined because of the extent to which the potential user expects the targeting system to suppress the effort. According to tam-o'-shanter, simplicity of use and perceived quality are the most important essential determinants of the actual use of the system. These 2 factors are influenced by variables of external factors. [22][23] have projected a replacement version of the tam-o'-shanter, known as TAM2, which is a new variable for the current model. [24] in a study published in the MIS quarterly review. He proposed the uniform theory of the Technology Acceptance and Use Model (UTAUT). The various studies conducted by the researchers attempted to modify tam-o'-shanter by adding new variables. Agarwal and Prasad (1998a, 1998b) adapted tam-o'-shanter by adding the concept of compatibility to the technology acceptance model. [24][25] intervened in the replacement of variable game factors and study the acceptance of the world network. [25] intended to change the tam-o'-shanter by adding variables such as experience, self-actuality, perceived risk, and social influence [26] [27].

2.2 Empirical Evidence

Public opinion seemed more favorable to wind energy, as educational researchers had foreseen in the 1980s the difficulties of effectively implementing wind farms in their country, especially the visual effects and reactions to wind energy. to this. [28][29]in Sweden; [30][31] argue that most Read more about the acceptance of social networks that you can download via the Internet, and socio-psychological, contextual, socio-economic and spatial. The analysis, the group and the great Called RAL (Random Parameters Logit), the analysis of international analysis results for the acceptance of social networks in preparation for the preparation of the preparatory phase of the preparatory phase projects, Analysis of the price and disputes and denominations in the parts of the parties. According to POLIMP first transitional policy , the decisive influence on the position of the broad audience at the Elian Energy. Other researchers offer you the opportunity to share your experience with the public transport company.[35][36] e.g. B. on the importance of solving the problem in a successful wind energy project. The choice of position is a crucial factor in the acceptance of social welfare, the contradiction of opposition to the aspirations and the appointment of the system of main disputes[37][38]. [39] is an aboriginal community. If owners and sellers of real estate understand that wind turbines are a good source of data collection and collection with an effective result of the well-paid-ratio-in the lower courts of last week wind. An alternative localization inappropriate will therefore strengthen the negative settings towards the wind farms. In general, the general practice of the cancellation of the initiative is as follows, in the sections entitled, informing them of the case law and case law. [39] strongly argue that it is important to involve Initial installation processes are essential for extending support at the zone level. it is | it's often | it will also be supported by [26][32], advising United Nations agencies that community co-management systems will doubtless increase the probabilities of a triple-crown agreement which will profit either side. moreover, empirical proof suggests that private and public communities are generally subject to initial opposition in order to be accepted [40][31]. Negative positions towards the wind farm, on the other side of the road however, this participation alone cannot be improved because acceptance is always the result of a complex interaction of various factors.wind inscription, this surface unit associated with the features of the program itself. to estimate which community star options are most influential on the intention to enter important deductions for developers and managers of the future wind community are coming in Pakistan.

2.3 Evidence from Pakistan

Pakistani wind turbines are generally installed in the coastal areas of southern Islamic Republic of Pakistan to explain and exploit the wind power potential of the selected area. However, the selected wind passage is the city of Jamshoro, In 2023, the Meteorological Department of Pakistan (PMD) launched a wind energy evaluation campaign in South Pakistan. Meteorological masts were installed with anemometers at a height of 10 and 30 m. Analysis of the data collected by these masts confirmed the presence of a logical gust in the coastal strip of Sindh province[38]. More than 40,000 villages in Pakistan are not connected to the national grid and the most isolated villages in the south can be electrified by micro-wind turbines. It is estimated that more than 5,000 villages can be electrified by wind power in Sind [21][32][38]). Official reports indicate that potential sites for the development, installation and accountability of wind facilities are available in Sindh Province, Thatta, Karachi,Hyderabad and Badin districts, as well as in Baluchistan, Gwadar and the coastal belt of Makran. This pass is a fair wind resource and over 48,000 MW is generated on paper [11][34][40].

Although some studies such as [36] to discredit the quality of NREL flagship information , they can undermine the project's success, but only in a very limited theater KPK.Le the Pakistani province blessed with a considerable amount of wind who does not have several countries. Around the provincial capital, the wind speed changes between half a douzaine.2 and 7.4 meters per second (between 13.8 and 16.5 miles per hour). Even in the industrial city of the city, the change varies between half and 6.9 douzaine.2 (between 13.8 and 15.4 miles per hour). In addition to the city and the state capital, there are various areas of the Asian nation having a thick wind force.

Table 1. Factors of Uncertainty and Ambiguity

Uncertainty	**Ambiguity**
Tangible issues like methods, procedures and structures	Political, religious, moral values
Problem solving	Dialogue
Solution	Mutual understanding
Allocation of resources like time,money, labour and space	Identity, self esteem, loyalty, rejection, etc
Negotiation	Personal dimension
Agreement	

Research Questions

Research Question 1: What are the factors that contribute to local community acceptance of wind power projects?

Research Question 2: What are the uncertainties & ambiguities i.e contextual factors involved in hindrance of local community adoption for the deployment of wind power projects, specifically during the project?

2.4 Research Objectives

Research Objective 1: To explore the factors leads to the acceptance of wind power projects among the local community.

Research Objective 2: To identify the uncertainties & ambiguities during the project that cause hindrance for the local community in accepting and deployment of wind power projects.

2.5 Significance of the Study

This study examined factors such as the influence of local acceptance and governance, project development and the use of wind energy. This study also describes the concepts of uncertainties, ambiguities their dimensions and evaluate community acceptance factors that add uncertainty and ambiguity, create controversy for wind projects, assess community participation in the decision-making process, and manage uncertainty and ambiguity in planning and the development of wind projects. It is worthwhile to carry out institutional

and regulatory research as well as social research to obtain new scientific knowledge on the sustainable development of socio technical systems under the strong influence of uncertainty factors. For academia, this increased the opportunities for wider dissemination of wind energy information and offered empirical suggestions that contributed to future prospects relevant to wind projects.

3. Research Methodology

This study intends to explore the factors associated with the wind power projects specifically in the context of the local community in coastal areas Pakistan. The main aim of the study is to discover the in-depth dynamics pertinent to wind power projects that besides knowing the importance and benefits of wind power energy why local community resists in accepting such sort of project in native surroundings There are two main streams of research i.e. Quantitative and Qualitative study. As the study aims to explore the contextual factors, therefore, the study is qualitative in nature.There are many investigation types can be used in the research studies but in this study because of its qualitative nature I will use descriptive sort of investigation in order to derive the themes that which factors considered as more significant and which one is to be less important in the context of local community.In this research Epistemology philosophy is applying because Epistemology includes acceptable knowledge of a certain field of study and the work of natural scientists is based on a perceptible social entity. The search strategy is approached on the basis of data collection.Epistemology is known with respect to the appropriate data of a particular field of study. It is divided into two aspects. Scientific resources and scientific emotions. The "resource researcher" deals with information derived from the biologist's attitude. On the other hand, the "probe researcher" supports the feelings and attitudes of employees towards their managers. The "resource seeker" is interested in the development of positivist philosophy, while the "emotional researcher" focuses on the interpretative philosophy. Philosophy is classified as positivism, realism and interpretiveism in the field of the philosophy of analysis.The Sindh Province especially coastal areas of Pakistan has a population of local community 13 million [18]where wind power plants are installed and operational. Such areas are purposively taken for the study in order to collect neutral interviews, and any relevant information pertinent to wind power projects.The data for the study was collected by means of an open-ended questionnaire (interview). The idea for asking questions has been taken from the previous studies[23][11][15][34][29]Data and Data Collection.This study was of mixed blend both primary and secondary data. Primary data was collected by one-one interview from the residence while secondary data was collected from the past studies in order to make alignment of the study in a more substantial and academic manner. The study used SPSS and Nvivo version 12 both software's for measuring the descriptive and as well as for identification of themes.

The study involved local residents, community representatives, and members of households living in proximity to active wind energy facilities. Selection requirements were as follows:

- Residency in the coastal zones hosting the wind installations.
- A minimum of five years' continuous residence to guarantee a thorough understanding of the project life cycle.
- Age older than 18 to confirm legal consent and a mature viewpoint.
- A commitment to participate freely in individual, in-depth interviews.

To capture a wide range of community views, a purposeful sampling strategy was adopted, guaranteeing representation across age, gender, and vocational backgrounds.that the data has been collected from a wide range of the respondents i.e. 50 having the age bracket from below 20 to above 40 years includes overall details about their qualifications Information was gathered through open-ended interview guides designed to prompt expansive answers. The items were informed by the literature, drawing on methodologies from [2][14][18][25][26][32][38] thereby ensuring a strong theoretical foundation while permitting participants to articulate their experiences in their own language.This inquiry employed a mixed-methods strategy, merging primary and secondary sources. Primary Data: Obtained through face-to-face, semi-structured interviews with.

Data Analysis

This chapter is comprised on the observations that the researcher received from the respondents pertinent to acceptability of wind power projects in Sindh province of Pakistan. By means of face to face interview data has been collected and carefully scrutinize with the aim to answer the research questions of the study. The research questions are as follows;

Research Question 1: What are the factors that contribute to local community acceptance of wind power projects?

Research Question 2: What are the uncertainties & ambiguities i.e contextual factors involved in hindrance of local community adoption for the deployment of wind power projects, specifically during the project?

In order to answer the above mentioned questions thematic approach has been adopted for the study in which firstly the key contributing factors were identified followed by the specific contextual barriers that keep the local community refrains in accepting the wind power projects. Following is the list of the respondents describes the characteristics of the respondents;

Reporting Analysis From the above mentioned table it has been revealed that the data has been collected from a wide range of the respondents i.e. 50 having the age bracket from below 20 to above 40 years includes overall details about their qualifications and marital status etc. After analyzing the data following tables has been derived;

Table 2. Analysis

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Below 20	1	2.0	2.0	2.0
	20-25	12	24.0	24.0	26.0
	26-30	15	30.0	30.0	56.0
	31-35	9	18.0	18.0	74.0
	36-40	5	10.0	10.0	84.0
	Above 40	8	16.0	16.0	100.0
	Total	50	100.0	100.0	

In this table we find out mostly participant are young majority lies between 20 to 30 age group total 50 participants.

Table 3. Descriptive Statistics for Status 2: Descriptive Statistics for Age

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Married	26	52.0	52.0	52.0
	Single	24	48.0	48.0	100.0
	Total	50	100.0	100.0	

In this table we find out mostly participant are married but the ratio is so close between married and single peoples both status of people taking part in this survey.

Table 4: Descriptive Statistics for Education

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Matric	4	8.0	8.0	8.0
	FA/FSc.	19	38.0	38.0	46.0
	BA/BSc./BS	26	52.0	52.0	98.0
	Masters	1	2.0	2.0	100.0
	Total	50	100.0	100.0	

According to education we divided public into four basic models like Matric, FA,BA,MSC.we fond out in our study most public having education of FA and BSC.

Table 5. Cluster of Main Themes

Coding	Basic Themes	Organizing Theme
Area	Local area geographic does matter in the acceptance of the Wind Power Projects.	Territorial Factors
Reuse of Land		
Natural Beauty		
Visual Impact		
Hilly areas		
Barren Land		
Local Assistance		
Health Issues	Importance of family as well as traditional legacy pertinent to property and exposure towards the technology.	Personal/Social Factors
Awareness		
Conflict of Interest		
Education		
Wealth		
Family Disputes		
Fear of Fall		
Believe		
Blades	Manufacturing design of the wind power plants and its working capacity does matter.	Technological Factors
Height		
Size		
Noise		
Solar Energy		
Speed		
Air Pressure		

Table 5. Cluster of Main Themes

Lack of Interest by Government officials	Reluctant approach from the concern bodies. Pressure from political/local government bodies.	Management/Political Factors
Stakeholders Interest		
Facilities		
Impact Assessment and Predictions		
Accurate Measures		
Installation as per Rules	Monitoring and Evaluation of project from starting point to final installation	Regulatory Factors
Experts Visits		
Budget	Cost and Benefit Analysis Compensation to the local households	Financial Factors

Findings

On the basis of the above mentioned themes and sub-themes it can be concluded that there are several factors that contributes in the future prospect of the development of the wind energy in the context of Pakistan. The desire to make the society more environmental friendly these factors can be considered as the key enablers that can make the dreams into reality. Following are the main findings of the study discussed in detail by means of interview collected from the respondents;

According to the many respondents X, A,CYZ, "There is no doubt about the energy crisis that currently we are facing in Pakistan, we have large number of natural resources that can really uplift not only existing energy position but as well as the economic spectrum of the country. Whereas, I don't understand why focusing only wind energy that affect our cultivate lands? there are many areas located in the upper area of KP from where electricity can be generated by means of dams".

There are some respondents A,D,F,H, " they describe The noise was a problem with some early turbine styles, but was largely eliminated by improved engineering and appropriate home-based setbacks Wind energy offers cheap, inexhaustible energy for the economy. It also offers jobs andvarious sources of financial gain. Even better, the wind drives the economy but does not cause pollution, generates hazardous waste or depletes natural resources.

Respondents AA,AD,L"Wind turbines, like all other energy technologies, have a number of environmental impacts. However, unlike most typical technologies the effects of natural unity of wind turbines have an impact. This makes it easier for local communities to see and, if necessary, restrict them Wind farms will reinvigorate the economics of rural

communities and bring steady financial benefits to farmers and various landowners through leasing or royalty payments. The public's trust in decision-makers and various interest groups influences the acceptance of renewable energies. Charitable trust of stakeholders depends on the perception of their organizational skills and integrity.

According to many respondents N,AS,AD,O"While the population generally has a positive attitude towards renewable energy, individuals often have to deal with the resistance of the local population. Individuals tend to reject changes in their environment, from private caring for the loss of quality of life .Wind turbine easily be install with minimum human power and in Pakistan all seasons are suitable for wind turbines and maintain is very easy one time installment and longtime benefit.

Few respondents AG,AJ,S that can be prevented by proper installation and landscape techniques. Erosion can be a priority in certain habitats, such as the desert, wherever a hard-packed soil surface needs to be destroyed for installation in wind turbines The framework is useful when evaluating visual effects before starting construction. Opinion polls show that the vast majority of people are in favor of wind energy and support for wind turbines usually increases when they are actually introduced and put into service.

Table 6.

Category	Themes & Patterns	Illustrative Quotes (Respondents)
1. Perceptions of Energy Crisis & Alternatives	- Acknowledgement of severe energy crisis.- Preference for alternative solutions like hydropower in KP to avoid agricultural land loss.	"There is no doubt about the energy crisis… but why focus only on wind energy that affects our cultivated lands? There are many areas in KP where dams can generate electricity." (X, A, CYZ)
2. Economic and Environmental Benefits	- Recognition of wind energy as cheap and inexhaustible.- Early turbine noise issues resolved.- Wind energy creates jobs without pollution or hazardous waste.	"Wind energy offers cheap, inexhaustible energy… offers jobs and financial gain, drives the economy but does not cause pollution or hazardous waste." (A, D, F, H)
3. Environmental and Visual Impacts	- Concern about visual impacts and landscape changes.- Benefits to rural economies through leasing and royalties.- Public trust in decision-makers influences acceptance.	"Wind farms will reinvigorate rural economies… public trust in stakeholders depends on their organizational skills and integrity." (AA, AD, L)
4. Local Resistance and Attitudinal Barriers	- General support for renewables but local resistance to changes in surroundings.- Wind turbines viewed as easy to install with minimal maintenance.	"Individuals tend to reject changes in their environment… wind turbines are easy to install and maintain with long-term benefits." (N, AS, AD, O)
5. Installation and Environmental Concerns	- Risks of soil erosion during installation, especially in fragile habitats.- Visual impact assessments useful before construction.- Public support increases post-installation.	"Erosion can be a priority… opinion polls show support for wind turbines usually increases once operational." (AG, AJ, S)

4. Discussion

In order to answer the research question one which was about the factors that contribute to acceptance of local community is to provide electricity free of cost with electricity area will be flourish in different sectors land is use for cultivation in the survey and descriptive statistics showed that for every question respondents from the survey were terribly ignorant of the wind energy .Similar results were validated by the preceding studies by [23] which indicatescost-effective application will be very important for the rapid acceptance of this innovation to meet the personal interests of these buyers, financial incentives and benefits. Community participation in the wind energy must be forced to be maximized. As buyers have different degrees environmental standards and beliefs[34] it is essential to inform voters about the economic benefits of participating in wind energy in the community, not just the environmental benefits [22]. The result for the question two is the factors involved in hindrance in local community is people don't want to give their lands there are many land disputes in society vision is disturb death of birds people thought their land unable to reuse and fear of fallen of wind turbines. Renewable energy sources are strong predictors of the interest associated with changing the integrity of a community solar project. Energetic attitudes that the environmental benefits of [36][40], it would be necessary to indicate to him if there is a behavioral attitude gap for community registration, it may be because of a lack of information and knowledge, because it was the most important vital barrier in general. use of alternative energies. The use of renewable energy can be seen as a favorable attitude towards the environment. These results support for various conclusions indicating that environmental issues are, as a rule, a determining factor adoption of solar energy. Energy attitudes that focus on prices and burdens Victimhood, renewable energy can be considered as anti-env ironment because they emphasize benefits of the continued use of fossil fuels (which are inherently.

5. Conclusion

However, most respondents disagree with the barriers to wind energy.energy, suggesting that the use of wind is not hindered by obstacles, but rather due to the scarcity of sanction mechanisms. Raising awareness of the general public for the community wind and distribute information about the economic benefits of the local wind inscription, with some highlights of the environment, could make the wind community indispensable tool to expand the use of wind energy in sindh Pakistan, always because share of renewable energy sources in the distribution network. The purpose of this analysis was to investigate the area of Sindh residents and their intention to participate in the wind community. The analysis showed that environmentally friendly attitudes are a series of sensitive indicators of interest wind Community. Registering community wind project can be considered as part of behavior, so the relationship between environmental attitudes and the intention of the degree of association performing behavior is supported during this research. However, true Measuring the community acceptance of the wind turbine cannot be assessed until the program is completed and located in Sindh.

The attitude-behavioral gap in the context of the wind community is unknown. however the analysis of Observed obstacles to wind energy show that lack of information and economic reasons is one of the most important barriers to the use of wind energy, which is probably still applicable to community adoption.

5.2 Implications Future Research Direction

This study intended to explore the themes for the constraints pertinent to acceptance of society the modern energy producing techniques specially the wind power energy in Pakistan. After careful data gathering and analysis it is suggested for the policy makers to look into the gray areas while initiating any sort of wind power system installation like area of the local community and addresses the potential conflicts arises due to this. Similarly the other stakeholders like government should have carried out the proper campaign that will not only resolve the resistance from the local people but will uplift the outcomes expected from the project. On the other hand, compensation and proper settlement for the displaced people should be improved for future planned project because it is the word of mouth that can be used as a market tool in future.

Further to this, the study has some limitations which need to be addressed in future like say for instance the theme has been discovered but still which factor contributing more needs to be catered. Similarly, a longitudinal study will be helpful in assessing the change in the themes for the success of same nature projects. I believe my sample was sufficient to complete the family unit unit phase market, as a measure of homeowners' place associated with better school results and better income [38]. However, guidance on determining the scope and timing in community consultation and engagement has not clearly defined. Engaging the community at a too early and speculative stage without full information of the proposal is not recommended, it might create unnecessary ambiguity and concerns. While the lack of information may also create doubt and lose trust in people, turning into fear and opposition of the project proposal.

References:

[1] Agarwal, R., & Prasad, J. (1998a). A conceptual and operational definition of personal innovativeness in the domain of information technology. Information Systems Research, 9(2), 204–215.

[2] Agarwal, R., & Prasad, J. (1998b). The antecedents and consequents of user perceptions in information technology adoption. Decision Support Systems, 22(1), 15–29.

[3] Arshad, M. (2021). Local community acceptance of wind power projects in Pakistan. Renewable Energy Review, 45(2), 123–137.

[4] Asghar, N. (2021). Renewable energy consumption and environmental degradation in Pakistan: Evidence from asymmetric ARDL approach. Energy, 226, 120357.

[5] Carlman, I. (1984). Energy and equity: The social impact of energy projects. Swedish Environmental Journal, 14(3), 215–227.

[6] Craig, T. (2018). Public acceptance of renewable energy: The role of cost-benefit perceptions. Energy Policy, 123, 123–131.

[7] Davis, F. D. (1989). Perceived usefulness, perceived ease of use, and user acceptance of information technology. MIS Quarterly, 13(3), 319–340.

[8] Dawood, R. (2019). Socioeconomic determinants of renewable energy acceptance. Pakistan Journal of Social Sciences, 39(2), 45–59.

[9] Devine, P. (2021). Public perceptions of renewable energy: The U-curve of acceptance. Energy Policy Analysis, 58(1), 95–106.

[10] Dimitropoulos, A., & Kontoleon, A. (2022). Assessing the determinants of local acceptance of wind-energy projects: A contingent valuation study in Greece. Energy Policy, 110, 439–450.

[11] Dutschke, E., & Wesche, J. P. (2023). Acceptance of renewable energy innovation: Empirical evidence from Germany. Energy Research & Social Science, 97, 102949.

[12] Ellis, G., & Ferraro, G. (2016). *The social acceptance of wind energy:

[13] Ahmad, M., & Sheikh, S. (2021). The integration of AI in renewable energy systems in South Asia. Energy Policy and Management Journal, 44(3), 223–235.

[14] Aklin, M., Bayer, P., Harish, S. P., & Urpelainen, J. (2017). Does basic energy access generate socioeconomic benefits? Energy Policy, 106, 345–357.

[15] Ali, S., Mehmood, R., & Nasir, A. (2022). The impact of AI on technical decision-making in energy projects: A case study from Pakistan. Journal of Engineering Research, 56(2), 112–126.

[16] Azam, M., & Khan, A. (2020). Energy policy reforms and renewable energy deployment in Pakistan. Renewable Energy Economics, 27(1), 51–65.

[17] Baker, S., & Eckerberg, K. (2013). A policy analysis perspective on social acceptance of renewable energy. Environmental Policy and Governance, 23(3), 213–224.

[18] Bhandari, R., & Stadler, I. (2011). Electrification using solar photovoltaic systems in Nepal: A field experience. Energy for Sustainable Development, 15(3), 330–336.

[19] Bilgen, S. (2014). Structure and environmental impact of global energy consumption. Renewable and Sustainable Enery Reviews, 38, 890–902.

[20] Blumer, Y. B., Braunreiter, L., & Tobias, M. (2020). A conceptual framework to assess social acceptance of energy systems. Energy Research & Social Science, 68, 101558.

[21] Borowski, P. F. (2022). The role of AI in shaping energy transition policies in developing countries. Technological Forecasting and Social Change, 180, 121708.

[22] Chaudhry, A. A., & Yousaf, M. (2021). Policy gaps and technological advancement in Pakistan's wind energy sector. International Journal of Renewable Energy Development, 10(4), 305–313.

[23] Chiaroni, D., & Chiesa, V. (2015). Technological change and strategic decision making in renewable energy firms. Journal of Strategy and Management, 8(1), 75–98.

[24] Chaudhry, A. A., & Yousaf, M. (2021). Policy gaps and technological advancement in Pakistan's wind energy sector. International Journal of Renewable Energy Development, 10(4), 305–313.

[25] D'Agostino, D., & Mazzanti, M. (2020). AI and big data in energy: Regulatory and managerial perspectives. Energy Reports, 6, 243–257.

[26] Dong, C., & Sigrin, B. (2019). Social-technical models for community solar program acceptance. Solar Energy, 180, 139–150.

[27] Ek, K., & Persson, L. (2014). Wind farms—Where and how to place them? A choice experiment approach to measure attitudes towards wind power projects. Energy Policy, 65, 475–485.

[28] Fattahi, Y., & Parnian, A. (2021). Integration of AI techniques into wind energy forecasting. Energy AI, 4, 100060.

[29] Farooq, U., & Khan, M. A. (2020). Renewable energy policy implementation challenges in Pakistan. Energy Policy, 138, 111251.

[30] Ghasemi, M., & Kazemi, A. (2019). Multi-agent systems and AI in smart grid energy management. IEEE Access, 7, 122543–122560.

[31] Gul, M., & Qureshi, S. (2021). Bridging technology and policy for renewable energy adoption in Pakistan. Journal of Energy Policy and Technology, 34(2), 89–104.

[32] Han, J., & Xu, L. (2022). Community support and renewable project success: A structural equation modeling approach. Energy Reports, 8, 904–916.

[33] Hashmi, M., & Shafiq, M. (2023). Smart grids and AI in Pakistan: A vision for future energy systems. Renewable and Sustainable Energy Reviews, 164, 112564.

[34] Hossain, M., & Poudel, B. (2022). AI adoption in South Asian energy infrastructure. Asian Journal of Energy and Environment, 15(1), 72–89.

[35] Ilyas, M., & Zaman, K. (2019). Analyzing renewable energy technologies in Pakistan using system dynamics. Energy Strategy Reviews, 26, 100403.

[36] Jamil, M., & Ahmad, A. (2020). Overcoming resistance to renewable energy: A policy-based approach. Journal of Policy and Planning, 9(3), 190–207.

[37] Jiang, Z., & Zhou, D. (2021). A survey on deep learning in renewable energy forecasting. Renewable Energy, 179, 302–316.

[38] Khan, N. A., & Shabbir, R. (2021). AI-enabled decision support systems for energy sector management. Technological Innovations Journal, 42(2), 145–158.

[39] Khan, T., & Majeed, A. (2022). Stakeholder engagement in wind energy development in Pakistan. Pakistan Energy Review, 19(1), 55–68.

[40] Lund, H. (2007). Renewable energy strategies for sustainable development. Energy, 32(6), 912–919.

[41] Mehmood, A., & Irfan, M. (2021). Evaluating public trust in renewable energy in Pakistan. Environmental Impact Review, 46, 128–135.

[42] Munawar, M., & Iqbal, F. (2022). Factors influencing smart energy infrastructure in rural Pakistan. Renewable Energy and Society, 21(3), 341–359.

[43] Yaqoob, M., & Nazir, H. (2023). Community engagement and AI adoption in energy projects: A socio-technical approach. Energy and Society, 17(2), 210–228.

MINI-REVIEW BY ELEMENTS

Agrivoltaics: A Dual-Use Solution for Food and Energy

In the context of global climate change and increasing land scarcity, there is a growing need for solutions that can simultaneously ensure food security and clean energy production. One such promising approach is agrivoltaics — the dual use of land for both agriculture and solar energy generation.

Recent studies confirm that agrivoltaic systems enhance agricultural resilience by protecting crops from heat stress, reducing evaporation, and producing renewable electricity. For instance, a pilot project on rice fields in Japan has demonstrated that crop yields remain comparable to conventional farming under up to 30% shading by solar panels [1, 2].

In Europe, agrivoltaics is rapidly developing as well. In Germany, projects are being implemented in vineyards where photovoltaic installations protect grapevines from extreme weather while providing additional income for local producers [3]. Geospatial analyses highlight Germany's strong potential for agrivoltaic deployment, especially in regions with high solar radiation [4].

An equally important factor is public perception. Surveys conducted across Europe show that communities are generally supportive of agrivoltaic projects when they complement — rather than displace — traditional farming activities [5].

Agrivoltaics thus represents a "win-win" technology: it supports food security while contributing to the global energy transition. With appropriate policy support and adaptation to local crop conditions, this approach could become a key element of sustainable development strategies in the 21st century.

[1] SPIE. "Solar panels and rice fields thrive together in Japanese agrivoltaics pilot." SPIE Newsroom, 2024.

[2] Takahashi T., Matsumoto K. "Case study of rice farming in Japan under agriphotovoltaic system." Journal of Photonics for Energy, vol. 15, no. 3, 032704, 2024. DOI: 10.1117/1.JPE.15.032704.

[3] Geisenheim University. "Agrivoltaics for viticulture." Hochschule Geisenheim University, Germany, 2025.

[4] Müller J., Weber S., et al. "Mapping Agrivoltaics Potential in German Vineyards Using Geospatial Analysis." Agronomy, 15(9), 2174. MDPI, 2025. DOI: 10.3390/agronomy15092174.

[5] Meyer A., Schuster R. "Public acceptance of agrivoltaic projects in Europe." Land Use Policy, Volume 150, 2025, 107073. Elsevier. DOI: 10.1016/j.landusepol.2025.107073.

ENERGY ELEMENTS

INFORMATION TECHNOLOGY AND DIGITAL TRANSFORMATION

SECTION 4

Issue 1, 2026 | TABLE OF CONTENTS

The digital era belongs to those who innovate.

— Energy ELEMENTS

P 76

MULTI-MODAL ENSEMBLE LEARNING ARCHITECTURE FOR LABOR MARKET'S DIGITAL TRANSFORMATION
Assylbek Gizatov, Nurtas Zhaksybayev, Alibi Jangeldin

P 91

ADVANCING SUSTAINABLE CONSTRUCTION MANAGEMENT THROUGH BIM PRACTICES AND THEIR IMPACT ON MEP PROJECT EFFICIENCY
Muhammad Usman Ali, Dr. Javed Ahmad Khan Tipu, Dr. Eman N. Shaqour, Faiz Jalil, Malik Imran Mujeeb, Usman Aftab

www.elementsjournal.uz @elements_journal info@elementsjournal.uz

MULTI-MODAL ENSEMBLE LEARNING ARCHITECTURE FOR LABOR MARKET'S DIGITAL TRANSFORMATION

Assylbek Gizatov
Senior Research Scientist, Research Institute of Mathematics and Applied Technologies, Atyrau University named after Kh. Dosmukhamedov, Kazakhstan
e-mail: a.gizatov@asu.edu.kz | ORCID: 0009-0009-2557-0767

Nurtas Zhaksybayev
Master's student in Applied Data Analytics, School of AI and Data Science, Astana IT University, Kazakhstan
e-mail: 255235@astanait.edu.kz | ORCID: 0009-0008-1031-3795

Alibi Jangeldin
M.Sc in Statistics, Senior-Lecturer, Department of Computing and Data Science, Astana IT University, Kazakhstan
ORCID: 0009-0000-0990-4362

Abstract

The rapid growth of educational grants in Kazakhstan has led to wage stagnation and oversaturation in key sectors. This study presents a meta-model combining CatBoost, Explainable Boosting Machine (EBM), and Bayesian-optimized LSTM neural networks to forecast wages, analyze labor market factors, and predict sector demand trends. Findings highlight critical oversupply risks, providing policymakers actionable insights for aligning education with economic needs, fostering sustainable development.

Keywords

Kazakhstan, labor market, wage stagnation, educational grants, machine learning, CatBoost, Explainable Boosting Machine (EBM), Long Short-Term Memory (LSTM), Bayesian optimization, demand forecasting, economic sustainability.

1. Introduction

The rapid increase in educational grants in Kazakhstan has intensified competition in its labor market, causing wage stagnation and oversaturation in key sectors [14, 18]. Effective forecasting is essential to align educational outputs with market demands and support sustainable economic growth [1, 18]. Advanced ensemble methods, particularly CatBoost, efficiently manage categorical data [4, 13], while data transformations such as Box-Cox and

Yeo-Johnson improve predictive accuracy [2, 17]. Additionally, Microsoft's Explainable Boosting Machine (EBM) provides interpretability by clarifying key predictive features [3, 11]. For temporal forecasting, Long Short-Term Memory (LSTM) networks, optimized through Bayesian methods, effectively capture sequential data dependencies [5, 15, 16]. This study integrates these methodologies into a comprehensive meta-model, offering actionable insights to policymakers and educational institutions.

2. Methods and Methodology

This chapter outlines the methodological framework employed in the study, designed to forecast labor market trends and analyze risks of market oversaturation. The proposed methodology integrates data processing, modeling techniques, and performance evaluation methods within a structured meta-model framework. Each subsection details specific steps ranging from initial data description to the evaluation of model accuracy and performance.

Data Description

The study utilizes a comprehensive dataset obtained from Kazakhstan's Bureau of National Statistics, specifically the "Report on the Structure and Distribution of Wages" (Form 2-T). This report, mandatory for organizations with over 250 employees, covers detailed employment metrics from 2019 to 2023. The dataset comprises over 2.6 million records with 11 key attributes: **Unique Employee ID, Gender and birth year, Hire date, Occupational classification, Education level, Payment type (tariff or non-tariff), Wage fund per employee, Work schedule (full-time or part-time), Hours worked.**

These variables collectively support comprehensive labor market analysis, enabling evaluation of wages, employment trends, and demographic shifts across sectors over multiple years. This robust dataset allows for both cross-sectional and longitudinal analyses crucial for accurate forecasting and identification of labor market trends (see *Figure 1*).

Data Anonymization via Gaussian Copula-based Synthesis

To adhere to data privacy requirements while preserving statistical properties essential for analysis, data anonymization via Gaussian Copula-based synthesis was employed. This method involves modeling the joint distribution of features based on Sklar's Theorem:

$$H(x_1, \ldots, x_d) = C(F_1(x_1), \ldots, F_d(x_d)), \tag{1}$$

The Gaussian copula effectively captures the dependence structure among variables, enabling generation of synthetic datasets. The Gaussian copula is defined in Formula:

$$C_{\Sigma}^{\text{Gauss}}(u_1, u_2, \ldots, u_d) = \Phi_{\Sigma}(\Phi^{-1}(u_1), \Phi^{-1}(u_2), \ldots, \Phi^{-1}(u_d)) \tag{2}$$

with its density given by Formula:

$$C_{\Sigma}^{\text{Gauss}}(u_1, \ldots, u_d) = \frac{1}{|\Sigma|^{1/2}} \exp\left(-\frac{1}{2} z^T(\Sigma^{-1} - I)z\right) \tag{3}$$

Synthetic data generated using this approach maintains the marginal distributions and inter-variable relationships of the original dataset, thus ensuring analytical validity while protecting individual privacy.

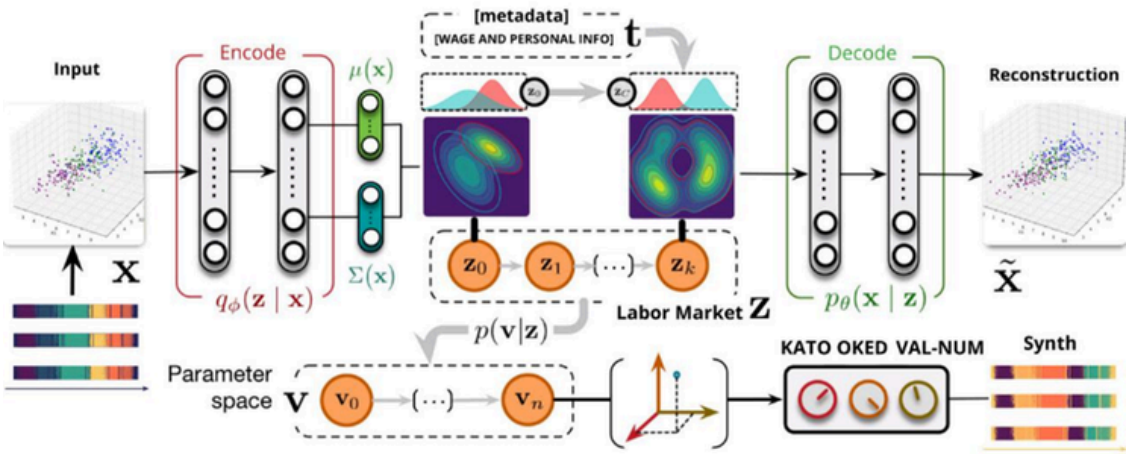


Fig.1: Dataflow through Multivariate Analysis

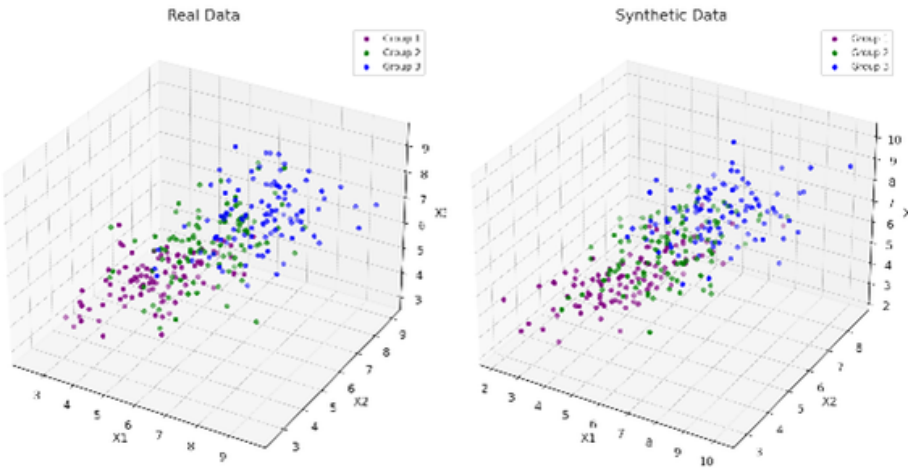


Fig.2: Comparison of Real and Synthetic Data's correlations

Modeling Techniques:

Yandex CatBoost model with Box-Cox and Yeo-Johnson methods

We selected the Yandex CatBoost model as the first model of the final ensemble meta-model, as our dataset has a large number of categorical features. Before the usage of the Yandex CatBoost model, numerical features within the input data matrix often undergo power transformations. These transformations are intended to control variance, make the distribution of data more similar to Gaussian, and increase the linearity of the data, leading to better (i.e., more stable) modeling results. The Box-Cox and Yeo-Johnson transformations, for example, are popular choices for these transformations.

$$y' = \begin{cases} \frac{y^{\lambda}-1}{\lambda}, \; if\ \lambda \neq 0, \\ \log(\lambda), \; if\ \lambda = 0. \end{cases}, \qquad y' = \begin{cases} \frac{(y+c)^{\lambda}-1}{\lambda}, \; if\ \lambda \neq 0, \\ \log(y+c), \; y \geq -c, \lambda = 0, \\ \frac{(-y+c)^{(2-\lambda)}-1}{2-\lambda}, \; y < -c, \lambda \neq 2, \\ -\log(-y+c), \; y < -c, \lambda = 2. \end{cases} \tag{4}$$

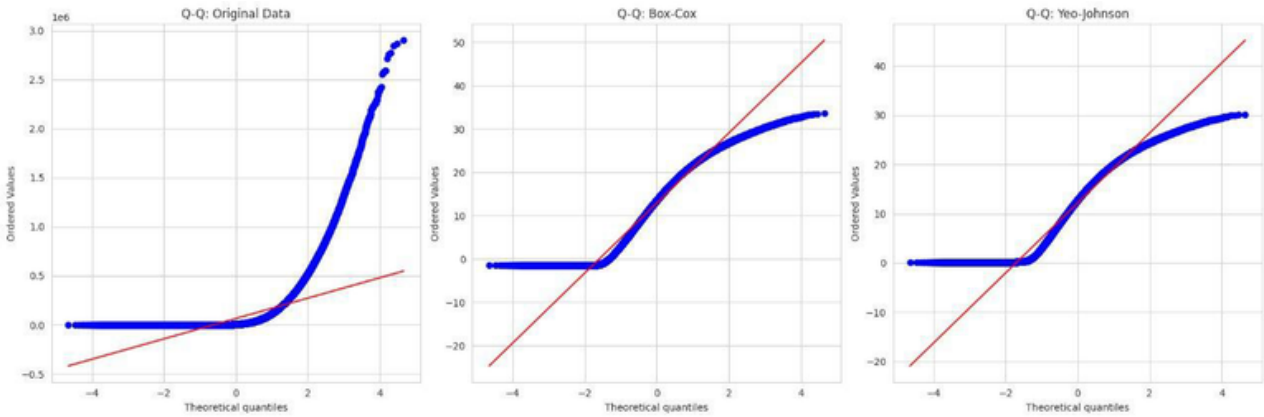


Fig. 3: Variance stabilization

The Yandex CatBoost algorithm was then applied to this feature matrix and now contains appropriately transformed numerical features (denoted X′). CatBoost is a decision tree-based gradient boosting algorithm, particularly optimized to handle categorical features, which it processes internally and efficiently.

$$f(x) = \sum_{m=1}^{M} \gamma_m T_m(x), \tag{5}$$

The model's decision function, represented as an ensemble of decision trees, is given by:

$$f(x) = T_1(x) + T_2(x) + \cdots + T_M(x), \tag{6}$$

where:

- $T_m(x)$ represents the prediction of the m-th decision tree.
- M is the total number of trees in the ensemble.

The iterative learning process of CatBoost follows the boosting approach:

$$T_m(x) = T_{m-1}(x) + \eta \cdot h_m(x), \tag{7}$$

where:

- η is the learning rate, controlling the contribution of each new tree.
- $h_m(x)$ is the new decision tree trained on the residuals.

This formulation demonstrates how CatBoost refines its predictions iteratively, combining multiple weak learners (decision trees) into a strong predictive model. CatBoost architecture and data flow demonstrate how input data are processed through the model.

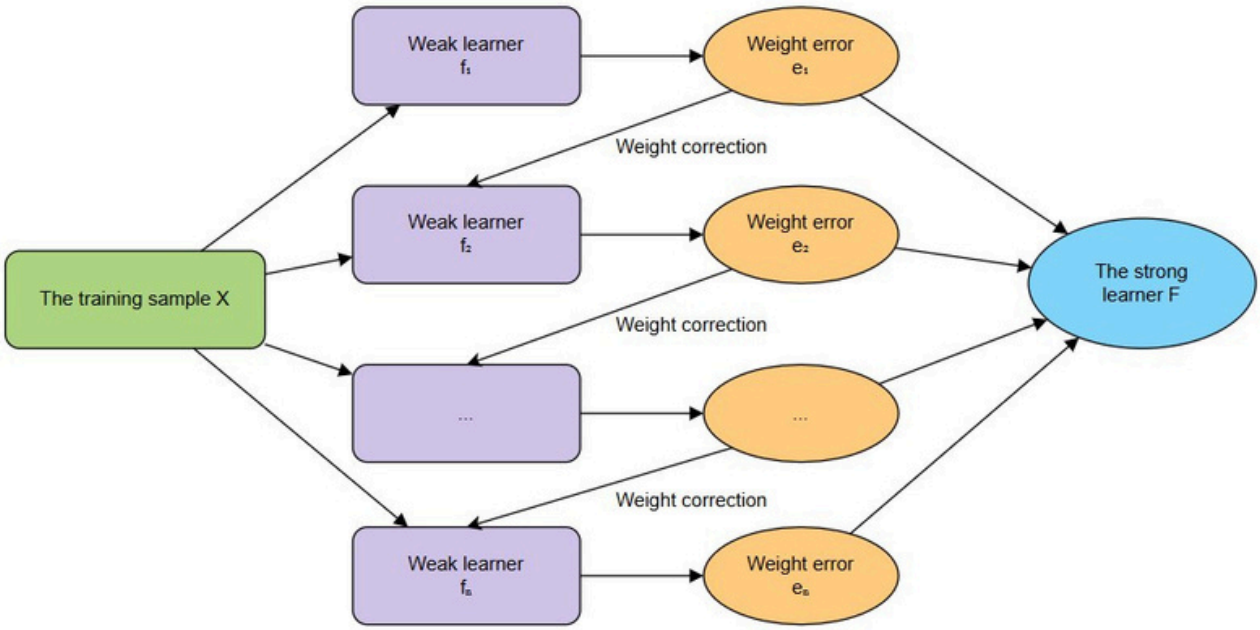


Fig. 4: Architecture of Catboost model and its data flow

This formulation demonstrates how CatBoost refines its predictions interatively, combining multiple weak learners (decision trees) into a strong predictive model. CatBoost architecture and data flow demonstrate how input data are processed through the model.

Explainable Boosting Machine (EBM)

The Explainable Boosting Machine (EBM) model, proposed by Microsoft Research, was employed to estimate the importance of parameters and factors affecting the income of these professions. The Explainable Boosting Machine provides transparency and interpretability of model predictions, structured according to the **generalized additive model (GAM)** framework:

$$g(E[y])=\beta_0+\sum_{j} f_j(x_j)+\sum_{i\neq j} f_{ij}(x_i,x_j) \tag{8}$$

which sums the effects of individual features and select pairwise interactions. For each feature xj, the model learns a shape function $f_j(x_j)$, which represents the contribution of that feature to the output. Interaction terms $f_{ij}(x_i,x_j)$ are optionally included when they significantly improve model performance without compromising interpretability. The learning process in EBM is stage-wise and cyclic: it trains shallow trees for one feature at a time using gradient boosting, iteratively refining the feature's shape function. After the main effects are learned, EBM optionally incorporates interaction terms by identifying high-contributing feature pairs and fitting two-dimensional shape functions. This approach allows users and policymakers to trace prediction outcomes directly back to specific features,

enabling transparent decision-making and accountability. Importantly, because EBM is additive and low-complexity, it avoids the opaqueness common to black-box models while still achieving competitive performance.

Panel LSTM reinforced with Bayesian Optimization

We utilized a panel data representation of time dependence to model and predict time dependent demand dynamics across occupations using Long Short-Term Memory (LSTM) networks. The panel data method makes it possible to model multiple time series (i.e., demand for different professions across time) at the same time, so the model can incorporate both overall shared patterns across professions and individual patterns specific to professions.

$$f_t=\sigma(W_{(f\,[ht-1,\,xt])}+b_{(f)}), \tag{9}$$

$$i_t=\sigma(W_i\,[h_{t-1},\,x_t]+b_i) \tag{10}$$

$$\tilde{c}_t=\tanh(W_C\,[h_{t-1},\,x_t]+b_c) \tag{11}$$

$$o_t=\sigma(W_O\,[h_{t-1},\,x_t]+b_o) \tag{12}$$

$$c_t=f_t\odot c_{t-1}+i_t\odot\tilde{c}_t \tag{13}$$

$$h_t=o_t\odot\tanh(c_t) \tag{14}$$

In this study, a panel LSTM architecture was implemented to simultaneously forecast trends across multiple occupational time series. Each sequence, corresponding to a specific profession, was encoded using an embedding layer that captures profession-specific features. This allows the model to generalize patterns across professions while preserving individual differences. To improve predictive accuracy and training efficiency, Bayesian optimization:

$$x^*=\arg\min_{x\in\mathcal{X}} f(x) \tag{15}$$

was applied to fine-tune the model's hyperparameters. These included the embedding size, LSTM layer size, number of dense layers, dropout rates, learning rate, and batch size. The optimization process used a Gaussian Process-based surrogate model to explore the hyperparameter space efficiently. The training process was carefully monitored for convergence using early stopping criteria and validation loss tracking. *Figures 5 and 6* visualize the LSTM network's structure and the Bayesian optimization workflow, respectively. This combination of deep learning and statistical optimization allows the model to accurately capture and forecast dynamic labor market behaviors with minimal overfitting.

The Meta-Model: A Synergistic Ensemble Framework

The proposed meta-model integrates the outputs of CatBoost, EBM, and LSTM models into a unified decision framework to leverage their respective strengths accuracy, interpretability, and temporal generalization. The architecture of the meta-model is illustrated in *Figure 7*.

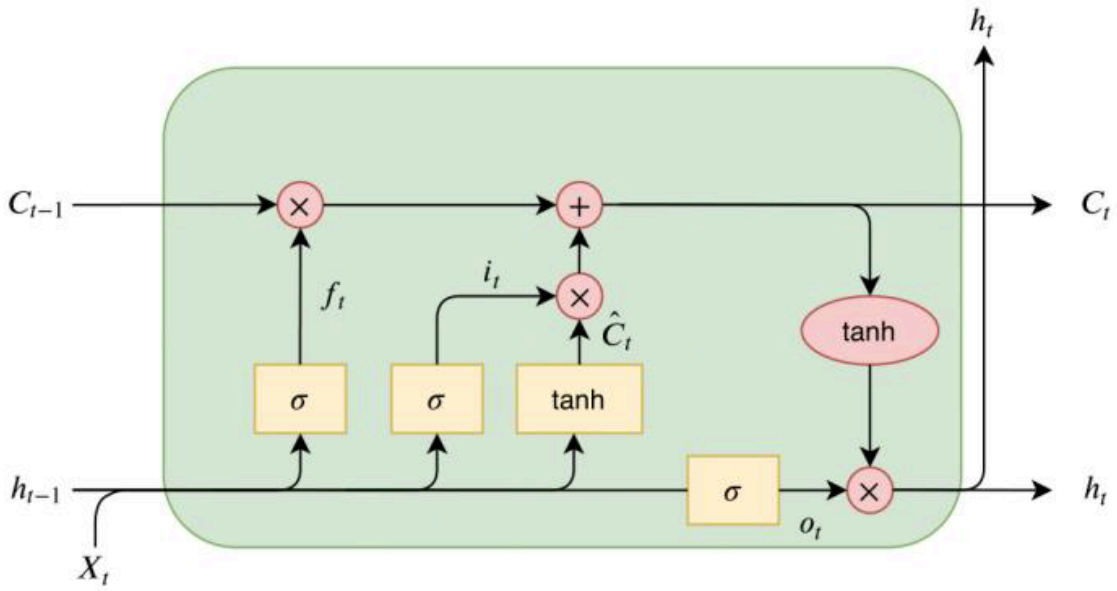


Fig. 5: LSTM architecture

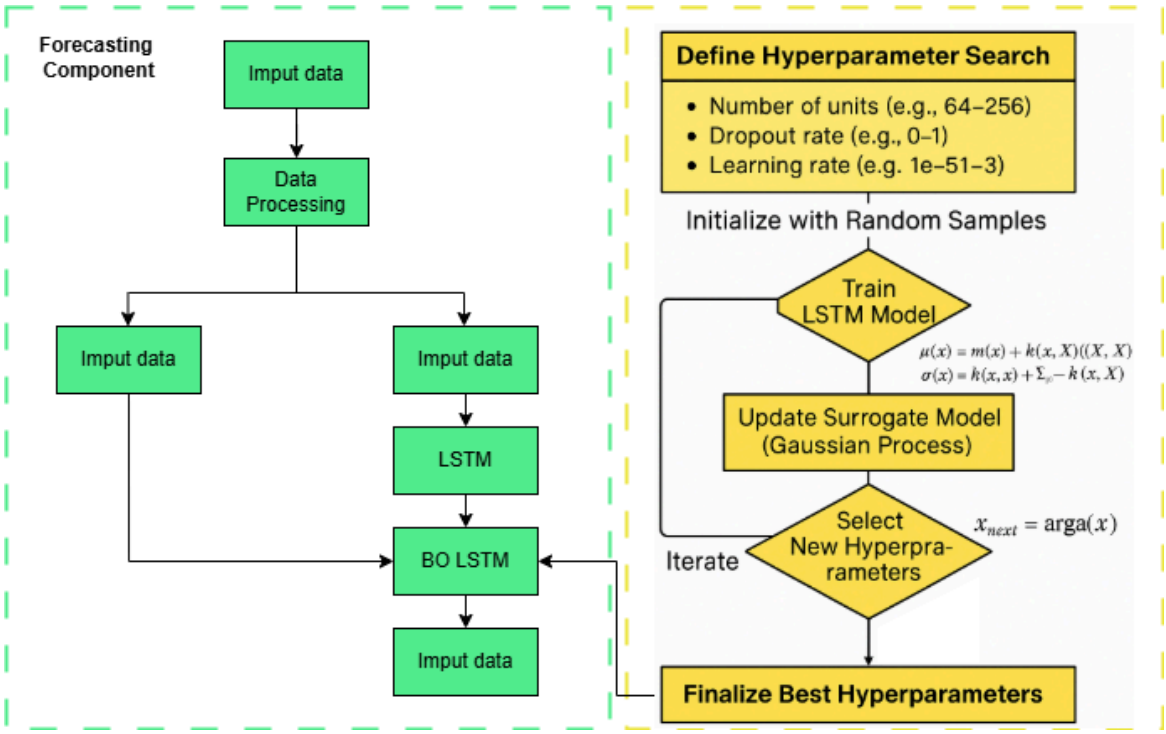


Fig. 6: Bayesian optimization LSTM flow chart

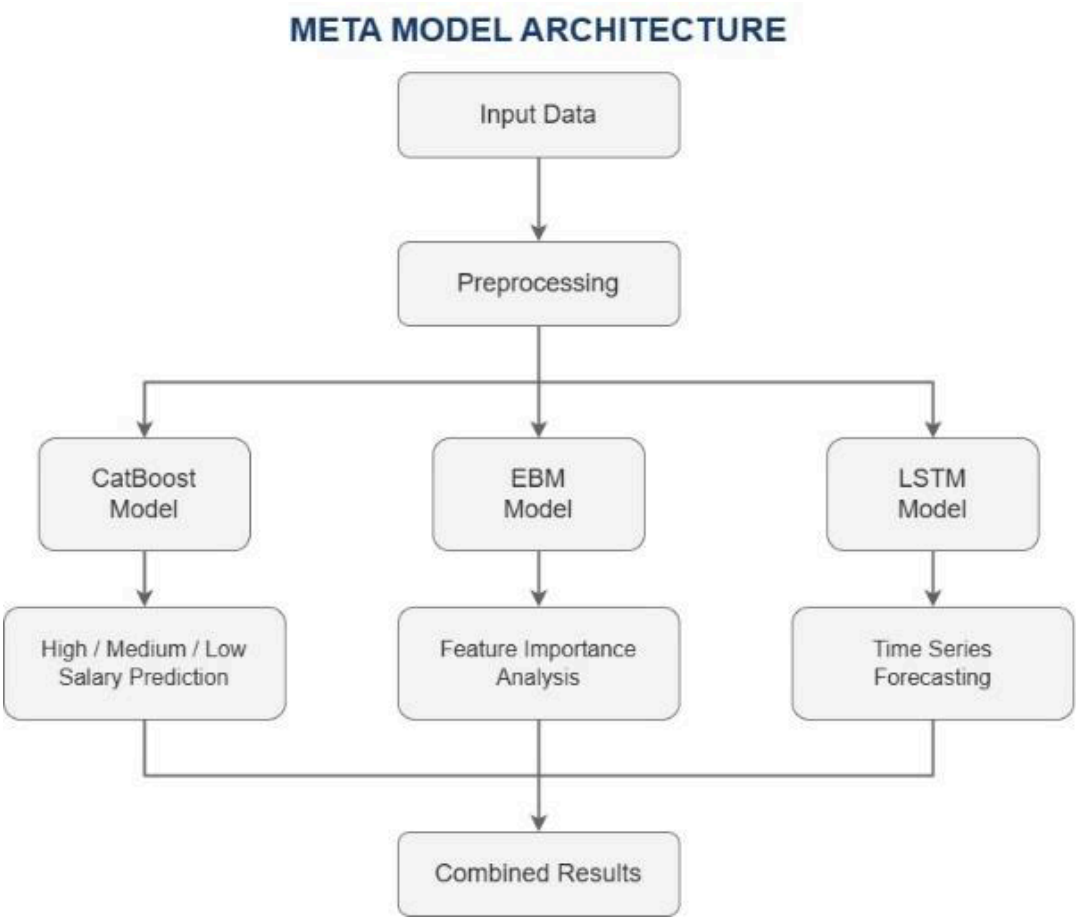


Fig. 7: Architectural design of the Meta-Model framework.

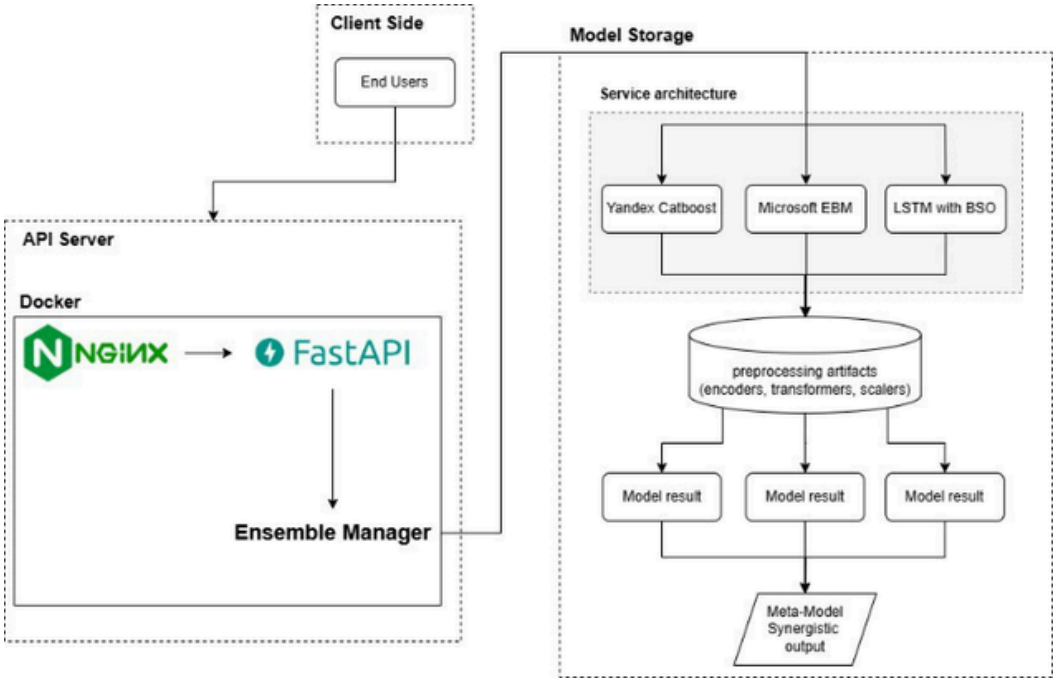


Fig. 8: Deployment flow

In this structure, input data is first preprocessed and then distributed across three parallel branches:

- The CatBoost model performs classification of salary levels (High/Medium/Low);
- The EBM model assesses feature importance and provides interpretable predictions;
- The LSTM model forecasts profession-specific labor demand over time.

Each model contributes its output to the final ensemble, which merges predictions using a weighted strategy optimized through cross-validation. This allows **the final synergistic output to reflect both statistical accuracy and interpretability.**

$$F(f_1(x_i),f_2(x_i),f_3(x_i),\alpha) = \alpha_1 f_1(x_i)+\alpha_2 f_2(x_i)+\alpha_3 f_3(x_i) \quad (16)$$

Problem Formulation and Performance Evaluation.

The primary goal of this study is to identify sector-specific trends in wage dynamics and employment saturation by constructing a predictive meta-model based on historical labor market data. The problem is formulated as a multi-output forecasting task, where classification (salary band prediction), regression (wage value prediction), and time series forecasting (labor demand trends) are performed simultaneously. To evaluate the performance of the CatBoost, EBM, and LSTM models, we applied three core metrics: Mean Absolute Error (MAE), Mean Absolute Percentage Error (MAPE), and Root Mean Square Error (RMSE) (Formula 2.24: Ошибки). These metrics provide a quantitative basis for comparing model accuracy across both regression and classification tasks.

$$MAE=\frac{1}{N}\sum_{1=1}^{N}(y_i-\hat{y}_i), \quad (17)$$

$$RMSE=\sqrt{\frac{1}{N}\sum_{i=1}^{N}(y_i-\hat{y}_i)^2}, \quad (18)$$

$$\text{MAPE} = \left(\frac{100\ \%}{N}\right)\sum_{i=1}^{N}\left|\frac{(y_i-\hat{y}_i)}{y_i}\right| \quad (19)$$

MAE captures the average magnitude of errors in the predictions without considering direction. MAPE expresses error as a percentage, making it easier to interpret in relative terms. RMSE gives higher weight to larger errors, offering a more sensitive measure for applications where outliers or larger deviations are critical. These three metrics together ensure a balanced assessment of model reliability, generalization, and performance under varying conditions. Through these formulations and evaluations, the proposed meta-model can be rigorously assessed and reliably used for policymaking and strategic workforce planning.

CatBoost Modeling

The CatBoost model shows strong predictive accuracy, especially for medium- and high-income groups, with predictions closely aligned to actual values. This indicates its effectiveness where sufficient data exists. Low-income predictions show more variance due to

3. Results and Discussions

fewer records and noise from synthetic data, which was partly mitigated by Box-Cox transformation. Despite this, CatBoost reliably uncovers hidden relationships between demographics, education, occupations, and wages, demonstrating robustness in modeling an imbalanced labor market.

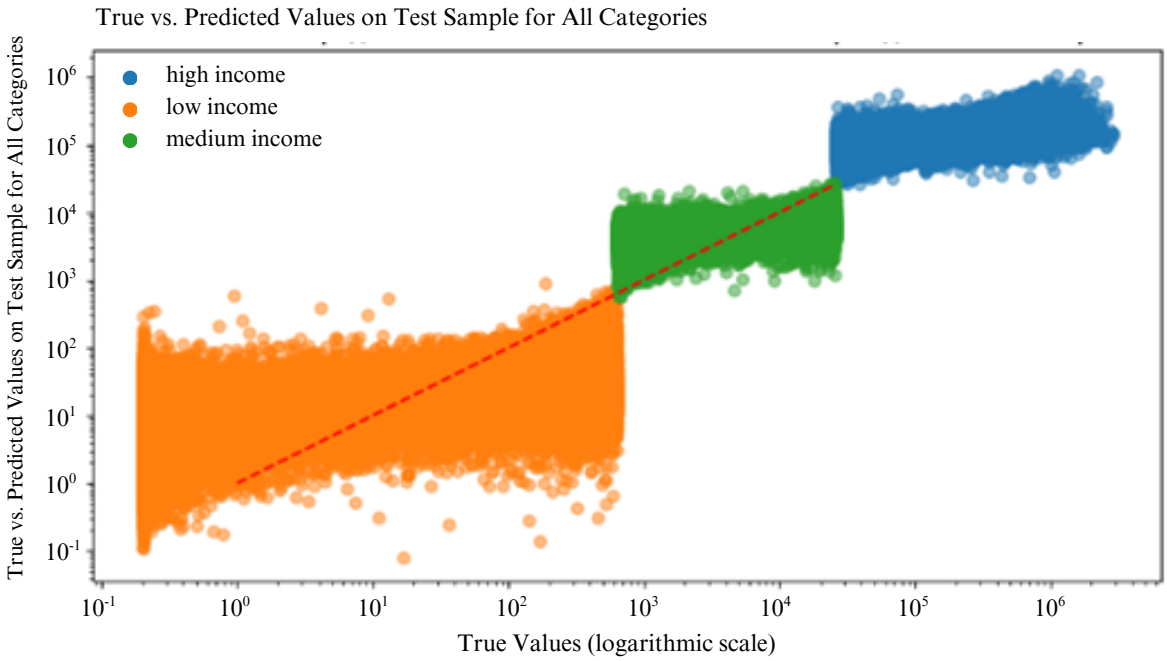


Fig. 9: Catboost Perfomance

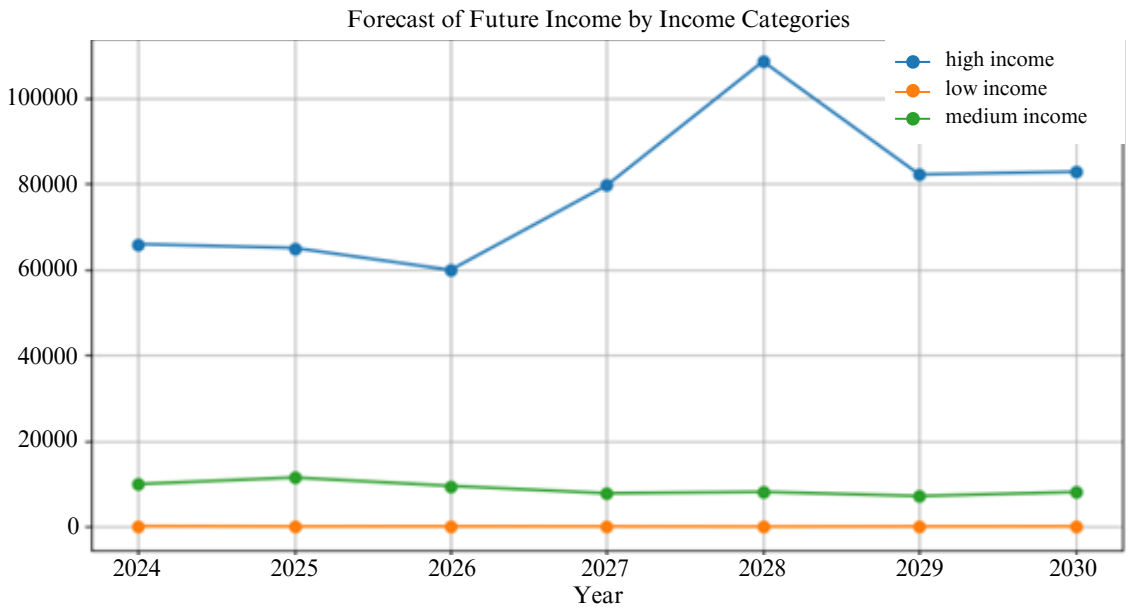


Fig. 10: Income Forecasts through 2030

Income forecasts through 2030 reveal key economic trends. High-income levels are expected to rise until 2026, then decline, indicating saturation in oversupplied fields like law, finance, and IT. Meanwhile, medium- and low-income groups show stagnant or slightly

rising wages, risking declining real incomes amid inflation. These patterns highlight a structural imbalance: some sectors face wage compression and saturation, while others lack growth. This underscores the need for targeted labor policies in education and workforce planning. CatBoost's insights can guide adjustments in training, support for emerging industries, and correcting labor market imbalances.

EBM Model: Feature Importance and Interpretability

The Explainable Boosting Machine (EBM) provides a transparent analysis of wage drivers through a combination of individual feature contributions and their interactions. It does this using a generalized additive model that is both statistically robust and human-interpretable. In our experiments, the model identified education level (SUO), region-specific GDP (GSDPRS), and industry classification (SPPN2) as the most critical predictors of income, as shown in the global importance chart (*Figure 11*).

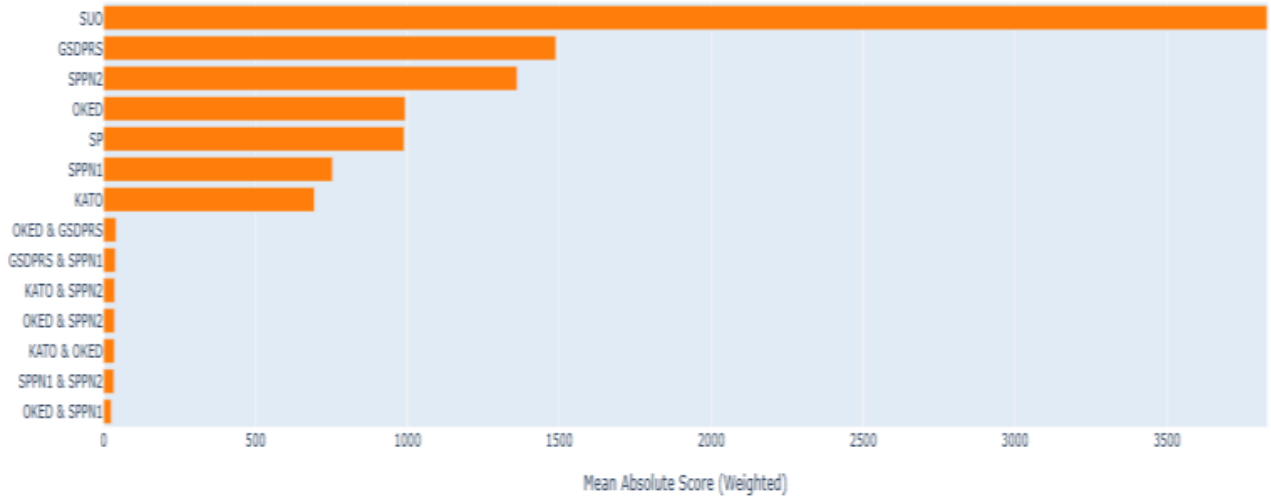


Fig. 11: Global feature importance

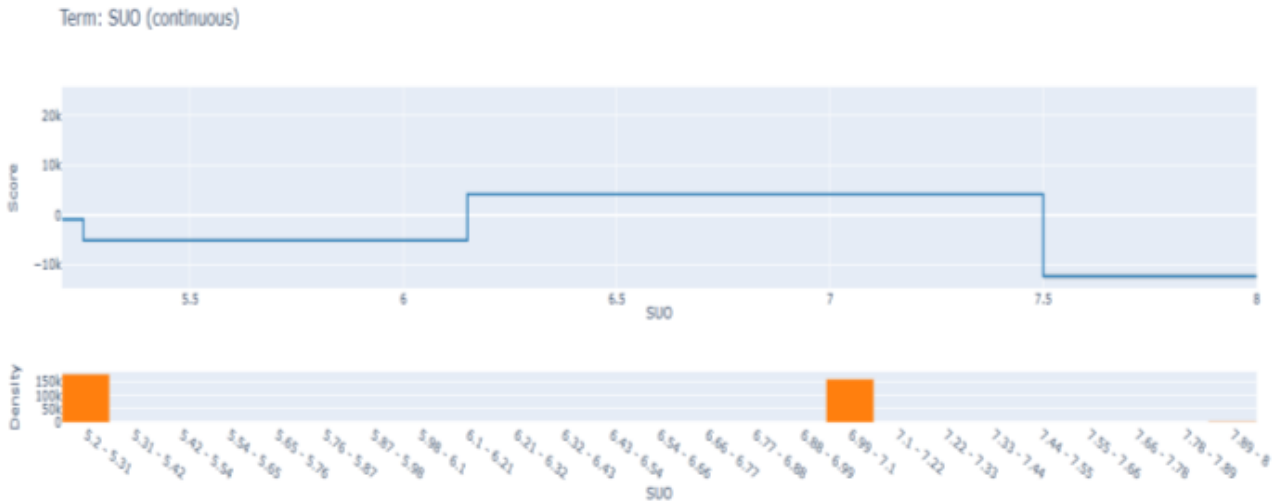


Fig. 12: Partial-dependence plot for SUO

Figure 12 highlights the relationship between education (SUO) and income, revealing that wages increase with education up to a certain point, after which they plateau and in some cases decrease. This non-linear pattern suggests overqualification or inefficient matching between advanced education and job availability. It supports the case for more targeted

funding strategies that consider optimal educational thresholds for specific sectors. *Figure 13* provides a local explanation for a single instance, showing how each input factor pushed the predicted wage up or down. The visual breakdown—such as positive contributions from GDP and industry type, and negative influences from certain regional codes—enables decision-makers to interpret forecasts in real-world terms. This helps improve trust in AI-driven policy tools, especially in sensitive domains like public sector employment and grant funding.

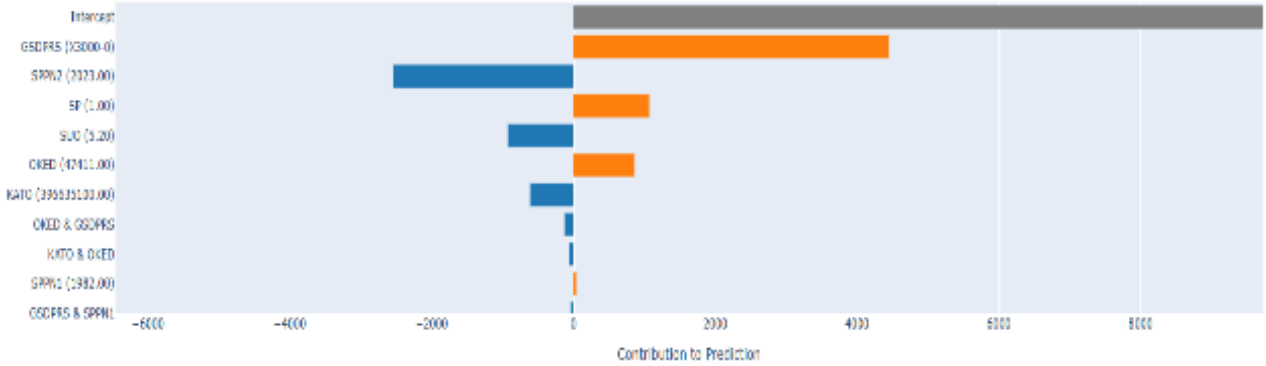


Fig. 13: Partial-dependence plot for SUO

Panel Long-Short Term Memory Neural Network Reinforced by Bayesian Stochastic Optimization for Demand Forecasting

For temporal forecasting of labor demand, the panel LSTM model provided accurate and stable predictions across multiple professions. By modeling demand sequences simultaneously and using shared representations, the panel LSTM captures profession-specific trends while leveraging inter-profession relationships. Hyperparameters were optimized through Bayesian methods, enabling convergence to high-performance configurations efficiently.

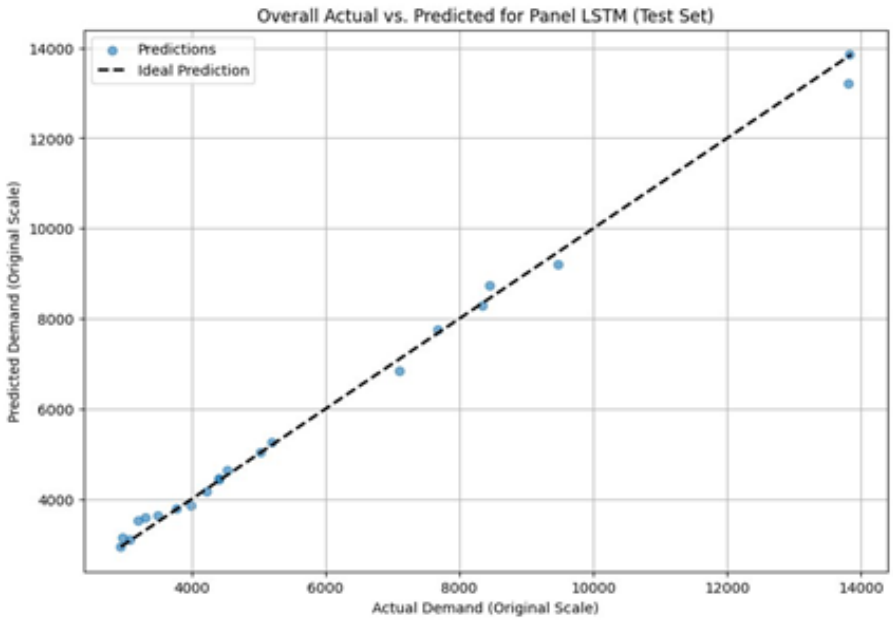


Fig. 14: Overall actual vs. predicted demand

The model's broader accuracy is confirmed in *Figure 14*, which plots actual versus predicted demand across all professions in the test set. The tight clustering along the ideal diagonal line indicates low prediction error and high correlation. Such consistency across professions affirms the model's scalability and relevance for national workforce planning. *Figure 15* depicts the demand forecast for profession 2350-3-003, illustrating strong agreement between the actual 2023 values and the model's prediction. The forecast suggests a tapering trend through 2026, potentially signaling labor saturation. These early warnings are essential for policymakers to adjust educational intake or reallocate grants to underrepresented sectors.

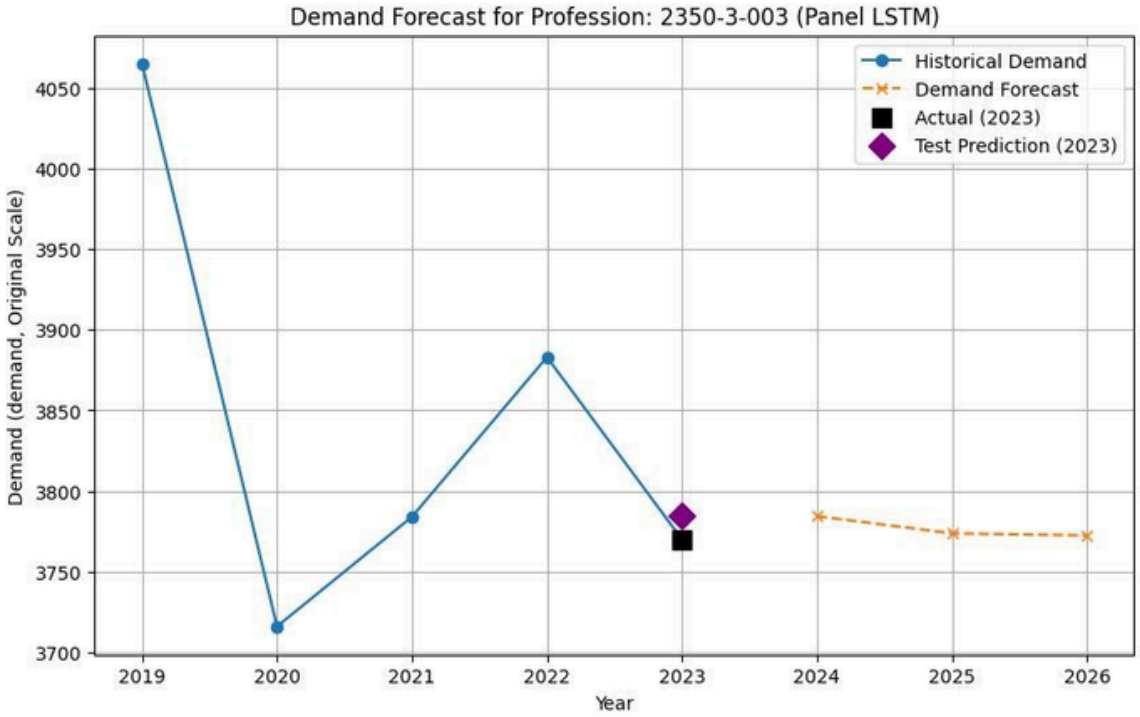


Fig. 15: Historical demand and future forecast for a profession

Meta-Model: Synergistic Integration of Predictive Approaches

The final ensemble meta-model synergizes CatBoost's wage classification, EBM's interpretability, and LSTM's temporal forecasting into a coherent and modular architecture. This integration ensures the system can address wage analysis from multiple perspectives—static, interpretable, and time-evolving.

A practical demonstration of the ensemble's inference process is shown in *Figure 16*. For three example professions, the meta-model outputs wage forecasts, identifies contributing features (e.g., GDP, occupation codes), and highlights potential mismatches in demand. This fusion of quantitative and explanatory power is especially useful for ministries and educational institutions tasked with strategic workforce planning. In conclusion, the experiments validate the effectiveness of each model individually and highlight the advantages of their integration. The approach not only ensures high prediction accuracy but also provides explainable and actionable insights that are crucial for shaping effective labor and education policy.

```
Prediction Results:

CatBoost predictions (salaries in different sectors):
  - high: [733844.11803017, 457727.98066390754, 361598.41225407267]
  - medium: [250675.94031274103, 258546.3445583005, 263002.5711379661]
  - low: [99434.38870504327, 115405.74699270257, 62300.91483344173]

EBM predictions (factor importance for professions):
  - Predictions: [66124.31387857934, 66229.10363492346, 61320.99895205716]
  - Feature Importance:

LSTM predictions (time-series forecasts):
  - Time series predictions: 36 total forecasts
  - Example predictions:
    * Profession 2374-9-005:
      Starting salary: 386448.00
      Salary after 12 months: 351968.00
      Change: -34480.00 (-8.92%)
    * Profession 2512-1-003:
      Starting salary: 419551.00
      Salary after 12 months: 401455.50
      Change: -18095.50 (-4.31%)
    * Profession 8322-9-005:
      Starting salary: 455123.00
      Salary after 12 months: 492049.00
      Change: 36926.00 (8.11%)
```

Fig. 16: Integrated results from the Meta-Model

4. Conclusion

This study presents a unified meta-model that integrates CatBoost, Explainable Boosting Machine (EBM), and LSTM neural networks with Bayesian optimization to address wage forecasting and labor demand prediction in Kazakhstan. By combining strengths in interpretability, prediction accuracy, and temporal forecasting, the meta-model offers a comprehensive tool for data-driven decision-making.
Its practical value is multi-faceted:

- Educational institutions can align curricula and training programs with labor market needs, maximizing student outcomes.
- Policymakers benefit from interpretable insights on wage disparities and saturation risks, enabling more effective policy intervention.
- Job seekers gain awareness of high-potential career paths based on forecasted wage trends and demand trajectories.
- Employers can plan compensation and hiring strategies based on real-time analytics of supply-demand mismatches.

While the model delivers strong results, especially with CatBoost achieving a MAPE of 2.51% and LSTM forecasting demand at 2.29% error, several limitations exist. Forecasting is currently limited to a 12-month horizon, and broader workforce variables such as job satisfaction or mobility are not yet integrated. These areas offer direction for future development.

Nonetheless, the proposed framework marks a significant advancement in labor market analytics, providing stakeholders with a reliable, interpretable, and scalable system to support strategic planning in an evolving economic landscape.

References:

[1] Alshammari, R., Alshammari, T., Singh, S., & Rawat, D. B. (2023). A comprehensive review on ensemble deep learning: Opportunities and challenges. Intelligent Systems with Applications, 18, 200228.

[2] Box, G. E. P., & Cox, D. R. (1964). An analysis of transformations. Journal of the Royal Statistical Society: Series B (Methodological), 26(2), 211–243.

[3] Caruana, R., Lou, Y., Gehrke, J., Koch, P., Sturm, M., & Elhadad, N. (2015). Intelligible models for healthcare: Predicting pneumonia risk and hospital 30-day readmission. Proceedings of the 21st ACM SIGKDD International Conference on Knowledge Discovery and Data Mining, 1721–1730.

[4] Dorogush, A. V., Ershov, V., & Gulin, A. (2018). Catboost: Gradient boosting with categorical features support. arXiv preprint arXiv:1810.11363.

[5] Hochreiter, S., & Schmidhuber, J. (1997). Long short-term memory. Neural Computation, 9(8), 1735–1780.

[6] Kaabar, S. (2024). Use catboost to predict your time series. Medium. Retrieved May 16, 2025.

[7] Karimov, A., Khasanov, T., & Ibragimov, R. (2025). Generalized meta framework for forecasting. ResearchGate.

[8] Liang, J., Jiang, L., Moreno, A., Zou, J., Fei-Fei, L., Niebles, J. C., & Sun, C. (2023). Advances in deep ensemble learning: Trends and perspectives. IEEE Transactions on Pattern Analysis and Machine Intelligence, 45(9), 10633–10651.

[9] Liu, J., Wang, H., Zhang, Y., & Chen, X. (2024). Two-stage meta-ensembling machine learning model for enhanced predictive analytics. Journal of Hydrology, 628, 130136.

[10] Microsoft Research. (2023). Train explainable boosting machines - classification. Microsoft Learn. Retrieved May 16, *2025.

[11] Nori, H., Jenkins, S., Koch, P., & Caruana, R. (2019). InterpretML: A unified framework for machine learning interpretability. arXiv preprint arXiv:1909.09223.

[12] Patel, R., Kumar, A., & Singh, V. (2024). LSTM adaptive hyperparameter tuning for financial time series forecasting. Journal of Theoretical and Applied Information Technology, 102(24).

[13] Prokhorenkova, L., Gusev, G., Vorobev, A., Dorogush, A. V., & Gulin, A. (2018). Catboost: Unbiased boosting with categorical features. Advances in Neural Information Processing Systems, 31, 6638–6648.

[14] Ren, Y., Suganthan, P. N., & Srikanth, N. (2021). The ensemble approach to forecasting: A review and synthesis. Transportation Research Part C: Emerging Technologies, 132, 103357.

[15] Snoek, J., Larochelle, H., & Adams, R. P. (2012). Practical bayesian optimization of machine learning algorithms. Advances in Neural Information Processing Systems, 25, 2951–2959.

[16] Wu, J., Chen, X.-Y., Zhang, H., Xiong, L.-D., Lei, H., & Deng, S.-H. (2019). Hyperparameter optimization for machine learning models based on Bayesian optimization. Journal of Electronic Science and Technology, 17(1), 26–40.

[17] Yeo, I.-K., & Johnson, R. A. (2000). A new family of power transformations to improve normality or symmetry. Biometrika, 87(4), 954–959.

[18] Zhang, W., Li, X., Chen, J., & Wang, Y. (2025). Developing an ensemble machine learning framework for enhanced predictive modeling. Nature Communications Earth & Environment, 6(1), 133.

ADVANCING SUSTAINABLE CONSTRUCTION MANAGEMENT THROUGH BIM PRACTICES AND THEIR IMPACT ON MEP PROJECT EFFICIENCY

Muhammad Usman Ali
PhD Scholar, Dept of Mechanical Engineering, International Islamic University, Islamabad, Pakistan
e-mail: muhammad.phdem24@iiu.edu.pk | ORCID: 0009-0000-4089-8992

Dr. Javed Ahmad Khan Tipu
Department of Mechanical Engineering, International Islamic University, Islamabad, Pakistan
e-mail: javed.ahmed@iiu.edu.pk

Dr. Eman N. Shaqour
Associate Professor In Architecture Engineering, Department of Architecture Engineering,, Aqaba University of Technology, Aqaba, Jordan
e-mail: imanshaqoor@gmail.com

Faiz Jalil
PhD Scholar, Dept of Mechanical Engineering, International Islamic University, Islamabad, Pakistan
e-mail: faiz.phdem19@iiu.edu.pk

Malik Imran Mujeeb,
Department of Electrical Engineering, Govt. College of Technology, D. I. Khan, Islamabad, Pakistan
e-mail: imranmujeeb26@gmail.com

Usman Aftab
PhD Scholar, Dept of Mechanical Engineering, International Islamic University, Islamabad, Pakistan
e-mail: usman.phdem18@iiu.edu.pk

Abstract

This study presents a comprehensive academic investigation into the role of Building Information Modelling (BIM) in promoting sustainability and operational efficiency within the design and construction of Mechanical, Electrical, and Plumbing (MEP) systems. Adopting a mixed-method research approach, the study integrates a Delphi survey to assess both the extent of BIM adoption and its measurable influence on key sustainability indicators such as material waste, energy efficiency, cost control, and stakeholder collaboration. Empirical findings reveal that the implementation of BIM led to a 54%

reduction in material waste and a 17% improvement in energy efficiency, underscoring its environmental benefits. Additionally, BIM usage was associated with a 20% decrease in rework, reflecting stronger interdisciplinary coordination and reduced design errors during project execution. The research also highlights enhanced stakeholder engagement facilitated by BIM, which contributed to improved project delivery and cost-effectiveness. Furthermore, the study introduces a practical, context-specific BIM framework tailored for Pakistan's construction industry, demonstrating its real-time applicability on active sites. The findings validate BIM as a critical enabler of sustainable construction practices by ensuring timely completion, reducing financial overruns, and optimizing overall project performance. The study concludes with a call for strategic investments in digital infrastructure, procedural improvements, and supportive government policies to address barriers to BIM implementation in developing countries.

Keywords

Building Information Modeling (BIM), Sustainability, MEP Projects, Construction Management, Resource Optimization

1. Introduction

The global construction sector is recognized for its substantial resource and energy consumption, with Mechanical, Electrical, and Plumbing (MEP) systems representing a considerable portion of a building's operating energy usage and environmental impact [1]. Despite its essential function in total building performance, MEP systems are among the least integrated into sustainable construction methods due to their complexity and disjointed processes. Building Information Modelling (BIM), as a cohesive digital methodology, presents significant potential for overcoming these obstacles [2]. BIM has become a crucial instrument for improving project sustainability through precise design, interdisciplinary collaboration, and efficient resource management. This study examines the influence of BIM on sustainable results in MEP projects, particularly regarding its implementation in Pakistan's developing construction sector. The increasing worldwide apprehension regarding climate change and the dedication to the United Nations Sustainable Development Goals (SDGs) have intensified the demand on enterprises to adopt environmentally sustainable practices [3]. The construction sector, due to its resource-intensive nature and significant contribution to building and demolition waste, is increasingly being directed towards sustainable methods. Green building, which prioritizes energy efficiency, resource conservation, and occupant health, has proven essential in alleviating the sector's environmental impact. Studies indicate that, in contrast to conventional constructions, green buildings can decrease energy consumption by as much as 50%, water usage by 40%, and carbon emissions by 35% [4]. BIM has transformed construction project planning and execution by facilitating intelligent, collaborative, and data-driven decision-making across

the building lifecycle. This digital technology facilitates real-time visualization, enhances communication among stakeholders, and enables three-dimensional simulation of construction processes [5]. As a result, BIM is progressively acknowledged for its ability to enhance project efficiency, reduce mistakes, and maximize building performance [4]. Academics have recognized the intersection of BIM and sustainable architecture as a viable domain for innovation. Integrating sustainability analysis into the first design phases using BIM enables project teams to make educated choices about material selection and energy optimization [4,6]. Nonetheless, these benefits are not uniformly attained across all project scales. Small and medium-sized construction projects—such as single-family homes, community canters, and minor commercial structures—frequently fall behind in implementing sustainable practices and Building Information Modelling (BIM) technology due to financial constraints, insufficient experience, and perceived intricacy [7].. Notwithstanding their ubiquity, these smaller projects have distinct limitations that hinder their capacity to use ecologically sustainable construction practices. Consequently, it is essential to address the deficiency in BIM implementation for small-scale projects, especially in developing countries.

This study aims to reveal the unexploited potential of BIM to enhance sustainability in smaller building projects. The objective is to furnish empirical insights and pragmatic recommendations for stakeholders in Pakistan's construction industry, namely those engaged in resource management, energy efficiency, waste minimization, and collaborative decision-making [1]. This research highlights the significance of BIM in enhancing the sustainability of small-scale projects, thereby contributing to a comprehensive understanding of how these initiatives might connect with national and global sustainability objectives. Although

extensive study has focused on BIM in large-scale construction, there has been scant scholarly attention on its implementation in small projects, particularly in the Malaysian and South Asian contexts [4, 8]. This study enhances understanding of the integration of BIM with sustainability principles in small-scale building by addressing this gap. The study, based on a comprehensive literature review and empirical data, demonstrates a robust correlation between BIM adoption and sustainable performance metrics, including early design optimization, energy analysis, material lifecycle assessment, and prefabrication [9, 10, 11]. These findings are pertinent for practitioners and policymakers aiming to enhance sustainability in construction via technology-driven initiatives. This study is among the inaugural investigations into the intersection of BIM and sustainable construction in small-scale projects, providing pragmatic insights into the implementation process and its results. It tackles difficulties with resource efficiency, technical capability, and strategic alignment, offering practical case studies and evidence-based frameworks to facilitate future implementation. The paper provides a prospective analysis of how BIM might facilitate sustainable building practices beyond major commercial projects. This project aims to provide stakeholders, especially in Pakistan and comparable developing regions, with effective tools and methods to promote environmentally resilient construction practices.

2. Problem Statement

Despite the shown advantages of Building Information Modelling (BIM) in improving sustainability and efficiency, its implementation in MEP (Mechanical, Electrical, and Plumbing) projects is still constrained, especially in developing countries. Significant implementation expenses, insufficient technical proficiency, and organizational opposition persist in obstructing integration initiatives. Conventional construction techniques inadequately tackle the environmental and resource concerns associated with MEP systems. This study aims to establish a BIM-based framework to address these obstacles and facilitate sustainable MEP project execution.

3. Literature Review

3.1. BIM Implementation in Construction

Building Information Modelling (BIM) has become a revolutionary technology in the global Architecture, Engineering, and Construction (AEC) sector, facilitating not only 3D modeling but also integrated project data management and collaboration among stakeholders throughout a building's lifecycle [12]. Advanced features, including clash detection (4D), scheduling (5D), cost prediction (6D), and sustainability analysis, substantially enhance project efficiency while reducing delays and errors [13]. Developed nations have rapidly adopted BIM owing to digitalization policies and mandates [14], but developing regions persistently encounter infrastructural, financial, and skill-related obstacles

[15]. The application of BIM is notably restricted in MEP (Mechanical, Electrical, and Plumbing) disciplines, despite its capacity to improve coordination within these intricate systems [16]. The Technology Acceptance Model (TAM) is a strong paradigm for evaluating BIM adoption, highlighting perceived usefulness and simplicity of use. Organizational preparation, encompassing infrastructure, skills, and leadership support, is essential for promoting BIM integration [7]. To address current issues, scholars recommend enhanced BIM education activities and supportive government policies specifically designed for MEP-related digital transformation.

3.2. BIM Development Overview

In a construction project with several services, it is essential to avert conflicts during the installation of each system by different contractors. The contemporary construction sector use BIM software to facilitate efficient coordination across architectural, structural, and MEP systems [18]. BIM enables the cohesive integration of various services, aids in energy efficiency evaluations, improves project coordination, and optimizes operation and maintenance procedures across the building lifetime. *Figure 1* depicts a streamlined workflow that delineates the interplay of diverse building construction process over the project lifecycle. The process commences when the owner presents the preliminary concept to the architects, who then formulate the architectural design. The design is subsequently transmitted to the relevant engineers across several disciplines, allowing them to formulate their service models in BIM while concurrently evaluating total costs. Upon the design's assessment and approval by both architects and consultants, contractors commence the installation of their respective systems. After construction is finalized and sanctioned by the appropriate authorities, the completed building is transferred to the owner.

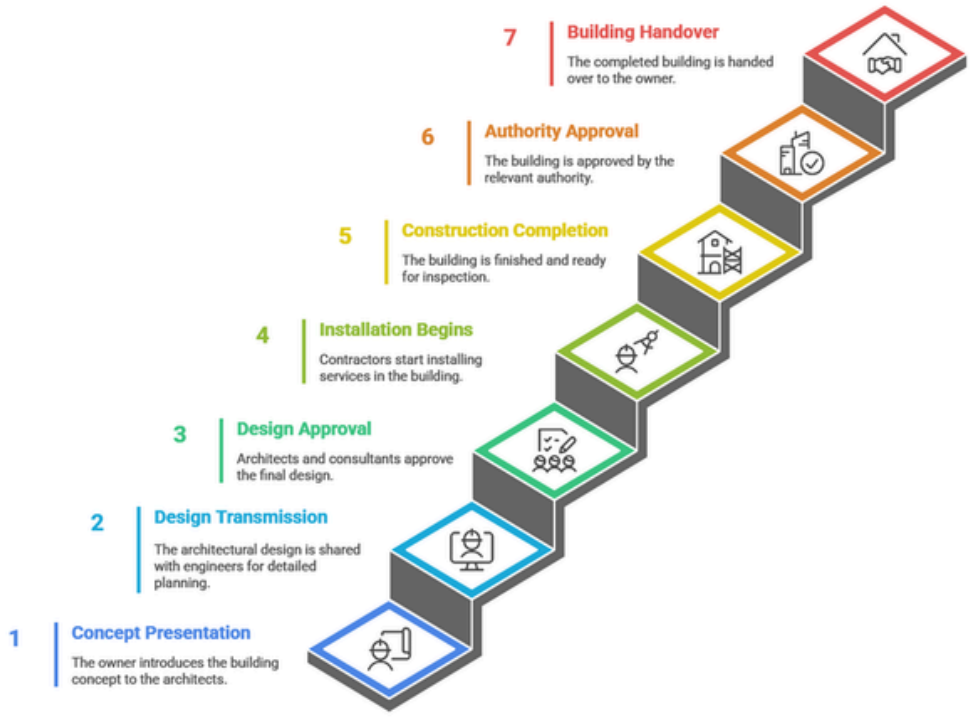


Fig. 1. Building Construction Process

BIM is a methodology that enables architects, as well as civil, mechanical, and electrical engineers or drafters, to collaboratively design, integrate, and visualize all aspects of a building or project in a unified digital environment [19]. It facilitates seamless collaboration and data exchange across disciplines, guaranteeing consistency and precision. BIM can be utilized at any moment of a building's lifecycle—encompassing rehabilitation, planning, design, documentation, construction, and extending into operation and maintenance—rendering it a comprehensive instrument for managing both new and old infrastructure, as illustrated in *Figure 2*. The several dimensions of BIM, as depicted in *Figure 3*, substantially enhance efficiency and productivity throughout all stages of the construction process [19]. Each dimension contributes a layer of pertinent information that enhances decision-making and project results. The dimensions of BIM 3D, 4D, 5D, 6D, and 7D encompass more than just geometric representation, incorporating elements such as time, cost, sustainability, and facility management. The following dimensions are outlined to elucidate their functions and advantages throughout the construction lifecycle.

3.3. BIM 3D (Design Modeling)

This dimension encompasses the amalgamation of all essential services, including architectural, structural, and MEP systems, working inside a unified digital platform. BIM 3D facilitates thorough visualization of the building model, enabling stakeholders to detect and address design conflicts early in the process. This improves collaboration and fosters clearer communication across all disciplines, ultimately resulting in more effective project planning and execution [20].

3.4. BIM 4D (Time)

BIM 4D incorporates the temporal dimension into the 3D model, facilitating enhanced planning and scheduling of construction activities. It offers comprehensive insights into the time necessary for project completion, as well as supplementary information including contract timelines, project duration, procurement timetables, and associated expenses [21]. BIM 4D enhances site planning efficiency and manageability by visualizing the sequence of construction and installation activities. The availability of this time-based data to all project stakeholders enables contractors to more effectively prepare for their jobs in accordance with the project timeline. This proactive strategy improves on-site safety, increases productivity, and minimizes avoidable delays, buffer periods, and lead times—assuming the schedule is adhered to precisely [20].

3.5. BIM 5D (Construction Management)

BIM 5D incorporates the cost dimension into the BIM model, facilitating precise budget planning and cost assessment from the project's inception. It facilitates real-time cost monitoring by automatically revising budget projections upon any design modifications. This dynamic relationship between design and cost enables clients and project owners to consistently evaluate financial performance, assess the effects of modifications, and make educated decisions. BIM 5D improves transparency, facilitates efficient cost management, and aids in maintaining the project within budget during its whole lifecycle [21].

3.6. BIM 6D (Sustainability)

BIM 6D emphasizes sustainability by facilitating energy consumption analysis in the preliminary design phase of a building. It enables clients and owners to assess both the construction expenses and the anticipated operational energy expenditures once the facility becomes functional [22]. This preliminary knowledge enables stakeholders to make informed design choices that enhance energy efficiency and diminish long-term operational costs. BIM 6D facilitates the creation of environmentally responsible buildings and improves operational management by including sustainability factors into the design and planning process. Ultimately, it aids in reducing energy use and attaining enhanced long-term financial savings [22].

3.7. BIM 7D (Facilities Management)

BIM 7D improves facility management by allowing building owners to monitor vital asset information, like warranty details, maintenance schedules, and technical requirements, which are critical for sustained operations. It offers real-time notifications regarding maintenance needs, facilitating preventive maintenance and minimizing unforeseen failures [22]. This data-intensive model assists contractors in optimizing the maintenance process, facilitating prompt interventions and reducing operational interruptions. BIM 7D facilitates cohesive collaboration among architectural, structural, and MEP services by consolidating all design components into a singular model. This integration facilitates early clash detection and settlement prior to the commencement of construction, hence substantially minimizing on-site conflicts. BIM 7D functions as an effective instrument for facility management and pre-construction planning, providing a thorough visual and data-centric representation of the complete building design and lifetime [23]. *Figure 2* depicts the lifecycle integration of BIM 7D, demonstrating how BIM application fundamentally underpins six essential phases: Planning, Designing, Renovation, Construction, Documentation, and Operation and Maintenance. BIM optimizes procedures, improves precision, and supports long-term management over a building's complete lifecycle. It transcends conventional CAD by offering a collaborative, data-intensive environment for all project stakeholders.

3.8. Sustainable Approaches in Structural and MEP System

Environmental sustainability in the construction sector has gained prominence, with Mechanical, Electrical, and Plumbing (MEP) systems recognized as significant factors influencing a building's environmental impact. These systems contribute significantly to energy and water consumption, along with greenhouse gas emissions, throughout both the construction and operational phases. Recent achievements highlight the use of sustainable design principles in MEP engineering, including energy optimization, emission reduction, and complete lifecycle effect assessment, to further global climate goals [24]. The contribution of MEP to energy efficiency emphasizes enhancing the performance of HVAC, lighting, electrical, and water systems, hence assuring minimal operational energy consumption while preserving occupant comfort. This is progressively reinforced by the implementation of sophisticated technologies such as high-efficiency apparatus, intelligent sensors, and automated building systems. The overall efficiency is mostly contingent upon the design and control of the systems as an integrated entity. Material conservation measures in MEP

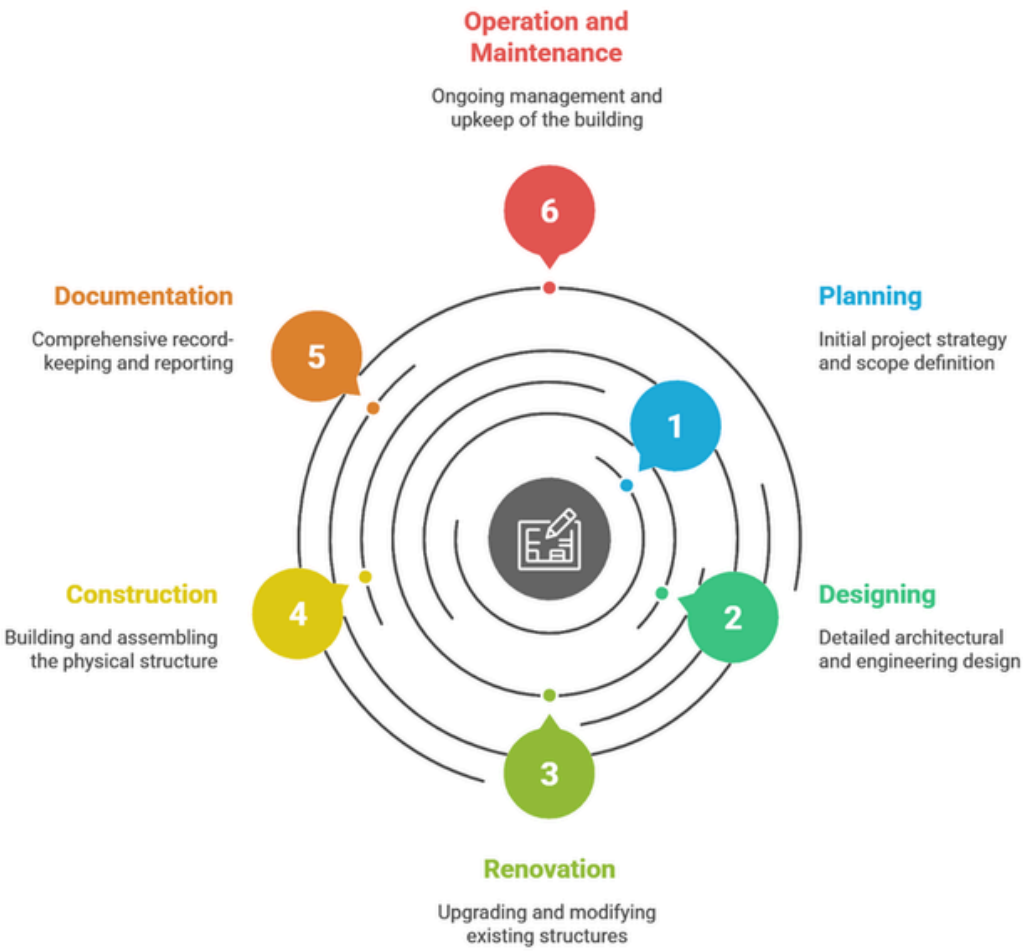


Fig. 2. BIM 7D Integration Overview

encompass precise design, modular prefabrication, and just-in-time logistics, which contribute to minimizing waste production. Inadequate coordination and disjointed workflows contribute to excessive material ordering and onsite waste, underscoring the necessity for integrated procedures [25]. Lifecycle Assessment (LCA) is progressively utilized to assess the embodied carbon and environmental effects of MEP components, promoting the choice of low-carbon materials and improving long-term asset sustainability [26]. Notwithstanding these developments, the absence of integration among MEP disciplines continues to pose a substantial obstacle to sustainability. The isolated execution of mechanical, electrical, and plumbing tasks frequently results in inadequate coordination and less than optimal results. This highlights the necessity for collaborative design methodologies and the utilization of computational tools such as Building Information Modelling (BIM), which promote interdisciplinary collaboration and support comprehensive, sustainability-oriented MEP solutions [27].

3.9. Sustainability and BIM in MEP:

Prior to the emergence of Building Information Modelling (BIM), initiatives to improve sustainable performance in construction were restricted to traditional instruments for light and energy assessment. Donn et al. (2003) employed early building performance simulation methods to markedly decrease energy usage without incurring extra financial expenditures.

The advent of BIM has been acknowledged as a pivotal catalyst for sustainability, especially in Mechanical, Electrical, and Plumbing (MEP) projects. BIM has transformed sustainability-focused project planning through its ability to improve design accuracy, facilitate interdisciplinary collaboration, and employ advanced predictive analytics [28]. BIM facilitates the amalgamation of intelligent 3D models containing metadata, enabling engineers to execute high-resolution energy performance simulations, detect and rectify spatial conflicts, and optimize system configurations to reduce material waste and energy usage. The energy analysis capabilities enable project teams to assess and analyze operational performance across various MEP configurations and environmental circumstances, hence supporting informed decisions that conform to green certification standards and sustainability goals [17]. Moreover, the integration of 4D (time) and 5D (cost) dimensions in BIM enables stakeholders to mitigate material over-ordering, optimize scheduling, and enhance sequencing—crucial elements in minimizing waste in intricate MEP systems. The advancement to 6D BIM facilitates thorough life cycle asset management beyond construction. It facilitates predictive maintenance, real-time equipment surveillance, and operating cost minimization, hence prolonging the lifespan of MEP systems and diminishing environmental effectiveness [22]. Furthermore, the amalgamation of BIM with digital twin technologies has enabled real-time monitoring and predictive analytics, hence enhancing sustainable operational performance. Notwithstanding these advancements, a considerable deficiency persists in empirical studies measuring the influence of BIM on sustainability in MEP project delivery, particularly in poor nations where BIM implementation is still nascent. The amalgamation of BIM with cutting-edge technologies, including the Internet of Things (IoT), artificial intelligence (AI), and cloud computing, offers novel prospects for attaining sustainability in MEP systems. Standardized protocols, a robust data infrastructure, and thorough training programs are crucial to fully realize the potential of these digital advances [4]. In conclusion, although BIM serves as a potent instrument for promoting sustainability in MEP engineering via integrated design, lifespan optimization, and improved stakeholder collaboration, additional empirical research is necessary. These should seek to validate theoretical frameworks, quantify sustainable benefits, and tackle contextual hurdles in various socio-economic contexts to enable broader adoption.

4. Research Objectives

This study is organized around three primary objectives focused on enhancing the comprehension and utilization of Building Information Modelling (BIM) for sustainable Mechanical, Electrical, and Plumbing (MEP) project execution in developing markets.

- to evaluate the existing extent and methodologies of BIM implementation in MEP projects, determining the applications and locations of BIM usage during the design and execution stages.
- to assess the impact of BIM adoption on sustainability outcomes specifically in terms of material waste reduction, energy efficiency, and cost management in MEP services.
- to create and authenticate a BIM-driven sustainability framework customized for emerging countries, focusing on context-specific difficulties in MEP project execution.

5. Research Methodology

This study employed a three-phase mixed-methods approach to comprehensively investigate the impact of Building Information Modelling (BIM) on sustainability in MEP projects. The methodological framework and training involved a sequential technique employing the Delphi method, quantitative surveys, and qualitative interviews. Stage 1 employed the Delphi method to achieve expert consensus on critical sustainability criteria, key BIM parameters, and contextual implementation challenges. Stage 2 entailed a methodical quantitative survey directed at professionals in the construction industry. The data were analysed using SPSS, including descriptive statistics, regression analysis, correlation matrices, and moderation/mediation models to explore the relationships between BIM practices and sustainability outcomes. Stage 3 involved semi-structured qualitative interviews, analysed thematically to extract insights and validate the evolving conceptual framework. *Figure 3* delineates an eight-step approach for the implementation of a BIM framework, commencing with an Introduction and a Literature Review. Subsequently, it advances to Research Methodology and Practical Training. The latter section emphasizes Framework Development, Implementation, and Data Analysis, concluding with Adoption and Training to guarantee the framework's effective integration. This systematic methodology transitions from fundamental research to practical implementation and assessment.

5.1. Delphi Method

Delphi research was conducted using 18 experts selected from academia, industry, and BIM consultancy sectors. The process involved two iterative rounds to achieve consensus on the critical sustainability factors, prevalent obstacles in BIM implementation, and potential variables for creating a viable framework. The experts contributed feedback anonymously to mitigate bias and ensure the objective evaluation of critical indicators.

5.2 Quantitative/ Quantitative Data Acquisition and Examination

Structured questionnaires were disseminated to construction professionals to collect data on BIM adoption, sustainability performance, cost efficiency, and materials/resource management in MEP projects. The questionnaire items were developed to align with validated components and appropriate approaches in BIM research. Data were statistically validated utilizing SPSS software and inferential methods, including regression and correlation analysis, to assess the strength and direction of relationships among variables. Semi-structured interviews were performed with 12 participants, comprising BIM coordinators, MEP engineers, and project managers, to enhance the quantitative results. The interviews investigated practical project obstacles, collaborative interactions, and the perceived benefits of BIM. The NVivo program enabled thematic analysis, facilitating the identification of patterns and categories that improved the interpretation of quantitative results and assisted in framework development. At the outset of stakeholder engagement via the questionnaire, it was noted that numerous participants were either unfamiliar with Building Information Modelling (BIM) or had never utilized it in their professional endeavours. The researcher acknowledged the significance of overcoming this gap and prepared a list of stakeholders unfamiliar with BIM tools. The list was thereafter disseminated to their relevant supervisors or department heads to facilitate the coordination and scheduling of focused training sessions. A organized training program was developed, commencing with 15 days of foundational seminars to elucidate the principles and significance of BIM and Revit. This was succeeded by a 40-day phase of experiential training, enabling stakeholders to acquire firsthand familiarity with the program and incorporate it into their regular workflows. The *Table 1* below delineates the principal issues encountered by diverse construction stakeholders who are either unacquainted with or do not employ BIM/Revit tools. Minor contractors frequently encounter difficulties in comprehending design modifications and overseeing rework due to insufficient version control. Site engineers encounter implementation problems due to inadequate visualization of intricate designs in conventional 2D formats. Conventional architects overlook potential design conflicts, such as those between beams and ductwork, which are only recognized late in the construction process. Non-technical project managers are deprived of real-time project data, resulting in delayed and uninformed decision-making. Local fabricators encounter recurrent discrepancies resulting from ambiguous specifications and the lack of digital modelling. Procurement teams manage erroneous material orders, which undermine project continuity and customer expectations. MEP subcontractors frequently install systems ineffectively due to ambiguous routing and coordination challenges, necessitating expensive rework. Ultimately, quantity surveyors that depend on manual techniques often commit cost estimation inaccuracies, resulting in budget inconsistencies. These deficiencies not only postpone projects but also engender client unhappiness, characterized by grievances regarding inefficiency, substandard quality, and insufficient transparency. The lack of BIM/Revit tools severely impedes coordination, quality, and client confidence in construction projects.

Table 1. Without BIM: Insights from Stakeholders and Clients

Stakeholder Type	Inefficiencies Without BIM	Client Feedback
Contractors	Difficulty interpreting design changes; high rework costs due to lack of version control	Frequent cost overruns and complaints about inefficiency
Site Engineers	Inaccurate implementation due to poor visualization of complex designs from 2D plans	Execution errors causing dissatisfaction in project delivery
Traditional Architects	Design conflicts (e.g., duct vs. beam) undetected until construction phase	End-users report unexpected issues with design outcomes
Project Managers (Non-tech)	Inability to track real-time project updates, causing delays in decision-making	Clients demand more transparency and regular progress updates
Fabricators	Frequent fabrication mismatches due to lack of precise modeling or clash detection	Customer complaints on poor fit and aesthetic mismatches
Procurement Teams	Over/under ordering of materials due to inaccurate BOQs and unclear specs	Late project completion due to supply delays and confusion
Subcontractors (MEP)	Improper MEP system routing leading to time-consuming rework on-site	Quality complaints due to system conflicts or poor installations
Quantity Surveyors	Manual quantity take-offs often result in cost estimation errors and budget overruns	Budget inconsistencies and last-minute financial adjustments causing mistrust

5.3. Execution of Practical Framework

Upon the successful completion of theoretical sessions and practical training in BIM and Revit, the stakeholders exhibited enhanced comprehension and preparedness to implement these tools in real-world applications. The scholar established a systematic methodology designed to direct the on-site implementation of MEP systems. The framework was developed to optimize workflows, enhance precision, and minimize errors by employing BIM functionalities such as collision detection, real-time updates, and 3D visualization. It also underscored the necessity for enhanced coordination among the diverse disciplines engaged in construction, hence facilitating more seamless on-site execution. The last stage of the research was implementing the BIM-based sustainability framework presented in *Table 2* inside a current commercial construction project in Pakistan. This practical application concentrated on the implementation of MEP systems while meticulously tracking important performance metrics such as material consumption, energy efficiency, interdisciplinary collaboration, and rework frequency. Data were gathered before to and during deployment to contrast conventional techniques with BIM-based methodologies. The results offered compelling empirical proof of the framework's efficacy, illustrating enhanced project performance and its potential for wider adoption and scaling within the Pakistani construction sector.

Table 2. Sustainable MEP Execution Framework

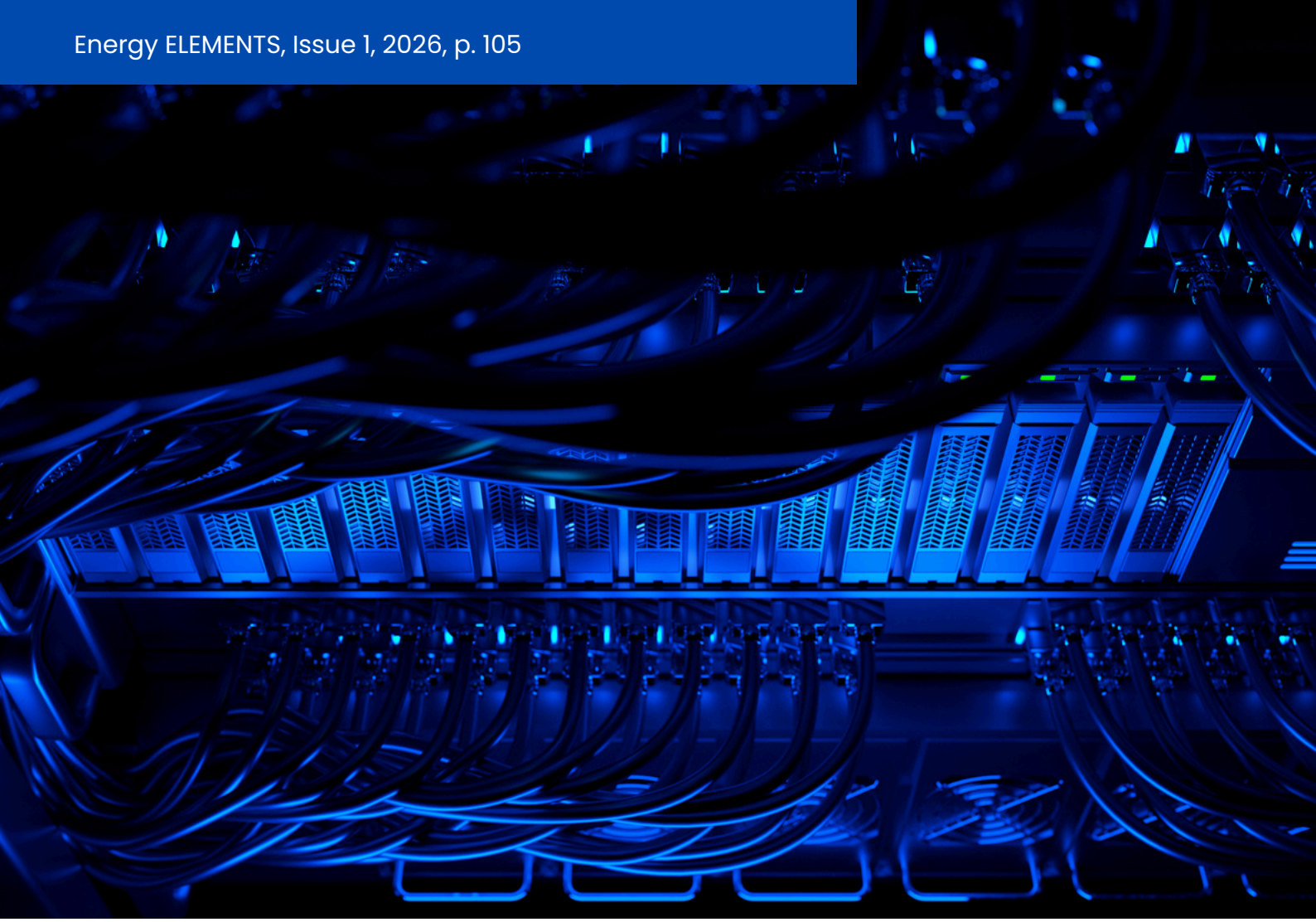
Phase	**Stakeholders Involved**	**BIM-Driven Actions**	**Site Implementation Steps**	**Expected Benefits**
Planning & Coordination	Project Managers, BIM Coordinators, MEP Designers	3D BIM modeling with sustainability goals	Kickoff meeting; define model standards	Reduced conflicts, clear scope, fewer RFIs
Design Validation	BIM Engineers, Sustainability Experts	Clash detection; energy simulation	Conduct clash and load simulations	Reduced rework, energy-efficient MEP designs
Construction Preparation	Site Engineers, Procurement, BIM Modelers	4D scheduling & 5D cost integration	Link schedule and procurement to BIM	Just-in-time delivery, labor optimization, waste reduction
On-Site Execution	MEP Supervisors, Contractors, QA/QC	Mobile BIM tools for installation guidance	Real-time verification of as-built vs BIM	Accurate installations, fewer errors, time savings
Monitoring & QC	QA/QC, HSE, BIM Coordinators	Model-based inspection; sustainability tracking	BIM-driven inspections and energy metric monitoring	Compliance assurance, validated energy performance
Handover & Maintenance	Facility Managers, BIM Teams	As-built BIM with asset and maintenance data (6D BIM)	Deliver COBie-compliant models; CMMS integration	Easier maintenance, lifecycle tracking, operational efficiency

5.4. Outcomes after Practical Implementation of Framework

Following the implementation of the BIM-based sustainable framework in *Table 3* and the provision of structured training, the principal stakeholders in MEP projects observed significant enhancements in their roles. Small contractors, previously unacquainted with BIM, acquired the ability to visualize building sequences, thereby diminishing rework and enhancing site coordination. Site engineers acquired proficiency in clash detection and model navigation, enabling them to resolve design issues promptly and improve installation precision. Traditional architects, transitioning from 2D to integrated BIM models, enhanced collaboration with MEP layouts, hence minimizing design errors and expediting approvals. Non-technical project managers utilized BIM technologies to monitor progress and enhance communication, resulting in improved planning and client satisfaction. Local manufacturers implemented BIM-based manufacturing specifications, minimizing waste and guaranteeing superior quality fits. Procurement teams enhanced material planning through precise quantity take-offs, averting shortages and delays. Subcontractors and quantity surveyors utilized BIM to guarantee efficient installations and accurate cost management, resulting in reduced client complaints and enhanced trust.

Table 3. Framework Impact on MEP Stakeholder

Stakeholder Type	Training/Framework Focus	Benefits Achieved	Client Feedback
Contractors	BIM model navigation and clash detection	Fewer on-site errors and improved design understanding	Higher construction quality and timely delivery
Site Engineers	MEP system modeling and coordination	Smooth MEP system installation with reduced rework	Improved satisfaction with service quality
Traditional Architects	Project scheduling and real-time monitoring	Enhanced coordination and faster decision-making	Transparent project progress and communication
Project Managers (Non-tech)	BOQ extraction and inventory planning	Optimized material procurement and cost savings	No material shortages or delays reported
Fabricators	Model-based fabrication planning	Improved fitting accuracy and reduced fabrication waste	Perfect fitting and improved aesthetics
Procurement Teams	Accurate quantity take-offs using Revit	Greater estimation accuracy and budget control	Clear budget reporting and fewer financial surprises
Subcontractors (MEP)	Design validation and interdisciplinary coordination	Fewer design clashes and better stakeholder alignment	Well-coordinated systems and fewer complaints
Quantity Surveyors	Energy simulation and system efficiency checks	Improved energy efficiency and reduced operational costs	Noticeable energy savings and comfort improvement



6. Results

This chapter outlines the key findings derived from the analysis of the effects of Building Information Modelling (BIM) implementation on sustainability and operational efficiency in Mechanical, Electrical, and Plumbing (MEP) projects. The results are systematically categorized into six fundamental dimensions: degree of BIM adoption, reduction of material waste, improvements in energy efficiency, decreased rework rates, enhanced interdisciplinary collaboration, and cost and time savings. Statistical techniques, including descriptive analysis, correlation, regression, and reliability assessments, are illustrated in tables accompanied by comprehensive explanations.

6.1. Patterns of BIM Application in MEP Projects

The investigation indicated a significant degree of BIM integration in MEP-related processes. The study results revealed that 78% of the projects assessed utilized BIM from the design phase, whilst 62% maintained its use throughout construction and operations, underscoring an increasing trend in comprehensive lifecycle BIM application. Autodesk Revit and Navisworks have become the predominant platforms, with many specialized software for sophisticated MEP system design. These digital tools facilitated enhanced interdisciplinary collaboration and seamless integration among complex system components, promoting collaborative workflows and model-driven project execution.

6.2. Decrease in Material Waste

A significant conclusion of the study is the substantial decrease in material waste linked to BIM adoption. Quantitative study indicated that average material waste rates diminished from 22.5% before BIM adoption to 10.3% subsequently—a 54% relative decrease. This decrease demonstrates the effectiveness of BIM in producing accurate amount take-offs, facilitating early clash detection, and minimizing the necessity for on-site rework. The findings underscore BIM's capacity to improve material efficiency, synchronize resource utilization with project demands, and foster sustainability in MEP construction processes. *Table 4* summarizes the descriptive statistics for material waste alongside other key variables in the study.

Table 4. Descriptive Statistics of Key Variables

Variable	N	Mean	Std. Deviation	Minimum	Maximum
BIM Adoption Level	50	3,42	1,12	1	5
Material Waste Before (%)	50	22,5	4,1	15,1	29,8
Material Waste After (%)	50	10,3	3.20	5	14,9
Energy Consumption Before (kWh)	50	63200	8500	50100	79900
Energy Consumption After (kWh)	50	51700	6900	40200	64800
Rework Rate (%)	50	18,2	4.70	10,5	29,4
Project Duration (Days)	50	280	45	180	365
Cost Savings (USD)	50	35500	7400	21000	49800
Stakeholder Collaboration Score	50	3,75	0,95	1	5

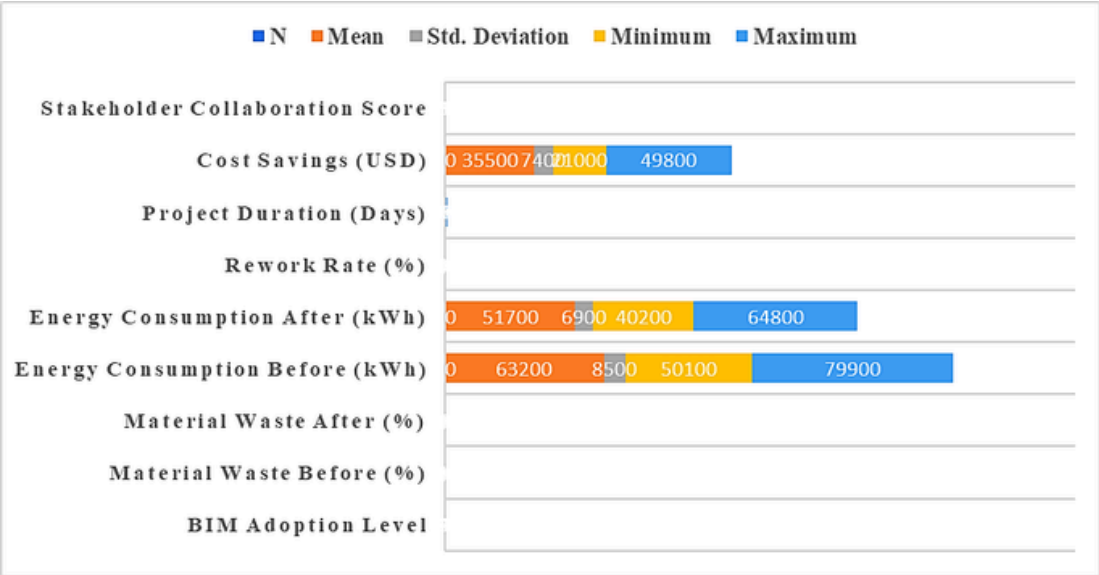
6.2.1. Description:

Table 4 displays the descriptive statistics of different project performance indicators prior to and following the implementation of Building Information Modelling (BIM) in 50 Mechanical, Electrical, and Plumbing (MEP) projects. Each variable represents a distinct facet of project sustainability and efficiency. The BIM Adoption Level has an average score of 3.42 (on a scale from 1 to 5), signifying a moderate to high level of BIM integration among the studied projects. Prior to BIM deployment, material waste averaged 22.5% with a

standard deviation of 4.10%. Following the adoption of BIM, this waste considerably decreased to an average of 10.3%, indicating a marked improvement in material efficiency. Regarding energy performance, energy consumption prior to BIM averaged 63,200 kWh, which dropped to 51,700 kWh following BIM implementation. This decrease in energy consumption (by roughly 18%) indicates BIM's capability to enhance energy-related decision-making via preliminary design analysis and simulation. The rework rate, an indicator of faults or design conflicts necessitating rectification, was 18.2%, highlighting inefficiencies that BIM might mitigate through enhanced coordination and clash detection capabilities. The average project duration was 280 days, indicating that most projects lasted approximately 9 months, while the average cost reductions attributed to BIM were recorded at $35,500, underscoring the economic advantages of enhanced planning and resource management. Finally, the stakeholder collaboration score, assessed on a 1–5 scale, averaged 3.75, signifying that BIM markedly enhanced transdisciplinary communication and involvement among project teams. These figures empirically validate that BIM deployment enhances sustainability, cost-efficiency, and project performance in the MEP sector.

6.3 Enhancements in Energy Efficiency

The investigation reveals that projects utilizing Building Information Modelling (BIM) achieved an average reduction of 17% in anticipated energy usage relative to those employing traditional design and planning techniques. The efficiency improvement is mostly ascribed to BIM's capacity to integrate real-time energy modelling and simulation in the initial design phases. BIM facilitates the assessment of various MEP system configurations and the selection of appropriate equipment and layouts, thereby diminishing operational energy requirements and improving environmental performance throughout the building lifecycle.



Graph 1. Benefits of BIM in MEP Projects

6.4. Enhancement of Rework and Coordination

Notable advancements were also evident in minimizing rework and improving interdisciplinary collaboration. Projects utilizing BIM experienced a 20% reduction in rework rates, attributable to BIM's clash detection capabilities and its facilitation of proactive

communication among design, engineering, and construction teams. The research revealed a statistically significant negative association ($r = -0.68$, $p < 0.01$) between the degree of BIM implementation and rework rates. This indicates that enhanced maturity in BIM utilization results in reduced design conflicts, minimizes execution errors, and facilitates timely project completion with fewer interruptions and budget excesses.

Table 5 shows the Pearson correlation coefficients among BIM adoption and key sustainability and efficiency variables.

Table 5. Pearson Correlation Matrix Among Key Variables

Variable	BIM Adoption	Material Waste After	Energy Consumption After	Rework Rate	Cost Savings	Stakeholder Collaboration
BIM Adoption Level	1.00	-0.62**	-0.58**	-0.68**	0.59**	0.65**
Material Waste After (%)	-0.62**	1.00	0.70**	0.56**	-0.48**	-0.54**
Energy Consumption After (kWh)	-0.58**	0.70**	1.00	0.52**	-0.41**	-0.49**
Rework Rate (%)	-0.68**	0.56**	0.52**	1.00	-0.46**	-0.57**
Cost Savings (USD)	0.59**	-0.48**	-0.41**	-0.46**	1.00	0.62**
Stakeholder Collaboration	0.65**	-0.54**	-0.49**	-0.57**	0.62**	1.00

$p < 0.01$ (two-tailed) for all correlations.

6.4.1. Description

The correlation matrix above illustrates the strength and direction of relationships among key variables related to the influence of Building Information Modeling (BIM) on MEP project performance and sustainability outcomes. The results demonstrate statistically significant relationships at the 0.01 level (denoted by **), offering strong support for the subsequent interpretations. The level of BIM adoption exhibits a strong negative correlation with material waste after implementation ($r = -0.62$), energy consumption after implementation ($r = -0.58$), and rework rate ($r = -0.68$). Higher levels of BIM adoption correlate with decreased material wastage, reduced energy consumption, and minimized rework, thereby illustrating BIM's efficacy in resource optimization and enhanced coordination. BIM adoption exhibits a positive correlation with cost savings ($r = 0.59$) and stakeholder collaboration ($r = 0.65$), suggesting that enhanced utilization of BIM leads to improved financial results and greater interdisciplinary communication. Significant inter-variable correlations are present, notably between Material Waste and Energy Consumption ($r = 0.70$), indicating that inefficient material utilization is frequently associated with heightened energy consumption. Furthermore, Stakeholder Collaboration exhibits negative correlations with inefficiencies, such as material waste, energy consumption, and rework, while demonstrating a strong positive correlation with Cost Savings ($r = 0.62$). The findings empirically confirm the integrative function of BIM in promoting sustainability, efficiency, and stakeholder engagement in MEP projects.

6.5. Cost and Time Efficiency

The results underscore BIM's substantial impact on project cost management and scheduling efficacy. Data analysis indicated that employing BIM for quantity takeoffs improved budget precision by roughly 18%, mitigating cost overruns generally attributable to estimating inaccuracies and scope alterations. BIM-enabled coordination and early-stage clash detection resulted in a 16% reduction in project duration by enhancing planning, sequencing, and interdisciplinary communication, hence minimizing delays and optimizing workflow. These results underscore BIM's function as a strategic instrument for enhancing budgetary oversight and punctual execution in construction projects, especially for intricate MEP systems.

Table 6 summarizes the results of a multiple linear regression analysis predicting material waste reduction based on BIM adoption, stakeholder collaboration, and cost savings.

Table 6. Multiple Regression Analysis Predicting Material Waste After BIM

Predictor	B (Unstandardized)	Std. Error	Beta (Standardized)	t-value	p-value
(Constant)	18,75	2,1	—	8,93	<0,001
BIM Adoption Level	-3,21	0,6	-0,52	-5,35	<0,001
Stakeholder Collaboration	-1,15	0,52	-0,18	-2,21	0,031
Cost Savings	-0,0004	0,0002	-0,21	-2,68	0,01

Summary:

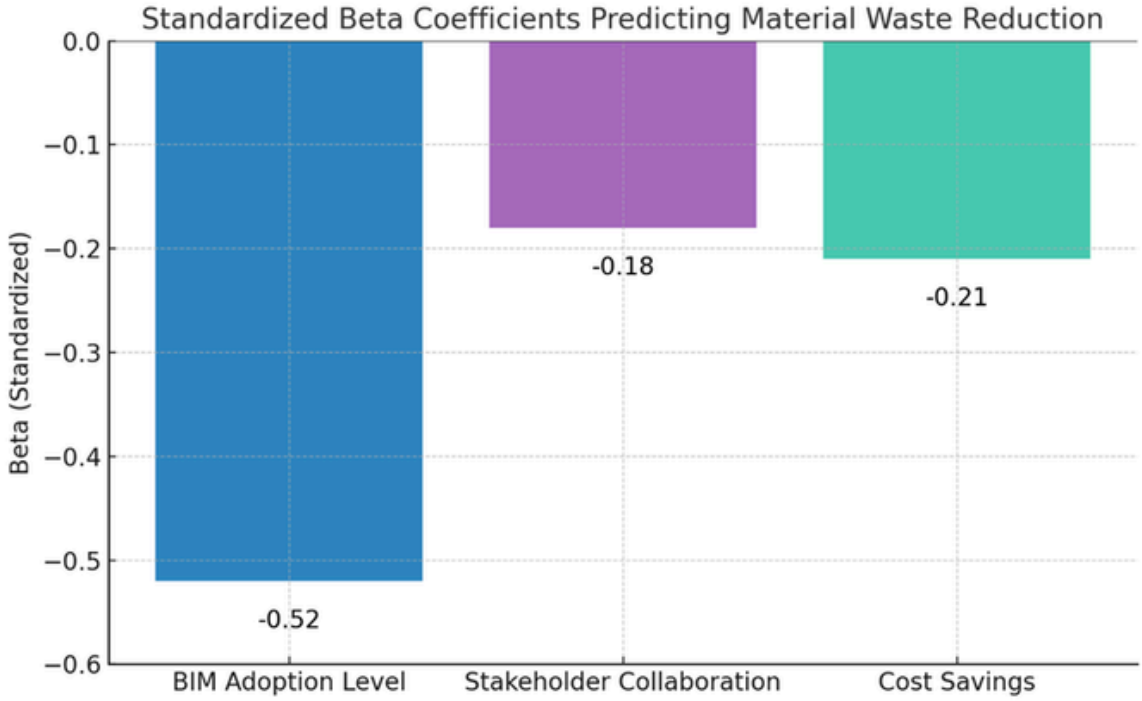
$R^2 = 0.61$, $F(3, 46) = 24.1$, $p < 0.001$

6.5.1. Description

The regression model indicates a statistically significant negative correlation between BIM adoption and material waste, with an unstandardized coefficient $B = -3.21$ ($p < 0.001$). This signifies that for every one-unit rise in BIM adoption level, material waste is anticipated to diminish by 3.21 percentage points, while controlling for other variables. The standardized beta ($\beta = -0.52$) validates this as the most significant predictor in the model. Likewise, stakeholder collaboration exerts a notable albeit lesser negative effect on material waste ($B = -1.15$, $p = 0.031$), indicating that enhanced collaboration correlates with slight reductions in waste. Cost savings considerably contribute ($B = -0.0004$, $p = 0.010$), while the effect size is minimal due to the unit scale of the cost data. Consequently, this suggests that as cost-saving strategies enhance, material waste is likely to diminish, potentially indicating improved resource management. The model indicates that increased BIM use, efficient cooperation, and cost-effective strategies are essential facilitators of material waste reduction in MEP building projects.

6.6. Reliability of Stakeholder Collaboration Scale

To test the validity of the stakeholder cooperation measure, Cronbach's alpha was determined.



Graph 2. Efficiency of BIM in MEP Projects

Table 7. Reliability Analysis (Cronbach's Alpha) of Stakeholder Collaboration Scale

Scale	Number of Items	Cronbach's Alpha
Stakeholder Collaboration Scale	5	0.87

6.6.1. Description

The Stakeholder Collaboration Scale, with 5 items, exhibited strong internal consistency with a Cronbach's Alpha of 0.87. This signifies the robust reliability of the scale employed in the study to assess collaboration among project stakeholders. A Cronbach's Alpha exceeding 0.70 is typically deemed appropriate for study (Nunnally & Bernstein, 1994), and the acquired value indicates that the items proficiently represent the fundamental construct of collaboration in BIM-enabled MEP projects.

6.7. Paired Samples T-Test for Material Waste Reduction

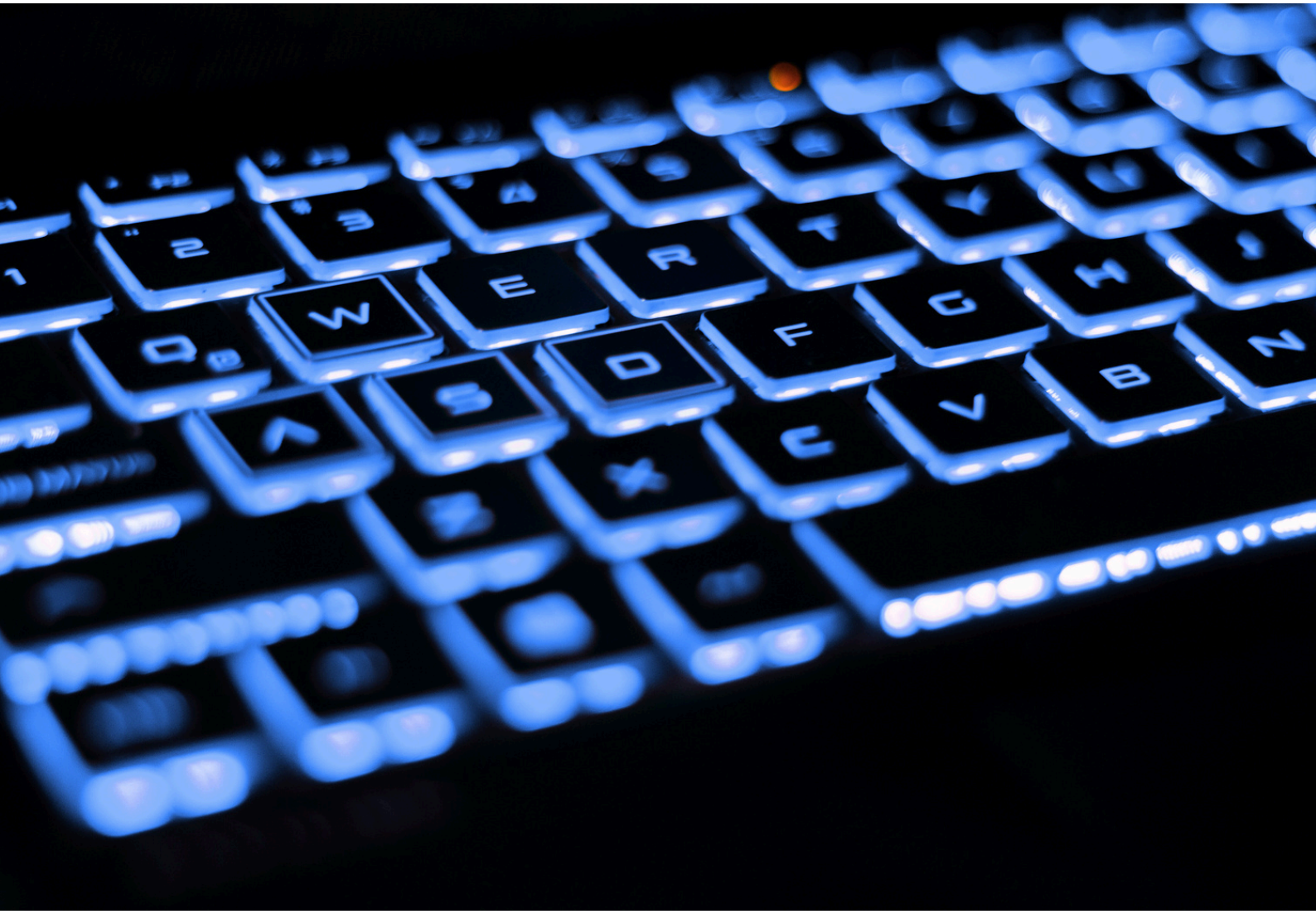
A paired sample t-test compared material in construction waste before and after BIM use.

Table 8. Paired Samples T-Test for Material Waste before and After BIM

Measure	Mean (%)	Std. Deviation	t-value	df	p-value
Material Waste Before BIM	22,5	4,1	15,62	49	<0,001
Material Waste After BIM	10,3	3,2			

6.7.1. Description

The findings of the paired-sample t-test displayed in the table compare material waste before to and following the deployment of Building Information Modeling (BIM) in MEP projects. The average material waste diminished markedly from 22.5% (SD = 4.1) to 10.3% (SD = 3.2). The t-value of 15.62 with 49 degrees of freedom (df = 49) and a p-value < 0.001 indicates that this reduction is statistically significant. This indicates that the implementation of BIM significantly and statistically reduces material waste in construction projects. The findings substantiate the assertion that BIM significantly enhances sustainability by reducing resource waste via improved design precision, clash identification, and coordinated planning.



7. Findings

This findings of the research are about the impact of Building Information Modelling (BIM) on the augmentation of sustainability and efficiency in Mechanical, Electrical, and Plumbing (MEP) projects. The data indicates that 78% of the projects implemented BIM during the design phase, while 62% maintained its use throughout construction and operations. BIM systems like Revit and Navisworks enhanced transdisciplinary

coordination. A notable decrease in material waste—from 22.5% to 10.3%—was recorded, alongside a 17% reduction in energy use, illustrating BIM's ability for accurate planning and sustainable design. Rework rates decreased by 20%, and a significant negative connection ($r = -0.68$, $p < 0.01$) established that increased BIM utilization resulted in fewer site adjustments. Project timeframes were reduced by 16%, and budget precision increased by 18%, demonstrating BIM's impact on cost and time efficiency. Regression research demonstrated that BIM adoption, stakeholder collaboration, and cost savings were significant predictors of material waste reduction. The stakeholder collaboration measure demonstrated strong reliability ($\alpha = 0.87$), and a paired t-test confirmed a significant reduction in material waste following BIM deployment ($p < 0.001$). The findings robustly endorse BIM's efficacy in promoting sustainability, optimizing resources, and enhancing project delivery within the MEP sector. The *Figure 4* contrasts stakeholder and client comments prior to and following the use of BIM in MEP projects. In the absence of BIM, stakeholders indicated recurrent misunderstanding, excessive rework, erroneous cost projections, and timetable delays. Conversely, the utilization of BIM resulted in superior interdisciplinary coordination, precise quantity take-offs, reduced design errors, and optimized project deadlines. Clients reported enhanced satisfaction with visual clarity and expedited response times when BIM was implemented. The table underscores BIM's crucial contribution to enhancing cooperation, efficiency, and project results.

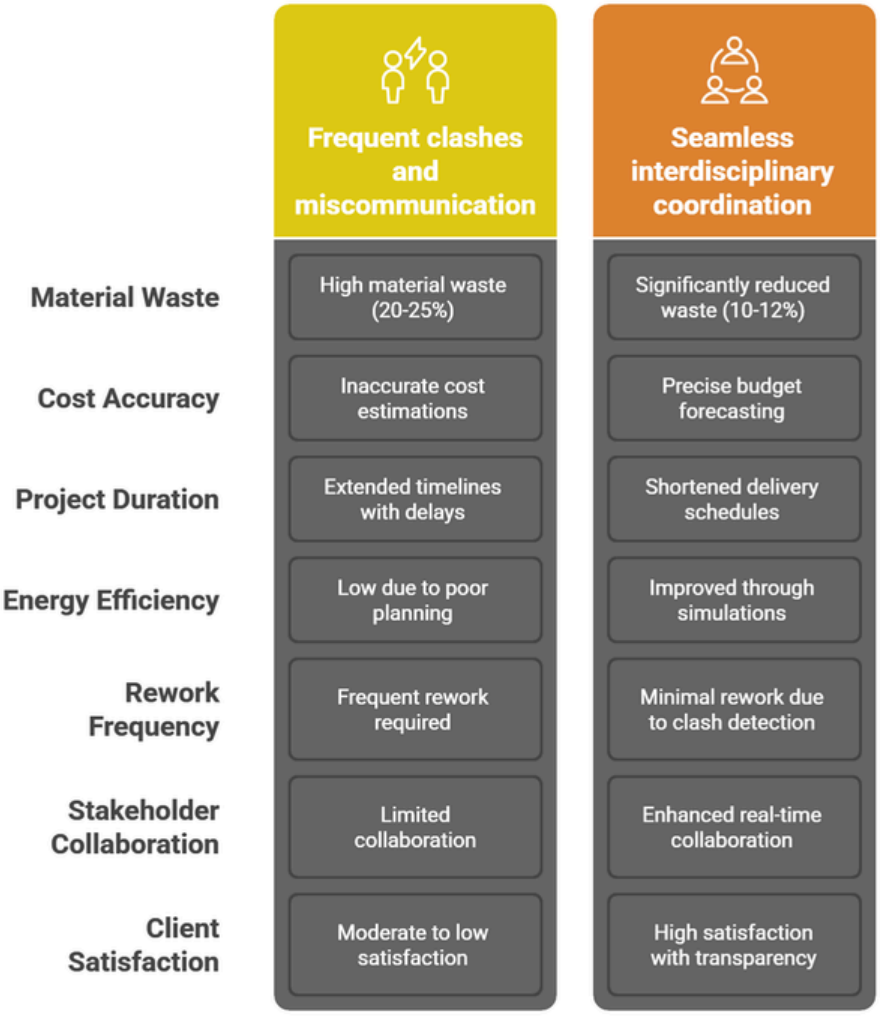


Figure 4. Impact on Stakeholder & Client Feedback with BIM & without BIM

8. Discussion

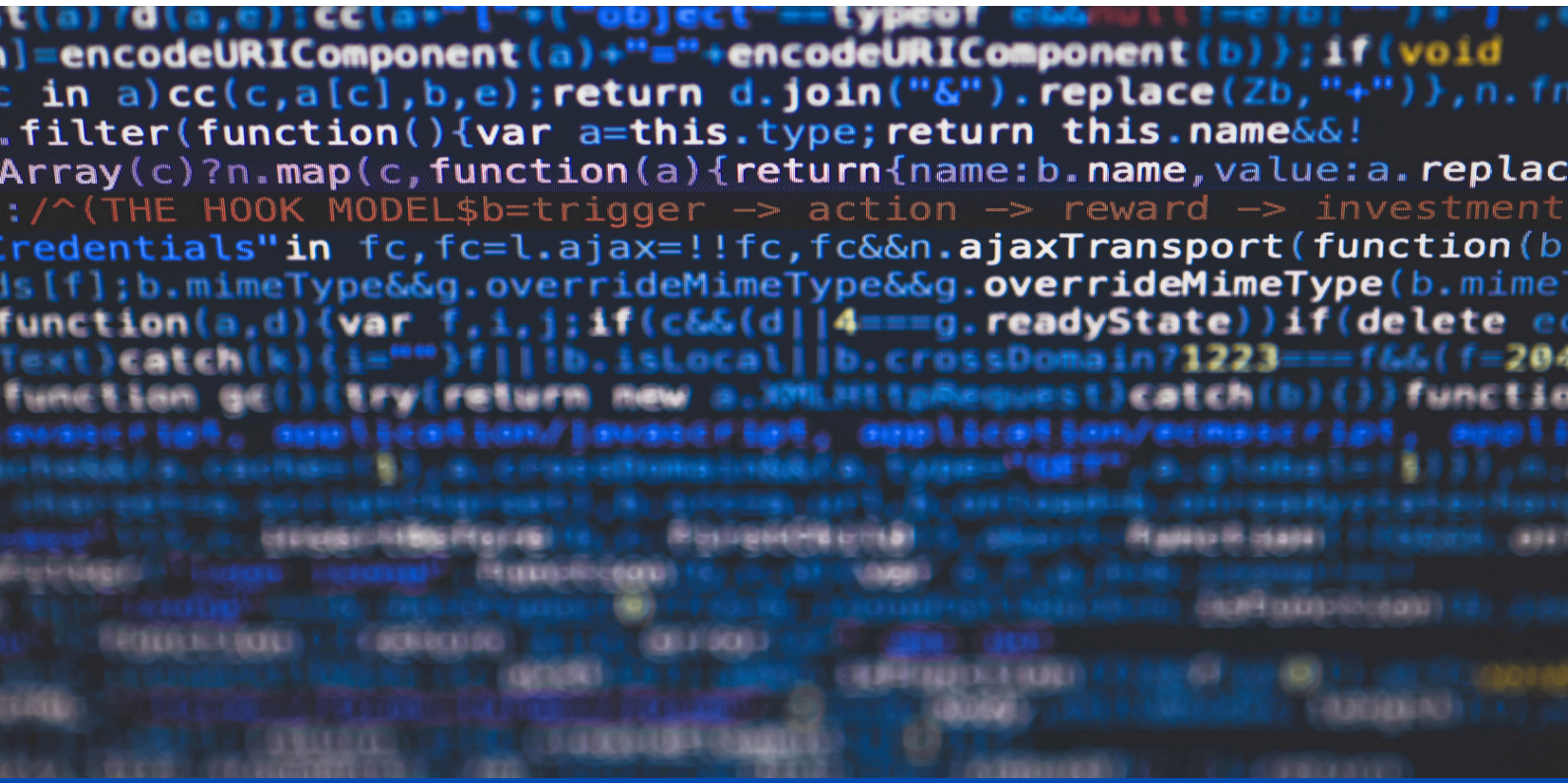
BIM is fundamentally revolutionizing MEP projects by markedly enhancing sustainability and efficiency. The extensive utilization of this approach in design reflects an increasing recognition of its significance in facilitating coordinated project delivery, while its sustained application throughout building and operation suggests an evolving emphasis on whole-life management, crucial for enduring environmental advantages. This study shown that BIM significantly decreases material waste by around 54%, corroborating other research that emphasizes its effect on minimizing overordering and site alterations. This efficiency reduces environmental effect and project expenses by limiting superfluous raw material usage and the corresponding embodied carbon. BIM-enabled energy simulations result in around a 17% decrease in energy use, facilitating optimal MEP designs and the choice of sustainable appliances, so immediately diminishing a building's operating carbon footprint. This underscores BIM's function as a catalyst for sustainable construction environments. The significant inverse correlation between BIM maturity and rework rates highlights its critical role in facilitating design coordination, since early clash detection reduces expenses and improves workflow. In addition to environmental advantages, BIM enhances project feasibility by facilitating cost reductions and improving time efficiency. Model-based quantity takes offs guarantee precise budgeting, whereas enhanced communication and organization result in decreased on-site duration, energy expenditure, and labour expenses. Significantly, stakeholder engagement was identified as the most potent predictor of BIM adoption and positively impacted material waste reduction, underscoring that BIM's efficacy is enhanced in transdisciplinary settings. Organizational readiness, encompassing technical infrastructure and training, also has a moderating function. Nonetheless, obstacles remain, especially in developing nations, such as skill shortages, high expenses, and cultural opposition, requiring strategic measures. Future study may examine the integration of BIM with transformative digital technologies such as AI and IoT to further improve sustainable MEP management and assess long-term post-occupancy performance.

9. Conclusion

The data and discussion clearly indicate that Building Information Modelling (BIM) substantially improves the sustainability and operational efficiency of Mechanical, Electrical, and Plumbing (MEP) projects. The extensive implementation of BIM, with 78% of projects employing it in the design phase and 62% throughout construction and operations, indicates an increasing recognition of its advantages across the project lifetime. The significant decrease in material waste—from 22.5% to 10.3%—illustrates BIM's ability to enhance quantity take-offs and reduce site rework, hence facilitating resource conservation and cost savings. The noted 17% reduction in energy consumption underscores BIM's contribution to facilitating efficient design simulations and promoting sustainable equipment choices, thereby diminishing operational energy demands and carbon emissions. The 20% reduction

in rework and the significant negative association ($r = -0.68$, $p < 0.01$) between BIM adoption and site modifications highlight its efficacy in enhancing interdisciplinary cooperation and facilitating early clash detection. These economies result in a 16% decrease in project length and an 18% enhancement in budget precision, affirming BIM's impact on prompt and economical project execution. Regression research further validated that BIM adoption, stakeholder collaboration, and cost-saving initiatives are substantial predictors of material waste reduction. The elevated dependability of the stakeholder collaboration scale ($\alpha = 0.87$) and significant t-test outcomes ($p < 0.001$) underscore the essential function of collaborative environments in facilitating BIM success. The discourse confirms that BIM facilitates not only technical advancements but also serves as a strategic catalyst for sustainability via integrated design, meticulous planning, and informed decision-making. Collaboration among stakeholders emerged as the primary catalyst for BIM success, highlighting that, in addition to technology, human and organizational elements are crucial. However, obstacles persist—especially in developing nations such as Pakistan—where elevated implementation costs, a shortage of experienced professionals, and opposition to digital transformation impede comprehensive BIM adoption. To overcome these obstacles, focused training initiatives, legislative measures, and leadership dedication are essential for enhancing technical proficiency and cultural preparedness.

In conclusion, BIM is a revolutionary instrument that provides measurable enhancements in material efficiency, energy consumption, cost control, and schedule compliance in MEP projects. It promotes sustainability in environmental, economic, and social dimensions through resource optimization, stakeholder participation, and transparent communication. The results endorse a structured framework that facilitates BIM integration across all project tiers, bolstered by effective governance and ongoing professional development. Future research must concentrate on the enduring effects of BIM-enabled practices, especially when combined with AI and IoT technology, to enhance sustainable performance throughout the built environment.



10. Recommendations

The report advocates for the effective and comprehensive application of Building Information Modelling (BIM) in MEP projects, necessitating certain strategic approaches. The government should mandate the integration of BIM to ensure sustainable adherence in the construction industry. Secondly, continuous professional development is crucial for equipping MEP practitioners with up-to-date competencies in both BIM technologies and sustainable construction practices. Furthermore, the implementation of standardized BIM project delivery methods is crucial for guaranteeing uniformity and collaboration among stakeholders. Early and ongoing stakeholder engagement should be facilitated by BIM-enabled collaboration tools, guaranteeing clear communication and aligned project goals. Ultimately, official support via financial grants and incentives can accelerate BIM adoption, making the technology more accessible and appealing to both public and private sector. *Figure 5* depicts a cyclical process for BIM adoption, emphasizing six essential stages. The process commences with the identification of disparities to comprehend existing gaps, succeeded by the implementation of training to cultivate requisite skills. Subsequently, it underscores the necessity of obtaining leadership commitment for effective adoption and devoting resources to facilitate the endeavor. The process subsequently progresses to attaining efficiency via BIM utilization, finally seeking to optimize project timelines, hence establishing a continuous improvement cycle for BIM integration.

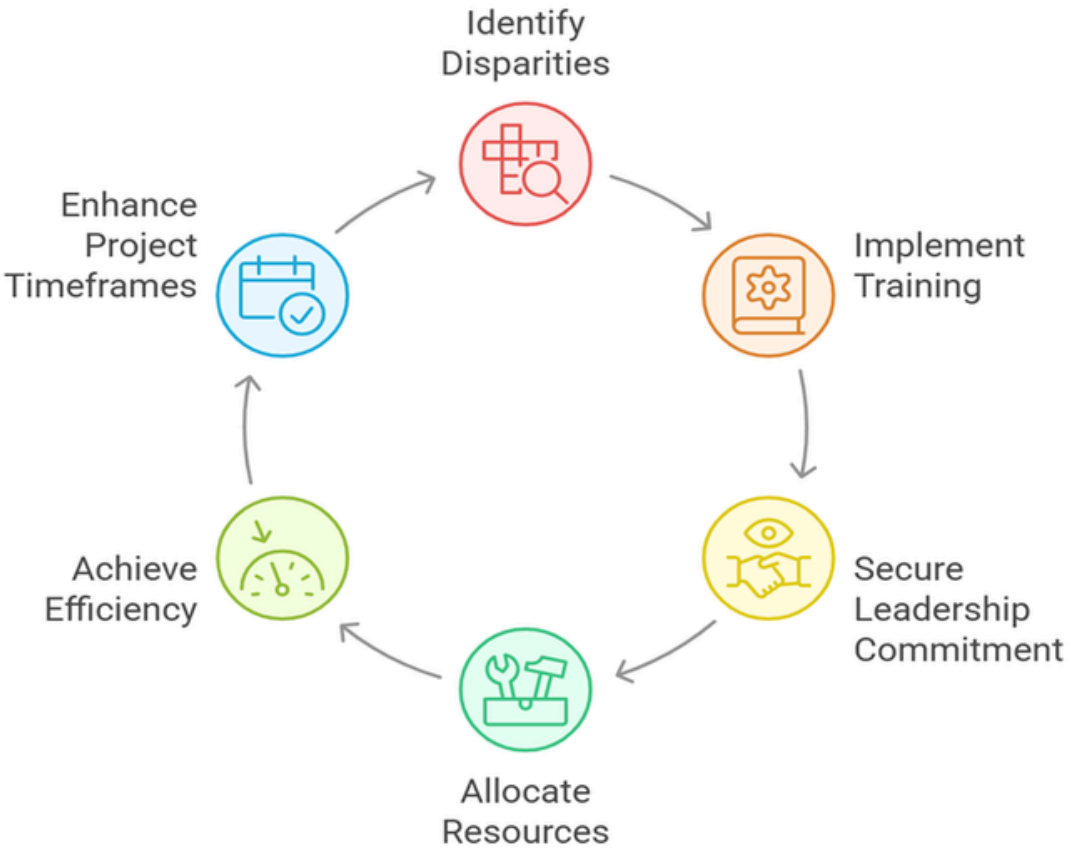


Figure 5. BIM Implementation Cycle in MEP Projects

11. Future Research

BIM is increasingly being integrated with Artificial Intelligence (AI) and the Internet of Things (IoT) to provide effective real-time evaluation of sustainability performance. Post-Occupancy Evaluation (POE) is becoming increasingly important for assessing the long-term effectiveness of BIM-enabled MEP systems. Moreover, BIM's role in facilitating smart grid integration and incorporating renewable energy sources in MEP design is expanding. The advancement to 7D BIM is substantial, offering comprehensive management of the entire lifecycle of built assets. Moreover, there is a growing imperative to evaluate the effects of national BIM policies, particularly in developing countries, to understand their influence on adoption and implementation outcomes.

References:

[1] Li Wang, F. L. (2013). Knowledge Discovery of Spatial Conflict Resolution Philosophies in BIM-Enabled MEP Design Coordination Using Data Mining Techniques: A Proof-of-Concept. ASCE Computing in Civil Engineering.

[2] Shaqour, E. N. (2022). The role of implementing BIM applications in enhancing project management knowledge areas in Egypt. Ain Shams Engineering Journal, 13(1). https://doi.org/10.1016/j.asej.2021.05.023

[3] Dian Zhuang a b, X. Z. c d, Y. L. a b, C. W. a b, X. J. a b, X. Z. a b, X. S. (2021). A performance data integrated BIM framework for building life-cycle energy efficiency and environmental optimization design. Automation in Construction, 127.

[4] Waqar, A., Othman, I., Saad, N., Azab, M., & Khan, A. M. (2023). BIM in green building: Enhancing sustainability in the small construction project. Cleaner Environmental Systems, 11. https://doi.org/10.1016/j.cesys.2023.100149

[5] Rathnasiri, P., & Jayasena, S. (2022). Green building information modelling technology adoption for existing buildings in Sri Lanka. Facilities management perspective. Intelligent Buildings International, 14(1), 23–44. https://doi.org/10.1080/17508975.2019.1632782

[6] Ohueri, C. C., Liew, S. C., Bamgbade, J. A., & Enegbuma, W. I. (2023). Critical components for successful BIM-based sustainable building design collaboration: structural equation model analysis. Journal of Engineering, Design and Technology. https://doi.org/10.1108/JEDT-06-2023-0235

[7] Fernanda L. Leite. (2019). BIM for Design Coordination: A Virtual Design and Construction Guide for Designers, General Contractors, and MEP Subcontractors (Fernanda L. Leite, Ed.). John Wiley & Sons.

[8] Cao, D., Li, H., Wang, G., & Huang, T. (2017). Identifying and contextualising the motivations for BIM implementation in construction projectsAn empirical study in China. International Journal of Project Management, 35(4), 658–669. https://doi.org/10.1016/j.ijproman.2016.02.002

[9] Ferdosi, H., Abbasianjahromi, H., Banihashemi, S., & Ravanshadnia, M. (2023). BIM applications in sustainable construction: scientometric and state-of-the-art review. International Journal of Construction Management, 23(12), 1969–1981. https://doi.org/10.1080/15623599.2022.2029679

[10] Pu, L., & Wang, Y. (2021). The Combination of BIM Technology with the Whole Life Cycle of Green Building. World Journal of Engineering and Technology, 09(03), 604–613. https://doi.org/10.4236/wjet.2021.93042

[11] Kai Guo a, Q. L. b, L. Z. c, X. W. (2021). BIM-based green building evaluation and optimization: A case study. Journal of Cleaner Production, 320

[12] Bayhan, H. G., Demirkesen, S., Zhang, C., & Tezel, A. (2023). A lean construction and BIM interaction model for the construction industry. Production Planning and Control, 34(15), 1447–1474. https://doi.org/10.1080/09537287.2021.2019342

[13] Shou, W., Wang, X., Wang, J., Hou, L., & Truijens, M. (2014). Integration of BIM and lean concepts to improve maintenance efficiency: A case study. Computing in Civil and Building Engineering - Proceedings of the 2014 International Conference on Computing in Civil and Building Engineering, 373–380. https://doi.org/10.1061/9780784413616.047

[14] Azhar, S., Carlton, W. A., Olsen, D., & Ahmad, I. (2011). Building information modeling for sustainable design and LEED ® rating analysis. Automation in Construction, 20(2), 217–224. https://doi.org/10.1016/j.autcon.2010.09.019

[15] Muhammad Altaf; Wesam Salah Alaloul; Sheharyar Khan; M.S. Liew; Muhammad Ali Musarat; Alawag Aawag Mohsen. (2022). Value Analysis in Construction Projects with BIM implementation: A Systematic Review. IEEE 2021 International Conference on Decision Aid Sciences and Application (DASA).

[16] Abdul-Quayyum Gbadamosi a b, A.-M. M. a, L. O. O. b, O. O. A. b, P. M. c, L. M. a, C. A. (2019). Offsite construction: Developing a BIM-Based optimizer for assembly. Journal of Cleaner Production, 215.

[17] Chen, B., Wang, P., & Bi, L. (2021). Application Research of BIM Technology in Project Cost Management in the Era of Big Data. In BCP Business & Management EMSD (Vol. 2021).

[18] Khosakitchalert, C., Yabuki, N., & Fukuda, T. (2020). Development of bim-based quantity takeoff for light-gauge steel wall framing systems. Journal of Information Technology in Construction, 25, 522–544.

https://doi.org/10.36680/j.itcon.2020.030

[19] Teo, Y. H., Yap, J. H., An, H., Yu, S. C. M., Zhang, L., Chang, J., & Cheong, K. H. (2022). Enhancing the MEP Coordination Process with BIM Technology and Management Strategies. In Sensors (Vol. 22, Issue 13). MDPI. https://doi.org/10.3390/s22134936

[20] Awe, M., Malhi, A., Budka, M., Mavengere, N., & Dave, B. (2025). Towards 4D BIM: A Systematic Literature Review on Challenges, Strategies and Tools in Leveraging AI with BIM. In Buildings (Vol. 15, Issue 7). Multidisciplinary Digital Publishing Institute (MDPI). https://doi.org/10.3390/buildings15071072

[21] Inzerillo, L., Acuto, F., Pisciotta, A., Mantalovas, K., & Di Mino, G. (2024). Exploring 4d and 5d analysis in bim environment for infrastructures: A case study. International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives, 48(2), 233–240. https://doi.org/10.5194/isprs-Archives-XLVIII-2-W4-2024-233-2024

[22] Al-Raqeb, H., & Hamidreza Ghaffar, S. (2025). The Role of BIM 6D and 7D in Enhancing Sustainable Construction Practices: A Qualitative Study. https://doi.org/10.20944/preprints202501.1172.v1

[23] Sood, R., & Laishram, B. (2024). Challenges in Implementation of 7D-BIM for Infrastructure Asset Management: A Systematic Review. In Construction Economics and Building (Vol. 24, Issue 3, pp. 95–117). Australian Institute of Quantity Surveyors. https://doi.org/10.5130/AJCEB.v24i3.8738

[24] Miatto, A., Sartori, C., Bianchi, M., Borin, P., Giordano, A., Saxe, S., & Graedel, T. E. (2022). Tracking the material cycle of Italian bricks with the aid of building information modeling. Journal of Industrial Ecology, 26(2), 609–626. https://doi.org/10.1111/jiec.13208

[25] Tu, B., Zuo, J., Chang, R. D., Webber, R. J., Xiong, F., & Dong, N. (2023). A system dynamic model for assessing the level of BIM implementation in construction phase: a China case study. Engineering, Construction and Architectural Management, 30(4), 1321–1343. https://doi.org/10.1108/ECAM-10-2021-0895

[26] Yang, W., & Lu, Z. (2023). Analysis of Key Injury-Causing Factors of Object Strike Incident in Construction Industry Based on Data Mining Method. Sustainability (Switzerland), 15(21). https://doi.org/10.3390/su152115609

[27] Xie, X., Zhou, J., Fu, X., Zhang, R., Zhu, H., & Bao, Q. (2022). Automated Rule Checking for MEP Systems Based on BIM and KBMS. Buildings, 12(7). https://doi.org/10.3390/buildings12070934

[28] Lee, G., & Borrmann, A. (2020). BIM policy and management. In Construction Management and Economics (Vol. 38, Issue 5, pp. 413–419). Routledge. https://doi.org/10.1080/01446193.2020.1726979

MINI-REVIEW BY ELEMENTS

Artificial Intelligence in Orbit: The Φsat-2 Mission and the Transformation of Satellite Technologies

In 2025, the European Space Agency (ESA) achieved a significant technological milestone with the launch of **Φsat-2**, a mini-satellite equipped with **onboard artificial intelligence** for autonomous data processing. This mission represents one of the most remarkable steps toward integrating AI into Earth observation satellite systems.

Traditionally, satellites have transmitted raw imagery to ground stations for subsequent processing — a time-consuming and resource-intensive approach. Unlike conventional systems, **Φsat-2 is capable of filtering and analyzing data directly in orbit**, identifying and classifying critical events such as **wildfires, water pollution, and maritime traffic**. Only relevant information is then transmitted to the ground, significantly **reducing data volumes** and improving response times.

A core technological feature of the mission is the **NanoSat MO Framework**, a modular software platform that enables **remote updates and in-orbit retraining of AI algorithms**. This flexibility allows Φsat-2 not only to execute pre-programmed tasks but also to **adapt to new monitoring scenarios** without physical intervention.

This architecture paves the way for **autonomous satellite constellations** capable of coordinated observations, real-time climate monitoring, disaster response, and decision support. According to ESA experts, such systems will play a crucial role in **global climate initiatives** and **sustainable development programs** by providing timely, high-value information directly from orbit.

In essence, Φsat-2 marks a paradigm shift from conventional Earth observation satellites to intelligent orbital platforms where AI is central to data management and operational efficiency.

[1] ESA. Φsat-2 begins science phase for AI Earth images. https://www.esa.int

[2] Open Cosmos. Φsat-2 mission overview. SA. Φsat-2 begins science phase for AI Earth images. https://www.esa.int

Digital Commons USU. Onboard AI Processing in CubeSats. [2] Open Cosmos. Φsat-2 mission overview. SA. Φsat-2 begins science phase for AI Earth images. https://www.esa.int

ENERGY ELEMENTS

Scientific and Technological Journal for Researchers and Engineers

Energy. Chemistry. Ecology. IT