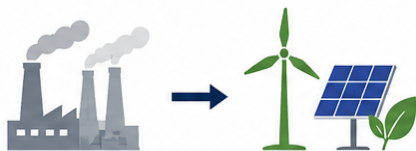


Integrated LCA– MCDA Assessment of Nuclear Power for a Sustainable Low-Carbon Energy Future

THE CHALLENGE

Rising energy demand and climate change require reliable electricity with minimal environmental impact and strong energy security.



Need for low-carbon, reliable and sustainable energy solutions



Nuclear Power as a Key Pillar
for Sustainable Energy Systems

INTEGRATED APPROACH



Life Cycle Assessment (LCA)
Cradle-to-grave evaluation of greenhouse gas emissions (1 kWh basis)



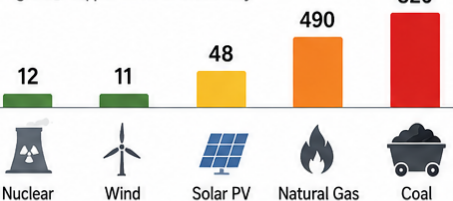
Multi-Criteria Decision Analysis (MCDA)
14 indicators across technical, environmental, economic, resource and strategic dimensions



Robustness & Sensitivity Analysis
Weight-perturbation ($\pm 20\%$)
130 simulations to test ranking stability

LCA HIGHLIGHT: LIFE-CYCLE GHG EMISSIONS

g CO₂-eq per kWh of electricity



Nuclear power has life-cycle emissions comparable to other low-carbon technologies and far lower than fossil fuels.

MCDA RESULT (Equal Weights)

1	 Nuclear	0.746
2	 Wind	0.706
3	 Solar PV	0.643
4	 Natural Gas	0.566
5	 Coal	0.404

Rank Stability



KEY TAKEAWAY



Provides reliable baseload power with high energy density



Low life-cycle emissions, essential for decarbonization



Strengthens energy security and reduces import dependence



Supports socioeconomic development through jobs and technology

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Chief Editor's Message

Editorial

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Decarbonisation & Sustainable Energy Systems for a Healthy India: Nuclear Power, Solar Cells & Hydroelectric Cell!

It is my privilege to write a preface about the very important and special emerging technologies from India in this issue of Current Natural Sciences & Engineering (CNS&E) Journal. Today India's nuclear roadmap aims to expand capacity from 8 GW to 100 GW by 2047, developing nuclear power towards its 2070 net-zero strategy. It also includes indigenous Pressurised Heavy Water Reactors, fast breeder reactors, and thorium-based designs, in parallel with new Small Modular Reactors (SMRs) for industrial decarbonisation. Although Nuclear power is not classified as renewable because it relies on finite uranium resources, it is considered a low-carbon energy source that plays a major role in decarbonisation. It can provide reliable, large-scale electricity with very low lifecycle emissions, though challenges include radioactive waste, accident risks, and high construction costs. Living near nuclear plants is generally safe under normal operations, but accidents or poor waste management can pose risks.

Healthcare is universally recognized as a fundamental right; however, ensuring quality remains indispensable. In this review, the authors highlighted the pressing need to strengthen healthcare standards in India. While numerous government schemes have been introduced to expand access and affordability, medical care delivery must adhere to standardized protocols to ensure reliability, safety, and equity. Within international frameworks, ISO standards provide essential guidance for minimizing risks and enhancing patient outcomes. Recent outbreak of the COVID-19 pandemic has further compelled all of us to recognize the urgency of reinforcing healthcare infrastructure and embedding quality assurance at every level of service delivery. However, addressing these challenges is critical to achieving sustainable, resilient, and patient-centered healthcare for all. Moreover, as the world increasingly turns to India for affordable medical treatment, implementing international standards is vital to sustain trust, ensure patient safety, and position India as a global leader in healthcare excellence.

The rapid expansion of wireless communication systems across microwave and millimetre-wave frequency bands has intensified the demand for compact, multi-band antenna solutions. Modern applications ranging from satellite television broadcasting and radar systems

to 5G millimetre-wave links and advanced sensing platforms require antennas capable of operating simultaneously across the C, Ku, and Ka bands with acceptable return loss, gain, and radiation characteristics within a single compact element. The C band (4–8 GHz) is extensively used for Wi-Fi hotspots, satellite communication uplinks, and weather radar, while the Ku band (12–18 GHz) supports direct broadcast satellite television, VSAT terminals, and airborne radar systems. The Ka band (26–40 GHz) has emerged as a critical frequency resource for 5G millimetre-wave access, high-throughput satellite internet, and advanced imaging radar platforms, making simultaneous multi-band coverage within a single antenna element highly desirable for system integration and cost reduction.

This study presents the design, simulation, and performance analysis of a Coplanar Waveguide (CPW)-fed circular microstrip patch antenna incorporating a strip-line feed mechanism. Fabricated on an FR4 ($\epsilon_r = 4.3$) substrate, it targets four operational frequency bands: 5.5 GHz (C-band, 4.8–6.0 GHz), 16.7 GHz (Ku-band, 15.8–17.5 GHz), 26.3 GHz (Ka-band / 5G mmWave, 25.5–27.5 GHz), and 34.6 GHz (Ka-band, 33.5–36.0 GHz). Two antenna configurations have been investigated. The optimised antenna achieves bandwidths of 1.2 GHz, 1.7 GHz, 2.0 GHz, and 2.5 GHz at the four resonance frequencies, covering applications spanning Wi-Fi, satellite communications, 5G mmWave, and advanced radar systems. Simulated E-plane and H-plane radiation patterns at all four operating frequencies, surface current density distributions, and S-parameter analysis confirm robust multi-band performance within a compact FR4-based physical footprint.

The global demand for a low-cost, 24-hour green energy device to replace solar cells led to the invention of the hydroelectric cell which generates green electricity using water splitting on nanoporous metal oxides, ferrites, and composites. Hydroelectric Cell (HEC), a green energy device, is a revolutionary ground breaking invention validated and recognised globally from India that generates green electricity and hydrogen directly from water at room temperature, without sunlight, acid, alkali, or catalyst, based on water splitting. HEC is an alternative to Solar Cell & Fuel Cell and is the biggest invention of the 21st century in the green & clean energy domain. Moreover, it is a unique path-breaking invention that holds immense potential for achieving net-zero carbon emissions and has been upheld as a potential game-changer in decarbonization to fight global warming & climate change, achieved within seven years of its invention in 2016.

The presented study investigates the Hydroelectric Cell (HEC) performance of pristine and lithium-doped tantalum oxide (Ta_2O_5), which is a 33rd compound used for Hydroelectric Cell device fabrication within nine years of HEC invention. Experimental results demonstrate that doping Ta_2O_5 with lithium significantly enhances current and power output compared to the pristine sample.



Nuclear Energy for Sustainable Power Systems: An Integrated Assessment Using Life Cycle and Multi-Criteria Decision Approaches

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Abstract

The transition toward secure, low-carbon electricity generation requires energy technologies to be evaluated simultaneously in terms of environmental performance, technical reliability, economic viability, resource requirements, and strategic value. Although nuclear power is widely recognized as a low-carbon and high-capacity-factor technology, its overall benefits remain sensitive to fuel-cycle characteristics, system boundaries, economic assumptions, and decision criteria. This study presents a transparent literature-based comparative assessment of nuclear power using an integrated life-cycle assessment (LCA) and multi-criteria decision analysis (MCDA) framework. The environmental assessment was performed on a cradle-to-grave basis using 1 kWh of net electricity as the functional unit, while the MCDA incorporated 14 technical, environmental, economic, resource, and strategic indicators. Min–max normalisation and equal baseline weighting were applied, followed by a $\pm 20\%$ weight-perturbation analysis over 130 simulations to examine ranking robustness. Literature-derived median life-cycle greenhouse-gas emissions were approximately 12 g CO₂-eq/kWh for nuclear, compared with 11, 48, 490 and 820 g CO₂-eq/kWh for wind, solar photovoltaic, natural gas and coal, respectively. The resulting MCDA scores were 0.746 for nuclear, 0.706 for wind, 0.643 for solar PV, 0.566 for natural gas, and 0.404 for coal. Nuclear retained the first position in 93.8% of sensitivity simulations, indicating robust performance within the defined decision space. The findings demonstrate that nuclear power can provide a strong combination of low life-cycle emissions, high energy density and reliable electricity generation, while limitations associated with capital intensity, radioactive-waste management and deployment conditions must remain integral to sustainability assessments.

Keywords: Nuclear Energy; Life Cycle Assessment; Multi-Criteria Decision Analysis; Low-Carbon Energy; Energy Sustainability; Energy Security.

1. Introduction and Literature Survey

Growing global energy demand is occurring alongside the increasing urgency to reduce climate-related impacts [1]. Conventional electricity generation based predominantly on coal, petroleum-derived fuels, and natural gas remains an important source of electricity but is associated with substantial greenhouse-gas emissions, atmospheric pollutants, and ecological impacts [2]. In this context, nuclear power has gained increasing attention as a component of low-carbon energy portfolios because of its ability to provide large-scale electricity with very low direct CO₂ emissions during normal operation [3]. The underlying conversion process is based on controlled nuclear fission, in which the splitting of fissile nuclei releases a large quantity of thermal energy. This heat is subsequently transferred through the reactor heat-transfer system and used to produce steam, which drives a turbine coupled to an electrical generator. The combination of high energy density and sustained power production distinguishes nuclear generation from several variable renewable technologies and makes it relevant to energy systems seeking to reduce carbon intensity while maintaining dependable electricity supply.

The generated heat is transferred to a working fluid, producing steam that drives a turbine-generator system to convert thermal energy into electrical power [4]. Unlike solar photovoltaic and wind technologies, whose electricity production varies with solar irradiance and wind availability, nuclear reactors can operate continuously for extended periods under controlled operating conditions [5]. This high availability and stable power output provide dependable generation for the electricity grid and can support system frequency stability, load balancing, and the integration of variable renewable energy sources [6].

Air pollution used to be very limited in the case of nuclear energy production, i.e. the emission of CO₂, SO_x, NO_x and PM used to be very limited. Thus, it helps in terms of Global Warming and Climate Change control also. [7]. Power generation with the help of uranium as a fuel also helps in huge energy generation within very limited space in comparison to other methods of electrical energy production like coal-based and wind farm-based [8][9]. Nowadays, many latest technologies are available for nuclear reactor construction in stepwise procedures, which are safer, easier and less costly compared to old methods used for the same requirements. (Tiwari R., 2008; L. Rajesh, 2025). Because of this shift, governments now consider atomic energy as an option to balance stable supplies, climate goals, and growth needs at once [12].

Recent research has increasingly examined nuclear power from a multidimensional perspective encompassing environmental impacts, economic performance, technological development, and its position relative to alternative energy technologies [13]. A central challenge in contemporary energy planning is to expand reliable electricity generation while limiting greenhouse-gas emissions and associated environmental degradation [14]. Within this context, nuclear power is distinguished by its comparatively low life-cycle carbon intensity and negligible direct atmospheric emissions during normal reactor operation. It was reported that the operational phase of nuclear generation produces very limited direct greenhouse-gas emissions and conventional air pollutants [15][16], although emissions associated with mining, fuel processing, plant construction, and waste management remain relevant to a complete life-cycle assessment. It was identified that nuclear generation is an important complement to variable renewable technologies [17], particularly where

continuous electricity supply is required. Similarly, the expansion of nuclear generation is associated with potential reductions in environmental pressure through displacement of higher-emission electricity sources [18] [19]. An additional advantage is the comparatively high operational availability of nuclear reactors, which allows electricity production to remain largely independent of short-term meteorological variations [20]. The high energy density of nuclear fuel further permits substantial electricity production from relatively small quantities of fuel and land compared with many energy-generation pathways [21], which further highlights the relevance of nuclear generation for maintaining energy-supply security [22], particularly in developing energy systems where electricity demand and infrastructure requirements are increasing. Recent studies have consequently shifted attention toward integrated nuclear–renewable configurations rather than treating the technologies as mutually exclusive options. It was demonstrated that coordinated operation of nuclear and renewable generation can improve grid reliability while potentially reducing overall system costs [23], whereas favourable characteristics of nuclear generation were reported when evaluated alongside solar and wind alternatives [24]. The relevance of nuclear power in long-term energy-system planning is aimed at limiting emissions while maintaining dependable electricity availability [25]. From an economic perspective, it was indicated that the long operating lifetimes and high utilisation rates of nuclear facilities can improve their long-term economic performance [26][27], although substantial initial capital requirements remain an important constraint. The potential for combined heat and power applications provides an additional pathway for improving energy utilisation; it was reported that efficiencies exceeding 80% for

suitable cogeneration configurations, demonstrating the possibility of simultaneously supplying electricity and useful thermal energy [28].

The contribution of nuclear power to deep decarbonization has also received considerable attention because of its potential to provide low-carbon electricity while supporting energy-intensive applications. Applications were identified extending beyond conventional electricity generation, including low-carbon hydrogen production and energy supply for industrial sectors that are difficult to decarbonise [29][30]. Technological development is further broadening the potential deployment envelope through advanced reactor concepts, including Generation IV systems and small modular reactors (SMRs), which incorporate enhanced safety characteristics, modular construction approaches, and greater flexibility for integration with evolving energy systems through comparative evaluation of alternative electricity-generation pathways [31][32][33]. It was demonstrated that nuclear technology can perform favourably when environmental, economic, and social dimensions are considered simultaneously. It was additionally reported that complex nonlinear relationships between nuclear-energy utilisation and ecological indicators, suggesting that the environmental consequences of nuclear deployment cannot be adequately represented by a single parameter or short-term observation [34]. Collectively, the literature indicates that nuclear power can contribute substantially to reliable low-carbon electricity supply and long-term energy-system resilience; however, its broader deployment remains conditioned by several unresolved considerations, including severe-accident risk, radioactive-waste management, large upfront investment requirements, project-

delivery challenges, and public acceptance. These factors highlight the need for a systematic assessment that considers environmental, technical, economic, and strategic dimensions concurrently rather than evaluating nuclear power solely based on operational emissions or electricity-generation capacity [35].

The present study does not seek to introduce a new reactor technology or a site-specific process model. Its contribution lies in integrating published life-cycle evidence with a transparent multi-criteria screening framework and explicit sensitivity analysis [36]. This structure enables technical, environmental, economic and strategic attributes of nuclear power to be examined within a common decision framework while identifying the dependence of the resulting ranking on indicator selection and weighting assumptions [37].

2. Methodology

The generated methodological framework, as mentioned in Figure 1, summarises the systematic procedure adopted to evaluate the benefits and broader role of nuclear energy through an integrated literature-based approach. The process begins with structured identification of relevant studies from major scientific databases, followed by screening and selection to retain literature directly related to nuclear power, life-cycle

performance, multi-criteria assessment, and low-carbon energy systems. Information concerning assessment methods, performance indicators, reported findings, and study conclusions is subsequently extracted using a standardised framework to improve consistency during comparative evaluation. The selected evidence is then examined through life-cycle assessment (LCA) to characterise environmental performance across the relevant energy chain and through multi-criteria decision analysis (MCDA) to incorporate technical, environmental, economic, resource, and strategic considerations within a common decision framework. Equal weighting is used for the baseline MCDA assessment, while sensitivity analysis examines the influence of changes in criterion importance on the resulting technology rankings [38], [39]. A quality-control stage is incorporated to check source reliability, consistency of extracted information, and methodological robustness before synthesis of the findings. The final analytical stage integrates the evidence to establish comparative trends among nuclear and alternative electricity-generation technologies and to identify their implications for reliable, low-carbon energy planning. This structured sequence provides a transparent basis for interpreting the diverse evidence reported in the literature while reducing dependence on a single performance indicator or isolated technological characteristic [40], [41].

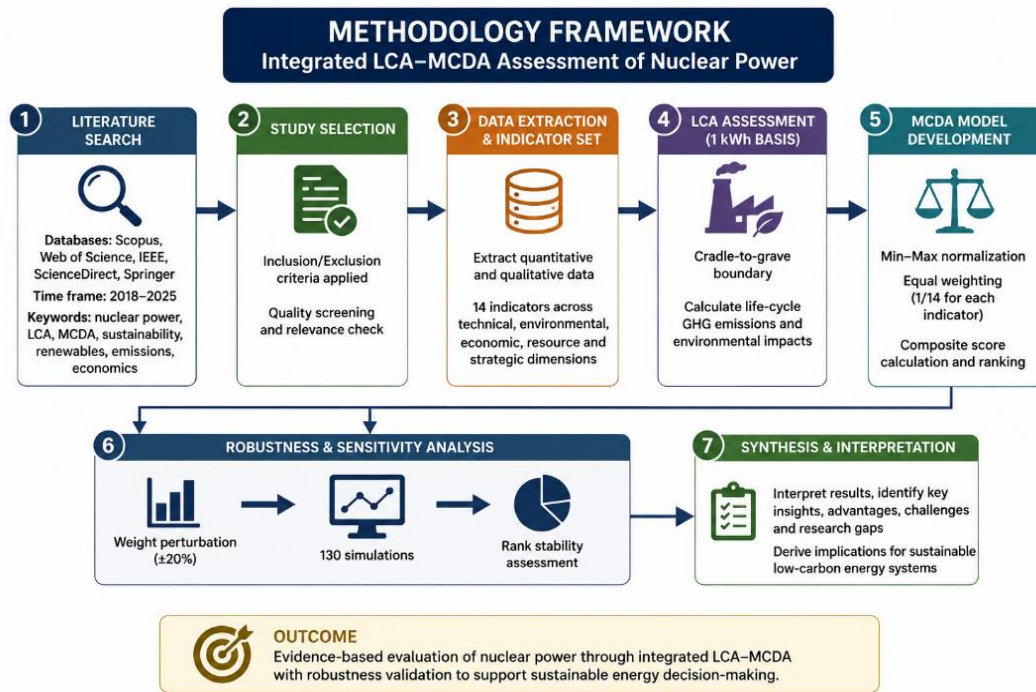


Figure 1. Methodological Framework for the Integrated Review and Assessment of Nuclear Energy Benefits

2.1 Research Framework and Approach

This research takes a close look at nuclear power using clear comparisons and structured analysis, especially how it fits into long-term sustainability, stable energy supply, and its effect on nature. Instead of gathering new numbers, it builds understanding by reviewing existing information, weighing different outcomes, and applying balanced scoring methods across several factors [42]. Information pulled from worldwide sources - such as figures tracked by the International Energy Agency (IEA) - helps measure just how much nuclear contributes to overall energy use and electric output around the globe. Its way of working follows paths laid out in current academic work that explores shifting toward cleaner grids and lower-emissions setups [43].

This work is a literature-based comparative assessment of nuclear power against selected electricity-generation technologies. The analysis integrates three complementary components: (i) a cradle-to-grave synthesis of published life-cycle greenhouse-gas (GHG) results, (ii) a transparent multi-criteria decision analysis (MCDA) based on published performance indicators, and (iii) sensitivity testing of the decision weights. The study therefore does not claim to constitute a site-specific process LCA, an expert-elicited preference model, or a reactor-level techno-economic design. Its purpose is to identify the conditions under which the commonly reported technical, environmental and strategic advantages of nuclear power remain evident when multiple indicators are considered simultaneously [44].

2.2 Data Collection and Source Integration

Most of the study relies on existing information like worldwide energy summaries, academic papers that have been checked by experts, and detailed technical numbers. From broad statistical visuals (Figure 2(a) and 2(b)), patterns in how power sources are shared and where electricity comes from were drawn out. Instead of relying only on one kind of source, newer studies about how well nuclear energy works, its effect on nature, along with cost aspects, found their way into the review, helping keep things accurate and up to date [45][46]. When different kinds of data come together, the overall picture becomes stronger and more trustworthy.

The functional unit for the comparative environmental assessment is 1 kWh of net electricity delivered by the generation technology. A cradle-to-grave perspective is adopted. For nuclear power, the boundary includes uranium mining and milling, conversion and enrichment, fuel fabrication, reactor construction, electricity generation,

spent-fuel and radioactive-waste management, and decommissioning [47]. For the comparator technologies, the corresponding fuel supply, plant construction, operation, decommissioning and waste-related stages are included where reported by the source study. The principal impact indicator is life-cycle GHG emissions, expressed as g CO₂-eq/kWh. Recent literature shows that reported nuclear values vary with uranium ore grade, enrichment route, electricity mix, reactor technology and system boundary; consequently, a single value is not treated as universal. A 2024 critical review reported a nuclear lifecycle range of 3.7–110 g CO₂-eq/kWh with a median of 12 g CO₂-eq/kWh, while a 2023 parametric LCA reported a global 2020 average of 6.1 g CO₂-eq/kWh and a broad scenario range [40]. These differences demonstrate why the present study reports literature-derived values together with their methodological context rather than presenting a single deterministic emission factor.

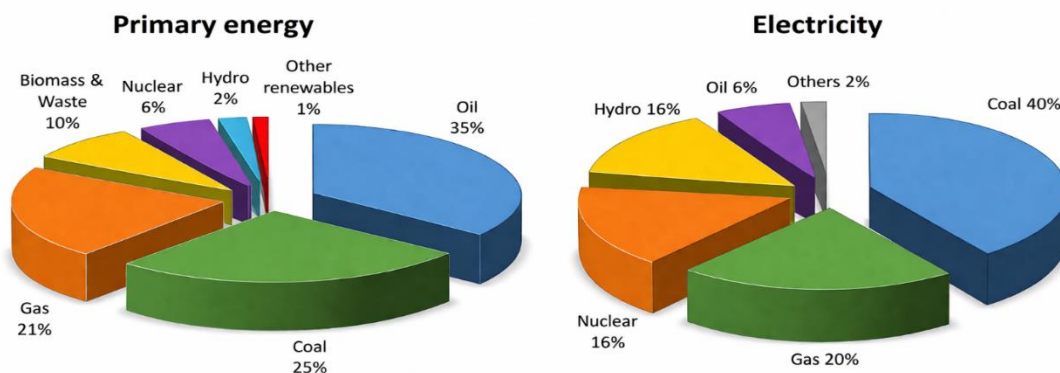


Figure 2(a) Primary energy and 2(b) Electricity supply [48]

2.3 Evaluation of Nuclear Energy Principles

The fundamental principles governing nuclear energy systems, such as safety, environmental protection, resource efficiency, transparency, and non-proliferation, were systematically analysed

as qualitative indicators. These principles form the basis for evaluating nuclear energy within a sustainability framework. The study applies a qualitative scoring approach to assess how effectively nuclear energy aligns with global sustainability goals, consistent

with methodologies adopted in recent nuclear policy and sustainability research.

2.4 Multidisciplinary Assessment Framework

Nuclear energy systems involve a wide range of scientific and engineering disciplines categorised into health, energy, and environmental domains (Figure 3). This study adopts a multidisciplinary evaluation

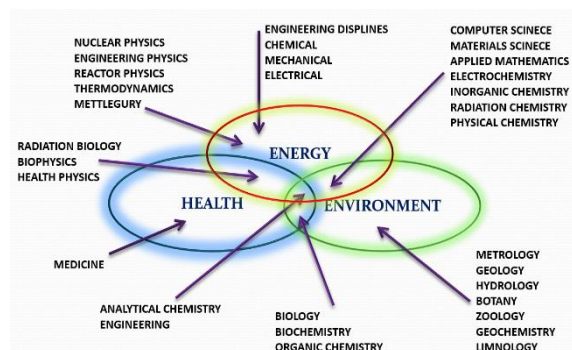


Figure 3. Division of scientific engineering disciplines and major categories

Multi-criteria decision analysis (MCDA) requires the performance values of different technologies to be transformed to a common dimensionless scale before the criteria can be aggregated. In the present literature-based assessment, min-max normalisation is used because the criteria are expressed in different units and have different directions of preference. The normalised value x'_{ij} ranges from 0 to 1, where a higher value represents a more favourable performance.

2.4.1 Normalisation of beneficial criteria

For a beneficial criterion, a higher raw value represents better performance. Examples include capacity factor, conversion efficiency, energy return on energy invested (EROI), and employment generation. The normalised score is calculated as:

$$x'_{ij} = (x_{ij} - x_{\min,j}) / (x_{\max,j} - x_{\min,j})$$

where x_{ij} is the reported value of technology i for criterion j ; $x_{\min,j}$ is the minimum value

approach, considering radiological safety, thermal efficiency, environmental impact, and socio-economic implications. Such an integrated framework is essential for capturing the holistic benefits of nuclear energy and is supported by recent interdisciplinary studies in nuclear engineering and energy systems analysis [49].

among the technologies being compared for criterion j ; $x_{\max,j}$ is the corresponding maximum value; and x'_{ij} is the resulting dimensionless normalised score. A technology with the maximum value receives a score of 1, whereas the technology with the minimum value receives a score of 0.

2.4.2 Normalisation of cost-type criteria

For a cost-type criterion, a lower raw value represents better performance. Examples include life-cycle greenhouse-gas emissions, water consumption, land requirement, capital cost, levelized cost of electricity (LCOE), external cost, SO_x, NO_x and PM_{2.5} emissions. The direction of preference is therefore reversed using:

$$x'_{ij} = (x_{\max,j} - x_{ij}) / (x_{\max,j} - x_{\min,j})$$

Under this formulation, the lowest-cost or lowest-impact technology receives a normalised score of 1 and the highest-cost or highest-impact technology receives a score of 0. The same transformation is applied independently to each criterion so that environmental, technical, economic and strategic indicators can be compared on a common scale.

2.4.3 Equal-weighting approach

The baseline MCDA assigns equal importance to all n criteria because the present study does not contain a defensible stakeholder survey, expert-elicitation

dataset, or nationally agreed policy preference structure from which unequal weights could be derived. Equal weighting avoids introducing subjective preferences that cannot be independently verified. The weight assigned to each criterion is therefore:

$$w_j = 1 / n$$

$$\sum_{j=1}^n w_j = 1$$

For the 14-criterion screening framework used in this study, $n = 14$ and therefore each criterion receives a baseline weight of $1/14 = 0.07143$. The weights are dimensionless and represent the relative contribution of each criterion to the aggregate screening score.

2.4.4 Overall MCDA score

After normalisation, the performance of each technology is aggregated using a weighted linear combination. The overall score for technology i is calculated as:

$$S_i = \sum_{j=1}^n w_j x'_{ij}$$

where S_i is the overall MCDA score of technology i , w_j is the normalised weight of criterion j , and x'_{ij} is the normalised performance of technology i under criterion j . Because the weights sum to unity and the normalised scores lie between 0 and 1, S_i also lies between 0 and 1. A larger S_i indicates a more favourable overall performance within the selected criteria and assumptions; it does not represent an absolute measure of sustainability.

2.4.5 Illustrative calculation

For illustration, consider a beneficial criterion for which the minimum and maximum reported values are 20 and 80 units, respectively. If technology i has a value of 50 units, its normalised score is:

$$x'_{ij} = (50 - 20) / (80 - 20) = 0.50$$

For a cost-type criterion with the same minimum and maximum values, a technology value of 50 units gives:

$$x'_{ij} = (80 - 50) / (80 - 20) = 0.50$$

These examples demonstrate that the normalisation procedure changes only the direction and scale of the original criterion; it does not change the relative ordering of the technologies within that criterion.

2.4.6 Interpretation and reproducibility

The normalisation and weighting procedure is intentionally simple and transparent. It permits the MCDA result to be reproduced from the reported performance matrix without requiring proprietary software or undocumented expert judgements [50]. Because the outcome depends on the selected criteria, source data, system boundaries and weighting assumptions, the resulting score is interpreted as a comparative screening indicator rather than as a universal sustainability index. Sensitivity analysis is subsequently used to examine whether reasonable changes in criterion weights alter the technology ranking. Summary of the MCDA normalisation and aggregation procedure is as defined in Table 1.

Table 1. Summary of the MCDA normalisation and aggregation procedure*

Step	Purpose	Expression	Interpretation
1	Beneficial criterion	$x'_{ij} = (x_{ij} - x_{\min,j}) / (x_{\max,j} - x_{\min,j})$	Higher raw value is preferred
2	Cost-type criterion	$x'_{ij} = (x_{\max,j} - x_{ij}) / (x_{\max,j} - x_{\min,j})$	Lower raw value is preferred
3	Equal weighting	$w_j = 1/n; \sum w_j = 1$	All criteria receive equal baseline importance
4	Aggregation	$S_i = \sum w_j x'_{ij}$	Higher S_i indicates better screening performance

***Methodological note:** The equations above define the calculation procedure used in the revised literature-based MCDA framework. The baseline equal-weighting assumption is adopted because no stakeholder or expert preference dataset was available for this study.

2.5 Sustainability Indicator-Based Comparative Analysis

Depending on the specific evidence being discussed regarding nuclear energy against other energy sources (coal, gas, hydro, wind, and solar PV) was conducted using

sustainability indicators categorised into economic, environmental, and social dimensions (Figure 4). Key indicators include lifecycle greenhouse gas emissions, land use, cost of electricity, reliability, and social acceptance.

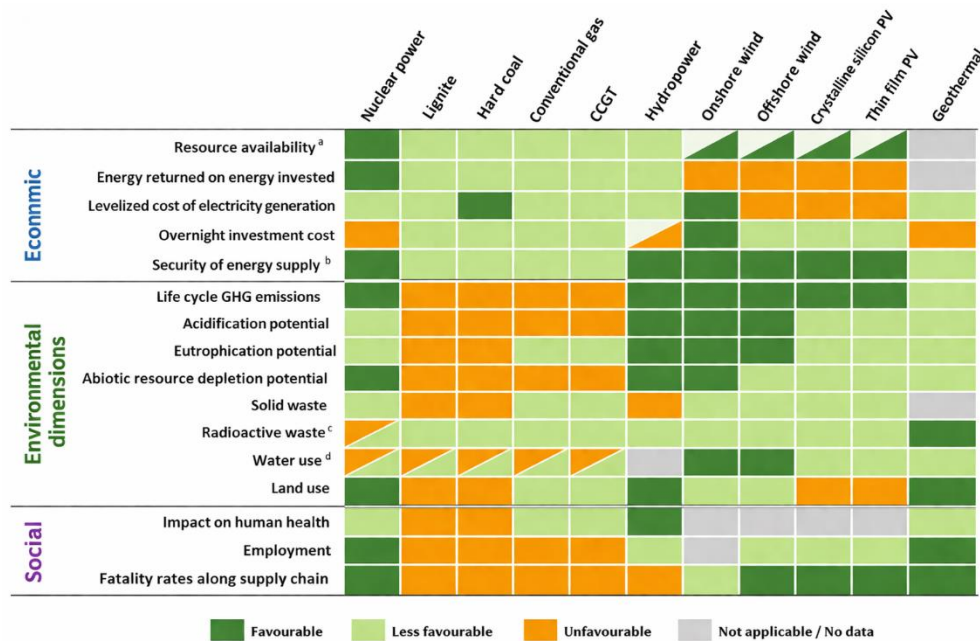


Figure 4. Selection of sustainability indicators for sources of power

2.6 Process-Based Analysis of Nuclear Fuel Cycle

The methodology includes a process flow analysis of nuclear fuel production

and the nuclear fuel cycle, based on the flowsheet of nuclear ore processing (Figure 5). Each stage—mining, milling, conversion, enrichment, fuel fabrication,

2.8 Analysis of Public Acceptance Factors

Public perception and acceptance of nuclear energy were analysed using a socio-technical evaluation framework, considering factors such as safety concerns, environmental awareness, regulatory trust, and policy support (Figure 7).

A qualitative assessment method was

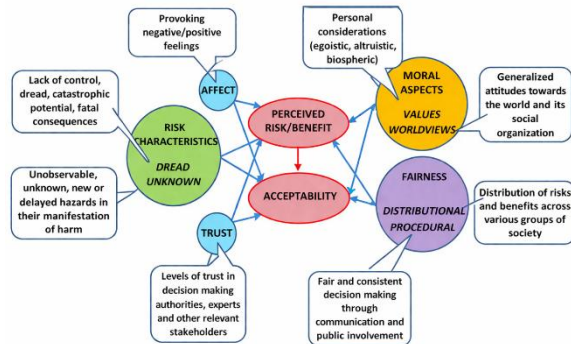


Figure 7. Factors influencing public acceptance of nuclear energy

applied to evaluate the influence of these factors on nuclear energy deployment. This approach is supported by recent research emphasising the role of societal acceptance in energy transition pathways. Uncertainty in the MCDA is examined through a weight-perturbation analysis. Each baseline criterion weight is independently perturbed within $\pm 20\%$, and the resulting weights are renormalised so that their sum remains unity. Several random weight sets are evaluated using a fixed random seed to ensure reproducibility. The stability of the technology ranking is expressed as the proportion of simulations in which each technology occupies each rank. This procedure does not represent a probabilistic forecast of future energy systems; rather, it tests whether the baseline ranking is highly dependent on small changes in decision priorities.

2.9 Benefit Identification and Categorisation The benefits of nuclear energy were systematically categorised into

technical, environmental, economic, and socio-political dimensions, based on the compiled dataset [17]. Parameters such as high energy density, low emissions, reliability, economic competitiveness, and energy security were analysed. A descriptive-analytical method was used to synthesise these benefits and correlate them with global energy transition goals. Similar categorisation approaches have been adopted in recent review studies.

2.10 Validation through Literature Correlation

The findings of this study were validated through cross-referencing with recent peer-reviewed literature (2020–2025). Comparative insights were drawn to ensure consistency with global research trends in nuclear energy systems, sustainability, and decarbonization. This step enhances the scientific credibility and generalizability of the results. The results are interpreted as comparative evidence rather than as an absolute hierarchy of energy technologies. Nuclear power is considered advantageous where high availability, low lifecycle GHG emissions and compact energy infrastructure are important. Conversely, capital intensity, construction duration, radioactive-waste management and public acceptance remain material constraints. The interpretation therefore distinguishes technology-level characteristics from context-dependent deployment outcomes [29].

3. Results and Discussion

3.1 Global Energy Mix and Role of Nuclear Energy

The analysis of global energy statistics (Figure 2(a) and 2(b)) indicates that fossil fuels still dominate primary energy consumption, whereas nuclear energy contributes a smaller but significant share of low-carbon electricity generation. Despite its lower percentage in primary energy, nuclear power plays a

disproportionate role in clean electricity supply due to its high capacity factor.

3.2 Sustainability-Based Comparative Assessment The literature-based life-cycle comparison indicates that nuclear power belongs to the low-carbon group of electricity-generation technologies, although its life-cycle emissions are not zero. Recent reviews report substantial variation in nuclear values because uranium ore grade, enrichment technology, electricity supply used in the fuel cycle, reactor configuration and system boundaries differ among studies. A 2024 synthesis reported median lifecycle emissions of approximately 12 g CO₂-

eq/kWh for nuclear power, compared with 820 g CO₂-eq/kWh for pulverised coal, 490 g CO₂-eq/kWh for combined-cycle gas, 48 g CO₂-eq/kWh for utility-scale photovoltaic generation and 11 g CO₂-eq/kWh for onshore wind. These values indicate a large lifecycle emissions advantage for nuclear power relative to fossil generation, while also showing that nuclear and renewable technologies occupy overlapping low-carbon ranges. A comparative evaluation was performed using sustainability indicators. The numerical dataset in Table 2 is taken from a published comparative Indian power-generation sustainability assessment.

Table 2. Comparative Performance of Energy Sources

Criterion	Coal	Gas	Nuclear	Solar PV	Wind
Land use (acre/MW)	0.91	0.75	0.24	5.0	27.5
Water use (m ³ /MWh)	2.44	0.75	5.7	0.95	0.03
Efficiency (%)	37.5	58.6	35.0	13.9	35.0
Capacity factor (%)	80.0	50.0	80.0	16.1	25.0
EROI	32	28	75	4	16
CO ₂ (g/kWh)	918	351	9.21	52.9	9.84
SO _x (g/kWh)	1.88	0.46	0.03	0.13	0.002
NO _x (g/kWh)	0.42	1.76	0.02	0.1	0.002
PM _{2.5} (g/kWh)	0.12	0.1	0.004	0.02	0.006
Capital cost (crore INR/MW)	6.0	4.3	10.0	5.3	4.5
LCOE (INR/kWh)	2.95	2.62	2.44	2.44	2.43
External cost (INR/kWh)	1.47	1.0	0.21	0.32	0.1
Energy insecurity	0.5	0.5	0.4	0.7	0.5
Job generation (jobs/MW)	1.35	0.94	1.6	8.2	4.5

Note: The matrix is a screening dataset rather than a current plant-specific database. Beneficial criteria are efficiency, capacity factor, EROI and

- Nuclear power shows a strong overall sustainability profile within the present screening framework; however, the relative ranking depends on the selected indicators, weighting assumptions, technology configuration and deployment context.
- Renewable sources exhibit low emissions but suffer from variability and storage dependency.
- Fossil fuels remain dominant but are environmentally unsustainable

3.3 Life Cycle Assessment (LCA) of Nuclear Energy

A literature-based comparative Life Cycle Assessment (LCA) approach was used to evaluate environmental impacts across the nuclear fuel cycle (Figure 5). LCA Equation can be defined as:

The total life-cycle emissions are expressed as:

$$E_{total} = E_{mining} + E_{processing} + E_{construction} + E_{operation} + E_{decommissioning}$$

- Operational emissions are negligible, with most emissions arising from construction and fuel processing.
- Total life-cycle emissions are significantly lower than those of fossil fuels.

Under the equal-weight baseline, nuclear power obtains a screening score of 0.746 and ranks first, followed by wind (0.706), solar PV (0.643), natural gas (0.566), and coal (0.404). In 130 $\pm 20\%$ weight-perturbation simulations, nuclear retained the first position in 93.8% of trials and moved to second place in the remaining trials. This result supports the robustness of the baseline screening result, but it does not imply that nuclear power is universally the preferred technology because the ranking remains conditional on the selected indicators and data source.

3.4 Multi-Criteria Decision Analysis (MCDA)

The screening MCDA considers 14 indicators grouped into technical, environmental, economic and strategic dimensions: land use, water use, conversion efficiency, capacity factor, energy return on energy invested (EROI), life-cycle CO₂ emissions, SO_x emissions, NO_x emissions, PM_{2.5} emissions, capital cost, levelized cost of electricity (LCOE), external cost, energy insecurity and employment generation. The comparative matrix is based on published energy-system data and is used only for

screening because values can vary by site, year, technology configuration and accounting boundary. A Multi-Criteria Decision Analysis (MCDA) model was applied using weighted sustainability indicators, and the ranking of energy sources is as mentioned in Table 3.

Table 3. MCDA Ranking of Energy Sources

Technology	Baseline score	Rank	Interpretation
Nuclear	0.746	1	Highest baseline screening score
Wind	0.706	2	Strong environmental performance
Solar PV	0.643	3	Strong environmental performance but lower availability
Natural gas	0.566	4	Intermediate overall profile
Coal	0.404	5	High environmental burden

3.5 Nuclear Fuel Cycle and Process Efficiency:

A looped system moves nuclear material through each step, recycling what it can. This setup keeps waste low while getting the most out of raw inputs. Results show that reprocessing cuts down unused potential. Efficiency climbs when spent fuel gets repurposed instead of discarded. The path shown in Figure 5 wraps back on itself, feeding outputs into new cycles. Resource recovery becomes steady, not one-time. Each stage connects, so nothing runs off track. A tiny bit of fuel creates lots of power. What matters is how much you get out versus what goes in. Efficiency shows up clearly when space or weight limits exist. A small amount of nuclear fuel creates a big impact on society in terms of energy production. Waste generation through nuclear energy generation is also much less in comparison to other energy production

methods [56]. Advanced reprocessing sustainability.

3.6 Analysis of India's Nuclear Energy Program A look at the three-part nuclear plan (Figure 6) shows how thorium might be 3. Thorium-based Reactors. Energy security is strengthened by maximizing the utilisation of domestically available resources while reducing dependence on external energy supplies. Such an approach supports a progressive transition toward a stable, resource-efficient, and environmentally sustainable energy system.

3.7 Public Views and Social Tech Influences

Factors influencing public acceptance (Figure 7) include:

- Safety perception
- Environmental awareness
- Policy transparency

Even with new technology, people slowly analyse the importance of nuclear energy and adopt it in future.

3.8 Technical, strategic and environmental interpretation

The principal technical advantage identified in the comparative assessment is high availability. Nuclear generation typically operates at high capacity factors, allowing substantial annual electricity production from a relatively compact generating site. Environmental performance is characterized by low lifecycle GHG emissions and very low routine atmospheric emissions during electricity generation. Strategically, nuclear power can diversify electricity supply and reduce exposure to fossil-fuel price and import risks. These advantages must be evaluated alongside high upfront capital requirements, long project development periods, spent-fuel management, decommissioning obligations, and the need

used over time. Each phase builds on what came before it, moving step by step toward that goal.

1. PHWR (Uranium-based)

2. Fast Breeder Reactors

for sustained regulatory and public confidence, as mentioned in Table 4.

Table 4. Categorisation of Nuclear Energy Benefits

Category	Key Benefits
Technical	High energy density, reliability
Environmental	Low emissions, no air pollutants
Economic	Stable costs, job creation
Strategic	Energy security, reduced imports

The high energy density of nuclear fuel enables substantial electricity generation from comparatively small fuel inventories, while reactor systems can sustain power production over extended operating periods. During normal operation, nuclear generation produces negligible direct carbon emissions, providing a marked advantage over coal- and oil-fired power plants. Although nuclear projects require substantial initial capital investment, their long operating lifetimes and high-capacity factors can support relatively predictable long-term electricity generation costs. In addition, nuclear facilities require highly trained personnel for reactor operation, maintenance, safety management, and specialized engineering activities, thereby creating skilled employment opportunities throughout the plant life cycle [30]. The principal technical advantage identified in the comparative assessment is its high availability and ability to provide continuous electricity generation. Nuclear power exhibits substantially lower life-cycle GHG emissions than coal- and natural-gas-based electricity generation in the literature dataset considered in this study [57]. It lines up close to wind and solar

when it comes to emissions. A steady player in cutting carbon emissions. This represents its importance in terms of low-carbon and

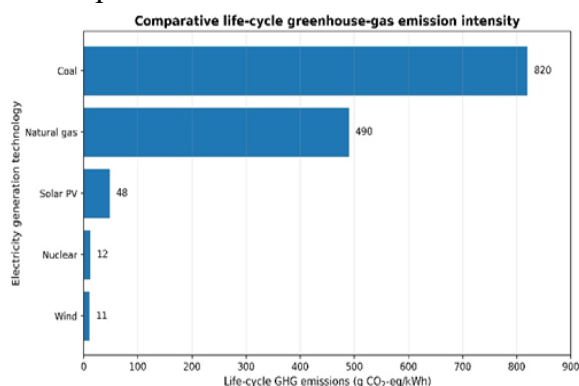


Figure 8. Comparative median life-cycle greenhouse-gas emission intensity of selected electricity-generation technologies.

sustainable energy options in future energy systems. Figure 8 therefore presents these literature-derived median values.

4. Conclusions: This study provides a transparent literature-based assessment of the principal benefits and limitations of nuclear power within a multi-dimensional sustainability framework. The revised analysis distinguishes clearly between published life-cycle evidence and the authors' comparative screening calculations. The literature indicates that nuclear power has a low life-cycle greenhouse-gas intensity relative to coal and natural gas, while its environmental performance is broadly within the low-carbon range occupied by wind and solar technologies. The MCDA screening, based on explicitly reported criteria, min-max normalisation, and equal baseline weights, produced scores of 0.746 for nuclear, 0.706 for wind, 0.643 for solar PV, 0.566 for natural gas and 0.404 for coal. A $\pm 20\%$ weight-perturbation analysis retained nuclear in first position in 93.8% of 130 simulations, indicating that the baseline result is reasonably robust within the tested decision space. The findings should not, however, be interpreted as evidence that

nuclear power is universally superior to all other energy technologies. Its overall performance depends on reactor design, fuel-cycle characteristics, uranium resource quality, financing conditions, construction performance, waste-management strategy and national electricity-system requirements. Nuclear power is therefore most appropriately considered as one component of a diversified low-carbon portfolio, particularly where firm electricity supply and system reliability are important. Future research should replace literature-derived screening data with harmonised country-specific inventories, probabilistic LCA, life-cycle costing and stakeholder-informed MCDA. Such work would provide a stronger basis for comparing nuclear power with renewable generation, storage and other low-carbon technologies under defined national transition scenarios. The graphical abstract in Figure 9 provides a concise visual synthesis of the study framework used to examine the role of nuclear power within a low-carbon and secure electricity system. The assessment begins with the growing requirement for dependable electricity generation capable of simultaneously addressing environmental constraints, energy security, and increasing demand, followed by an integrated evaluation in which nuclear power is compared with wind, solar photovoltaic, natural gas, and coal. The figure additionally presents a $\pm 20\%$ criterion-weight perturbation exercise comprising 130 sensitivity cases and indicates that nuclear power retains the first position in 122 cases, corresponding to a reported ranking stability of 93.8%. This sensitivity component is important because it demonstrates that the comparative outcome is not evaluated solely from a single fixed weighting configuration, although the reported stability remains

Integrated LCA–MCDA Assessment of Nuclear Power for a Sustainable Low-Carbon Energy Future

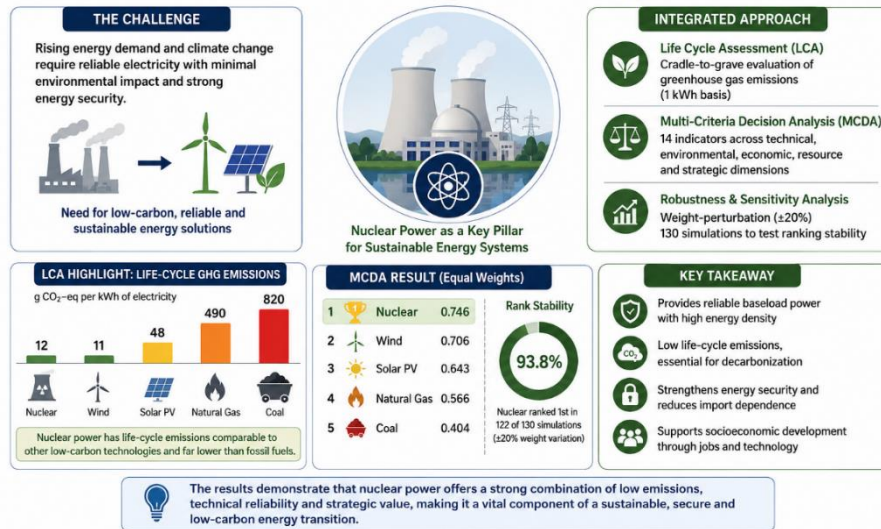


Figure 9. Integrated LCA–MCDA Assessment of Nuclear Power for a Sustainable Low-Carbon Energy Future

conditional on the selected criteria, input data, normalisation method, and weighting range. The final section of the graphical abstract emphasises the principal implications of the assessment: nuclear generation combines high energy density and dependable electricity supply with comparatively low life-cycle carbon emissions, while also contributing to energy-security objectives and reducing reliance on imported fuels. Its potential socioeconomic contribution through skilled employment and technological development further strengthens its strategic relevance. At the same time, the graphical representation is intended to position nuclear power as a component of a diversified energy portfolio rather than as an exclusive substitute for renewable generation. Overall, the figure summarises the study's central finding that nuclear power can provide a technically dependable and environmentally favourable option for supporting long-term electricity decarbonization when its benefits are evaluated across multiple dimensions rather than through emissions performance alone.

4.1 Key Findings:

The present assessment indicates that nuclear power can make a substantial contribution to reliable electricity generation while maintaining a comparatively low environmental burden. The integrated evaluation shows that its combination of sustained generation capability and low life-cycle emissions provides advantages over fossil-fuel-based electricity pathways, particularly in the context of long-term decarbonization. At the same time, nuclear generation can complement variable renewable sources such as solar and wind by providing a more consistent electricity supply when renewable output fluctuates. The findings therefore support nuclear power as an important component of a diversified energy portfolio, particularly where reliability, environmental performance, and long-term energy security are considered together. Nevertheless, its broader deployment must be assessed alongside capital requirements, radioactive-waste management, safety considerations, and site-specific conditions. Overall, the study identifies nuclear energy as a technically viable low-carbon generation pathway with potential to contribute

meaningfully to future energy-system resilience and emissions reduction.

4.2 Scientific Contributions:

- Established a multi-dimensional evaluation framework integrating literature-based LCA and MCDA.
- Demonstrated nuclear energy's superior sustainability performance.
- Provided process-level insights into fuel cycle efficiency and resource utilisation.

4.3 Practical Implications:

- Nuclear energy can play a central role in achieving net-zero emissions.
- It provides stable baseload power, essential for renewable integration.
- National programs (e.g., India's three-stage strategy) offer scalable models for long-term energy planning [58].

4.4 Limitations and Future Scope:

High capital costs and waste management require further innovation. Future work should focus on: Advanced reactors (SMRs, Gen-IV) Hybrid nuclear-renewable systems AI-based optimisation of nuclear operations. Nuclear energy, when combined with robust safety frameworks and technological advancements, represents a cornerstone of sustainable and secure energy systems for the future.

Abbreviations

AI	Artificial Intelligence
CO	Carbon Monoxide
FBR	Fast Breeder Reactor
Gen-IV	Generation-IV
GHG	Greenhouse Gas
IEA	International Energy Agency
LCA	Life Cycle Assessment
MCDA	Multi-Criteria Decision Analysis
MT	Metric Ton
MWh	Megawatt-hours
NOx	Nitrogen Oxides

PHWR	Pressurised Heavy Water Reactor
PV	Photo Voltaic
SMR	Small Modular Reactors
SOx	Sulfur Oxides

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Competing Interests

No, I declare that the authors have no competing interests or other interests that might be perceived to influence the results and/or discussion reported in this paper.

Ethical Approval

Not Applicable

Consent to Participate

Informed consent was obtained from all individual participants included in the study.

Consent to Publish

Consent for publication was obtained from all individuals for this technical paper.

Data Availability Statement

The data used to support the findings of this study are included in the article.

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Importance of Quality Implementation in Healthcare in India

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Abstract

Healthcare is universally recognized as a fundamental right; however, the assurance of quality remains indispensable. This review highlights the pressing need to strengthen healthcare standards in India. While numerous government schemes have been introduced to expand access and affordability, the delivery of medical care must adhere to standardized protocols to ensure reliability, safety, and equity. International frameworks, such as ISO standards, provide essential guidance for minimizing risks and enhancing patient outcomes. The COVID-19 pandemic has further underscored the urgency of reinforcing healthcare infrastructure and embedding quality assurance at every level of service delivery. Addressing these challenges is critical to achieving sustainable, resilient, and patient-centered healthcare for all. Moreover, as the world increasingly turns to India for affordable medical treatment, the implementation of international standards becomes vital to sustain trust, ensure patient safety, and position India as a global leader in healthcare excellence. Addressing these challenges is critical to achieving sustainable, resilient, and patient-centered healthcare for all.

Keywords: Healthcare, Quality system, ISO, ABHA, Ayushman Bharat

1. Introduction

The Covid-19 pandemic has created an unprecedented scenario which acted as an eyeopener towards the status of the healthcare system in the country. The lack of beds, intensive care units and oxygen cylinders all point towards a collapsed and failed healthcare system [1,2]. Healthcare system refers to a group of individuals, organizations and institutions that are involved in fulfilling the requirements of the community and providing resources to cater to the health needs of masses [3].

Healthcare in India is a very big domain which comprises of both the public and private healthcare sectors in rural as well as urban areas. There exists a huge gap in the quality of healthcare in these domains, in terms of infrastructure, the available facilities (medicines, instruments, trained staff) and the access of people to these facilities. The healthcare facilities are divided into the primary, secondary and tertiary level facilities [4].

In India, the responsibility and accountability in healthcare is shared by the central and state governments. The central government make policy, provides resources and technical assistance to the states. The Union Ministry of Health & Family Welfare (MoHFW) takes care of the implementation of various programs at the national level [5].

2. Understanding Quality in Healthcare

Quality is a term used to describe the inherent characteristics of any object, product or service, which makes it fit for its intended use. According to WHO, the Sustainable Development Goals (SDGs) point towards a global health coverage with access to quality healthcare services including essential medicines and vaccines at an affordable rate for all. It includes the quality of care in hospitals, public health

centres, emergency services etc. “Quality in Healthcare” is a multifaceted issue. The meaning of QUALITY in healthcare can be different for researchers, healthcare workers, doctors, patients and public. For example, for patients a good healthcare facility would be the one where they are listened to and treated politely, while for a doctor availability of specified drugs and working condition of the medical equipment is a matter of quality in healthcare [6].

To ensure quality in healthcare services, MoHFW launched the National Quality Assurance Standards (NQAS) in 2013. These standards are accredited by the International Society for Quality in Healthcare (ISQua) and are in line with the WHO global benchmarks. The aim of NQAS is to improve the quality of healthcare to make it more efficient and user friendly. According to a report by MoHFW, about 1600 public health facilities received National Quality Certification and 154 health facilities were NQAS certified till November 2020 [7].

3. Different Policies for Healthcare in India

• National Health Policy

The first National Health policy was initiated in 1983, followed by that in 2002 and the current National Health policy came into effect in 2017. The aim of the National Health Policy is to ensure that all people have access to the available healthcare facilities. This has to be done by improving the quality and minimizing the cost of the healthcare services. The gap between the public and private healthcare systems needs to be bridged by making the health-related services in private sector more affordable, efficient and aligned with the public demands. In India, the healthcare amounts to 1.8% of the GDP currently [8]. The National Health policy envisages to

increase the healthcare contribution to GDP to 2.5% by 2025 [9].

The major areas covered under the National health policy are:

- Swachh Bharat Mission, which focusses on cleanliness, hygiene, solid waste management, wastewater treatment and creating awareness among people regarding healthy sanitation practices.
- Providing a well-balanced, nutritional and healthy diet to all
- Addressing the issue of tobacco, alcohol and substance (drugs) abuse
- Improving the safety and addressing the issue of gender discrimination at workplaces
- Making health education an integral part of the school curriculum and promoting safe and hygienic health practices among students.
- Implementation of programs at national level for detection and elimination of communicable diseases like TB, HIV, leprosy, and non-communicable diseases like diabetes, hypertension, thalassemia etc. strengthen the healthcare system.

The National Health policy focusses on providing quality healthcare to all with major emphasis on poor, vulnerable and marginalised section of the society. The concept of preventive and promotive healthcare has been constantly stressed upon to ensure the highest level of well-being for masses.

- **Ayushman Bharat**

The Ayushman Bharat, launched in 2018, aims to achieve universal, accessible and affordable healthcare for all. One target of

this mission is to provide primary healthcare to the needy people by creation of 1.5 lakhs health and wellness centres throughout the country. The second part of the mission is to create the world's largest Public Healthcare Insurance Scheme which provides a health cover of Rs. 5 lakh per family in a year for the secondary and tertiary care hospitalization services, to around 10 crore poor and vulnerable families. The free drugs initiative plays an integral role in improving the quality of healthcare. Under this scheme, states have been given extra funds to provides essential drugs to people free of cost [10].

Some Important National health programs are:

- **RMNCH+A:** Reproductive, Maternal, Newborn, Child and Adolescent Healthcare: Under the RMNCH+A strategy of NHM, significant improvements have been achieved with regard to reduction of maternal mortality ratio, MMR and child mortality rates.

The MMR refers to the number of maternal deaths per 100000 births. MMR is an important factor as it signifies the quality of healthcare in a country. The Indian National Health Policy is dedicated to decrease the MMR in the country. Some of the initiatives taken by the government in this direction are: Janani Suraksha Yojana (JSY), Janani Shishu Suraksha Karyakaram (JSSK), Pradhan Mantri Surakshit Matritva Abhiyan (PMSMA), LaQshya Programme. The main objective of all these programmes is to provide a safe motherhood by giving proper care, free of cost medicines, regular check-ups and no expense delivery to the pregnant woman in all the public health facilities. The LaQshya Programme ensures that the services related to maternity are assessed on the NQAS standards [11–13].

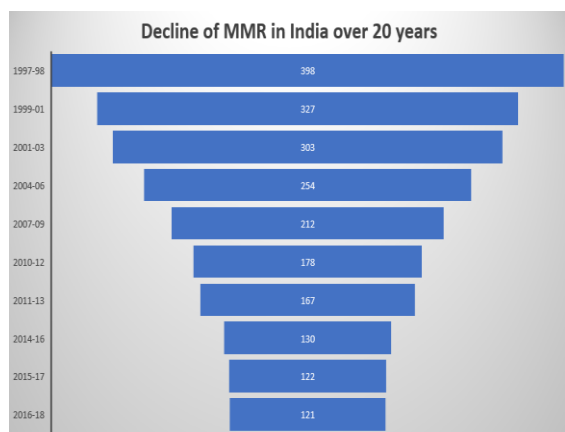


Figure 1: Mother mortality trend over the years

- **Universal Immunization Programme (UIP):**

This is world's largest public health programme, started in 1978, is one of the top programmes under the National Health Mission. Approximately 5.5 crore pregnant women and newborns are vaccinated annually under this mission, free of cost, for twelve preventable diseases.

Government launched Mission Indra Dhanush to aim towards full immunization coverage for children specially in hard-to-reach areas. Also, proper cold chain equipment for vaccine storage have been developed in various districts across the country. The Pulse polio programme is still going on a large scale to maintain the polio free status of the country. To keep the program going as desired, it is crucial that the production as well as distribution of the vaccines should be done through standard quality checks at each step [14,15].

- **National Vector Borne Disease Control Program (NVBDCP)**

For the prevention and control of vector borne diseases like Malaria, Japanese Encephalitis (JE), Dengue, Chikungunya, Kala-azar and Lymphatic Filariasis (LF), the National Vector Borne Disease Control Program (NVBDCP) was started. The spread of these diseases depends on many

factors like climate, cleanliness, types of vectors and their prevalence and may other ecological and social factors. The only way to prevent these diseases is to keep one's surroundings clean [16].

- **National Tuberculosis Elimination programme (NTEP)**

Government started the battle to fight tuberculosis (TB) in 1962. The programme was renamed as NTEP in 2020, which aims to make India TB free by 2025. Around 26.4 lakh people are suffering from TB in India alone which makes it 27% of the TB cases in the world. The main objective of NTEP is the timely detection and treatment of TB infected people for which the government has started 5 lakh DOT centres and around 21000 microscopy centres across the country. To further prevent the spread, section 269 and 270 of the Indian Penal Code have been applied. Even in the private sector, free diagnosis, treatment and drugs are given to all patients. The need is to spread awareness among people to report the disease and get treatment as soon as possible and stop it from further spreading [17].

- **Nations AIDS Control programme (NACP)**

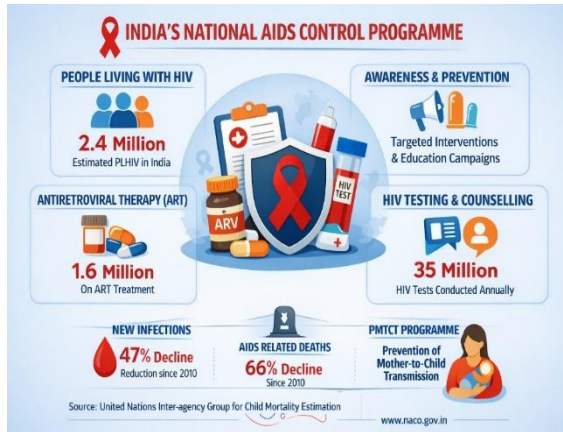


Figure 2: Source: www.naco.gov.in, image credit: AI copilot

A flagship programme of National AIDS Control Organization (NACO) which ensures safe blood transfusion practices and provides free of cost Anti-Retroviral Therapy (ART) to the infected people (Figure 2). Under its “Test and Treat” policy, free drugs and services for HIV and TB are available at all the ART centres. A network of laboratories is involved in quality testing in association with the non-government organizations (NGOs) and community-based organizations (CBOs). An HIV/AIDS prevention act is passed by the Indian Parliament in 2017 to prevent any kind of discrimination towards the HIV infected people. Literacy and open discussions are necessary to remove the taboo and make people understand the seriousness of the issue and come together to create a healthy environment so that more and more people can get diagnosed and treated [18].

A lot of other small and big programmes have been initiated by the government for improving the quality of healthcare. Some of them are:

- Rashtriya Bal Swasthya Karyakram
- National Leprosy Eradication Program
- National Mental Health Program
- Rashtriya Arogya Nidhi

- National Tobacco Control Program
- Integrated Child Development Service
- National Iodine Deficiency Disease Control Programme
- National Policy for Rare Diseases
- WASH programme: To improve water, sanitation and hygiene etc.

People will only benefit from these schemes if they are implemented properly keeping all the standards and quality checks in place.

4. Benefits of Quality in Healthcare

Quality in healthcare means the presence of a safe, efficient, and patient friendly system which not only avoids any kind of harm but also reduces wastage of resources [19]. There are a lot of benefits of quality in healthcare (figure 3). Many deaths occur due to human negligence and poorly maintained medical equipment. A study by Harvard University reveals that by improving the quality of treatment given to the critically injured patients, the deaths can be reduced to 50% [20]. Quality here means fast and reliable emergency services, accessibility of essential drugs at cost-effective price and the availability of well-trained doctors and medical workers. A patient-centric environment is the need of any healthcare facility.



Figure 3: Various benefits of quality in healthcare, image credit: AI copilot

Proper implementation of various government schemes also increases the quality of healthcare. Maintaining quality in these government schemes is a matter of serious concern. Since there are many stages from initiation to implementation, each stage should have separate quality checks to ensure that the purpose of the policy is fulfilled [21]. All the medical instruments should be well maintained and calibrated against the national standards. The storage of vaccines should be done at the desired temperature which again have to be maintained in good quality cold storage boxes. Maintaining uniform quality of healthcare in India is difficult due to its diversified cultural, social and economic variations. One way is to improve the quality of medical education, training the healthcare workers, developing their knowledge and skills, regular monitoring and evaluation and proper record keeping.

• Medical Tourism:

Due to the development of world-class healthcare facilities at an affordable rate, India has become the destination of choice for many people across the globe who are in dire need of medical treatment (figure 4) [22].

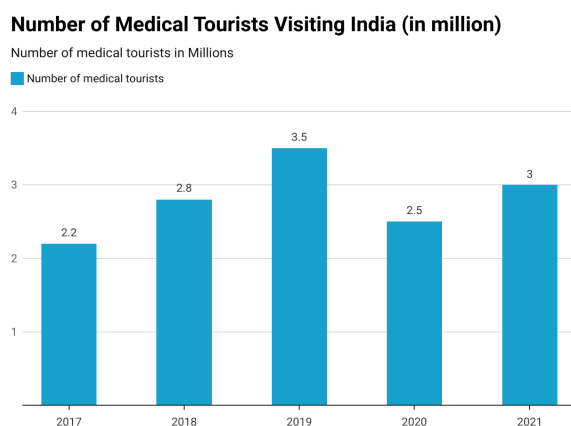


Figure 4: Number of tourist visiting India on medical visa

Less waiting time and state of the art healthcare facilities attract tourists towards

India. The Indian government has also started the facility of Medical Visa for such patients and their families. According to a report by the Ministry of Tourism, 1,82,945 foreign nationals came to India on medical visas in the year 2020 [23]. India receives majority of medical tourists from South Asian countries like Afghanistan, Bangladesh, Iraq, Bhutan, Sri Lanka, Maldives along with Canada, Australia etc. The traditional Indian medicinal system, AYUSH- Ayurveda, Yoga, Unani, Siddha, Homeopathy, combined with allopathy make an attractive offer for the tourists. The Indian pharmaceutical industry is a key player in exporting medicines throughout the world. Also, the market for medical devices in India is growing fast, becoming 4th largest in Asia. The ongoing Covid-19 pandemic has already created a disturbance in the lifestyle of public at a large scale and its after effects will put more burden on the healthcare sector. Looking at the other side, this might pave way for a big increase in the medical tourism and generation of high revenue.

5. Quality Implementation in Health Care: International Organization for Standardization (ISO)

The International Organization for Standardization (ISO) provides a platform for developing standards through common understanding and cooperation with all stakeholders. The implementation of standards is basically conformity assessment process of evaluating or measuring whether materials, products, processes, services, systems or persons meet requirements.

The conformity assessment for any standards implemented by any laboratories has been given by a third party known as accreditation body like for testing and calibration laboratories NABL in India accreditate that is recognized by an

independent body like International Accreditation Forum, IAF [24]. International Accreditation Forum operates a worldwide mutual recognition arrangement among Accreditation Bodies (ABs) in order that the results issued by Conformity Assessment Bodies (CABs) accredited by IAF members are accepted globally. The United Nations new road map is to improve health services and well-being of people's lives by 2030 is one of the UN Sustainable Development Goals [25]. To meet the ambitious Goal to improve people's health, implementation of Standardization in healthcare system is utmost important. ISO standards make it easier to compare health services, exchange information, aggregate data and safeguard the privacy of an individual's health. Implementation of ISO standards, organizations and companies make a proactive commitment to the principles of quality, transparency, accountability and safety. However, healthcare system is an increasingly complex and high-risk activity [26]. There are more than 1400 ISO health standards available Medical or Healthcare organizations. ISO 13485:2016 Medical Devices Certification, ISO 17025:2017 Laboratory Testing Standard, are the well known standards for the healthcare organizations.

In India the Association of Indian Medical Device Industry (AIMED) in collaboration with the Quality Council of India (QCI) and the National Accreditation Board for certification bodies (NABCB) has established a voluntary quality certification scheme for medical devices in India, ICMED 13485 to help ensure quality in manufacturing of medical devices [27]. ICMED 13485 - Based on the International Harmonized Standard (ISO 13485) "Quality Management Systems for Medical Devices" plus additional requirements specified under the scheme. National

Accreditation Board for Testing and Calibration Laboratories (NABL) provide third party laboratory accreditation services in performing tests and calibration in accordance with ISO/IEC 17025.

Healthcare services for the peoples increase the likelihood of desired health outcomes and are consistent with evidence-based professional knowledge decides the Quality of care. For achieving the quality in healthcare the following ISO Standards should be adopted by the health care organizations:

9001 Quality Management

ISO: 13485 Medical devices certification

ISO: 14001 Environmental Management Standard

ISO: 14064 Green House Gases

ISO: 15189 Medical Laboratories Quality Systems

ISO: 15700 Service Quality Management System

ISO: 16001 Social Accountability

ISO: 17021 Conformity Assessment

ISO: 17025 Testing and Calibration Laboratories

ISO: 18001 Occupational Health and Safety Management Series

ISO: 22000 Food Safety Management

ISO: 26000 Social Responsibility

ISO: 27001 Information Security Management Standard

ISO: 31000 Risk Management

ISO: 37001 Anti-bribery Management System

ISO: 45001 Occupational health and safety

ISO: 50001 Energy Management

ISO1789 Medical vehicle and their equipment. Road ambulance.

ISO standards make it easier to compare health services, exchange information, aggregate data and safeguard the privacy of an individual's health. By implementing ISO standards, organizations and companies make a proactive commitment to the principles of quality, transparency, accountability, and safety.

6. Importance of Standards for biomedical Devices in Healthcare system

Medical Devices: A medical device may be defined as a kit, apparatus, instrument, appliance, implant, or other article, intended to be used specially for human beings or animals for the specific purposes of:

- (i) Prevention, detection, diagnosis or monitoring of a disease or problem;
- (ii) Treatment or mitigation of any physiological condition or illness;
- (iii) Replacement or modification or support of the anatomy or inherited abnormality;
- (iv) Supporting or sustaining life;
- (v) Control of conception or
- (vi) Sanitization of medical devices [28].

According to Article 21 of Indian Constitution, Right to Health is one of the fundamental rights of every Indian citizen. The medical devices provide healthcare and help in improving the health of the individual of a nation. Therefore, quality control for biomedical devices is the foremost requirement for the running of a smooth and successful healthcare system. It acutely impacts the health of the nation's citizens along with the economy of the country and hence, the healthcare policies must focus on the "healthy equipments" in hospitals, pathology and imaging laboratories, pharmaceutical industries etc. Our government has already taken many initiatives in this direction. In spite of that, a large number of populations in India are

getting low quality healthcare facilities due to lack of well-equipped instruments, skilled staff, knowledge and last but not least a huge population. As per United Nation's child mortality estimates, around 7,21,000 infants deaths are reported in India in 2018 (Figure 5).

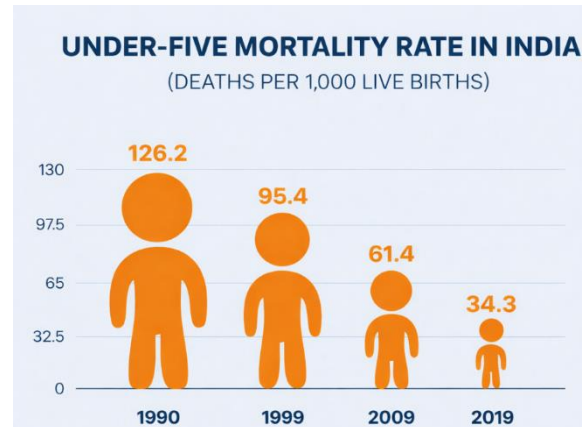


Figure 5: Source: United Nation's inter-agency group for child mortality estimation (UN IGME) 2020

According to UNICEF report 2020 Nigeria and India alone accounts for the one third of total under five deaths in children [29]. A study published in the Lancet, 2018, states that in spite of the different programs like Janani Suraksha Yojna which was launched in April 2005 have not improved the maternal and new born survival due to unskilled staff and low quality healthcare facilities. According to the report 15.6 million excess deaths were recorded in 2016 in 137 low and middle income countries including India out of which 8.6 million deaths were due to the poor quality of care or non- utilization of healthcare. The Report concludes that these deaths could be averted by investments into high quality health systems [30]. Being a low income country India lacks the quality healthcare infrastructure from beginning. A number of examples have been cited in literature in reputed journals regarding the poor, ignorant and corrupt healthcare structure. According to a world report, published in The Lancet in 2009, the trade of second hand/used equipments like

unsterilized used syringes were found responsible for causing the widespread Hepatitis B and consequent deaths in Gujarat, India [31]. Although after the incident, Indian government imposed the compulsory use of disposable syringes but we are not sure that how effectively the rules are being followed as the black marketing of medical waste still exists in the Indian healthcare system. The recent black marketing of used mask and gloves during Covid-19 second wave is the live example of playing with the life of citizens and failed medical waste disposal policies along with fractured healthcare system [32].

Even in super and multispecialty hospitals which are equipped with the modern high-tech facilities the inefficiency or ignorance (for example time to time calibration of the instrument) or the lack of standard or calibration facility may lead to the erroneous results or treatment which consequently may be fatal to the individual. Acquiring reliable high-quality data is also a huge constraint in improving the quality of healthcare system because most of the time the concerned staff is unaware of the errors in testing, treating or tracking biomedical devices. How dangerous this ignorance or unawareness or the flawed healthcare policies can be this can be understood from the following case studies. In a remarkable case a petition filed by a Delhi resident vs. Union health ministry in 2011, to Central information commission demanded that the hospital equipment procurement details and their maintenance schedule should be reflected on the website as many of the infants meet an untimely death due to the poor maintenance of the incubators or due to the equipment failure. Dr. Paul who was representing Director AIIMS stated that during the procurement of the medical equipment the quality of the equipment is compromised as during the bidding high quality equipment gets out of the league while competing with their cheaper counter parts and these cheap

equipments here for example incubators due to fault or design flaw end up with burning itself along with baby [33]. It is a horrible situation and these types of incidents are really very unfortunate. Here is a need to amend the government policies which emphasis more on quantity than quality. At least healthcare system should be exempted from these fixed criteria. A recent incident came across during the second Covid-19 wave in 2021 when Mumbai High Court admonished the Ministry of health and family Welfare, Govt. of India for indirectly defending the manufacturer of ventilators who delivered faulty ventilators to Maharashtra and might become the cause of casualties during the pandemic [34]. No doubt India has become more vigilant and concerned about its health facilities and infrastructure but more has to be done in this direction.

Not only in India, but worldwide these types of incidents have been reported where the malpractice in hospitals and path labs resulted into hospitalization and even deaths [35]. According to WHO millions of people die each year due to medical negligence and malpractices and its personal and socio-economic impact leads to the loss of around trillions of US dollars[36]. Globally many researchers have reported the losses and deaths due to the malpractices in healthcare sector since long back [37,38]. These instances triggered the need for regulations, standards and traceability in medical sector, concerning to the health and life of an individual. Out of which one of the most important is biomedical devices regulation, which has least developed among medicines and vaccines [39]. Although a lot of efforts in this direction have been made by national and international regulatory bodies in recent past years.

• **International Medical Device regulation**

According to WHO, the regulatory guidelines for the medical products whether

medical devices, equipment or medicines serve to limit the harmful impact of the product to the end user, non-compliance of the product with standards and or being ineffective. The government of a nation has a major role in the implementation of these regulatory guidelines as a law and its proper enforcement. All the major medical equipment and devices manufacturer countries have very important components in common. The first is the quality assurance system to ensure the compliance of device with the existing standards and norms and a system assuring clinical safety and performance of the device [40]. WHO defines standards as “documented agreements containing technical specifications or other precise criteria to be used consistently as rules, guidelines or definitions of characteristics, to ensure that materials, products, processes, and services are fit for their purpose” [41]. The widely accepted international standards in this field have been developed by organizations like international organization for standardization (ISO), International Electro technical Commission (IEC) and International Telecommunication Union (ITU). The global harmonization task force (GHTF) advises the nations to apply these standards according to their requirement and conditions in their countries so that a quality care can be provided to the end user/Patient.

7. India’s Movement on Quality Control of Biomedical Devices

It has been estimated that around 80% of the total required medical devices and equipments are being imported in India [42]. The fact is of great concern that we don’t stand with our own in the area of biomedical equipments and devices. Manufacturers are promoted for the production of the medical equipments but the major reason for their failure is the poor quality which does not meet the international standards. Therefore, with promotion of indigenous manufacturing quality control of the products is equally

important and the equipment traceability to international standards should be fixed. Although small and cheap medical devices with poor quality openly circulates in the country as we cannot afford the high-quality care for each and every individual of the nation. There is only one solution that we manufacture these devices independently but with regulation of strict quality guidelines. National Health Policy, 2017 promotes the domestic manufactures to produce indigenous medical devices to endorse the “Make in India” concept but with the condition the devices should comply with the quality standards. Harmonization of domestic medical standards with international standards, strengthening of medical devices regulation and the formation of a regulatory body on it, was recommended in the policy so that it will promote the manufacturing of indigenous medical devices with international standards [9]. The implementation of medical device rule, 2017 has effectively initiated the quality control of the equipments with international standards including Horizontal, semi horizontal and vertical standards, which state that “For all manufacturing sites, Quality Management System will need to be aligned with ISO 13485. Import of all medical devices will continue to be regulated by CDSCO. A network of NABL accredited laboratories will be set up both, by the Government and by other entities, for testing medical devices” [43]. It is of great importance to understand that a large number of health complications can be prevented by following the standards and norms related to the medical device and hence minimizing its error. The traceability of the measurement of the medical device should be fixed by authority to international organization to get the reliable data. Let us have a look at various medical segments and the quality required and maintained for medical devices in that sector in India.

- **Standards for Medical Equipments in Hospitals**

In Hospitals various types of medical equipments and devices are used for the diagnosis, testing and treatments. These instruments/devices fall in different categories according to their specialized functioning. There are certain standards and protocols not only for their operation but also for their storage, transportation, handling, maintenance etc. of the quality procedure ensures the safety of the patients and the paramedical staff.

Medical Radiation Equipment/treatment

Nuclear medicine imaging, sterilization of medical equipments using radiation, X-ray machines, Linac (linear accelerator), etc. falls in the category which uses high energy radiations or radioactive materials. For example, a medical equipment for treating a cancer patient may contain radioactive material. Radioactive materials are also used frequently in biomedical research. Basically, these materials are highly hazardous if used improperly, the exposure time and quantity is not properly controlled or is not disposed properly. Many such incidents have been reported in India. It may not only affect the operator of the machine but can be dangerous to patient and the persons in vicinity. Therefore, there are certain national/international guidelines by the respective agencies (Figure 6) regarding safety aspects, operation and disposal of the equipment/radioactive material which should be strictly followed to avoid the adverse effects during and after its use.

INTERNATIONAL	INDIA
International atomic energy (IAEA)	Atomic energy regulatory board (AERB)
International Commission on Radiological Protection (ICRP)	
National council on radiation protection and measurements	
U.S.FDA (Food and drug administration)	

Figure 6: International and national regulatory bodies for radiation

Atomic energy Acts 1962, along with the subsequent amendments Atomic Energy (Radiation Protection) Rules, 2004 (G.S.R. 303) provides the regulatory framework for the development control and use of radioactive material for the public welfare in India [44]. According to its section 21, it is the responsibility of the licensee to comply with the specified safety standards, time to time assessment of the exposure to the radiation for ensuring the safety of workers, patients or public. The licensee should ensure the preventive and remedial maintenance and satisfactory performance of the radiation protection and radiation monitoring equipments. Central government has designated Atomic Energy Regulatory Board (AERB) a competent authority which looks after all the radiation related affairs like licensing, approvals, renewals etc and enforcement of the regulatory framework for radioactive materials. As national accreditation board for calibration and testing laboratories (NABL) is the accreditation body for radiological calibration and testing under Quality Control of India (QCI), AERB recently on February 2021 signed an agreement with NABL that, as the radiation imaging it will accredit the quality assurance agencies in this area.

• Quality Control in Nanomedicine

Nanomaterials are defined as the materials having at least one dimension at nano scale specifically between 1-100 nm or upto 1000 nm in some cases. These nano materials have unique tunable physicochemical properties specific to their nano dimension which are absent in their bulk form [45]. Recently, nanotechnology has contributed to the noteworthy contribution to various drugs and medical products development. Nano medicine is a term frequently encountered in medical sector, which is defined as the use of nanomaterials for diagnosis, treatment, monitoring or control of disease or therapeutics. It has revolutionized the area of medical field but has several associated regulatory issues

also. Due to the alteration in the properties at nano scale nano medicine may stay for long and can easily penetrate the biological barriers in human body. Moreover, their pharmacokinetic parameters viz. metabolism, distribution and absorption in the body may vary drastically in comparison to their bulk counterparts (figure 7).

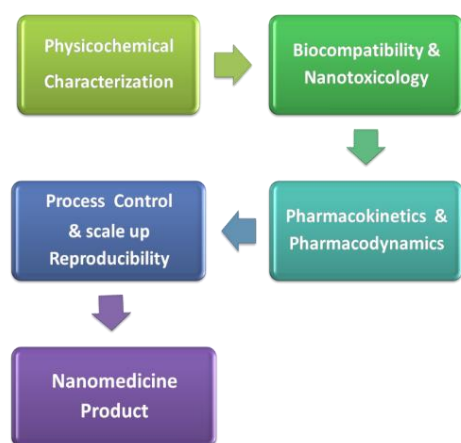


Figure 7: Challenges for the development of nano medicine [46].

Therefore, they can become detrimental to human health and their application in medical field requires strict quality control and regulatory guidelines. In other developed countries the nano pharmaceuticals guidelines are regulated by the drug related regulatory bodies like food and drug administration (FDA) in USA, medicines and healthcare products regulatory authority (MHRA) in UK, European medicine union (EMU) in Europe, Ministry of Health, Labour and Welfare (MHLW)/the Pharmaceuticals and Medical Devices Agency (PMDA) in Japan. Among all only European agencies have widely studied and published a broad range of guidelines related to nano materials and nano medicine. The other countries are still lacking the clear regulations regarding the implementation of nano medicine in the country [47]. In 2019, CDSCO, DBT, ICMR and MoHFW in coordination with

the stake holders in the area released some guidelines for the evaluation of nano pharmaceuticals. The guideline focuses on the development of new competitive and robust drugs with complete in-vitro and in-vivo study profiling according to the existing guidelines conforming to Drugs and Cosmetics Act, 1940 and New Drugs and Clinical Trials Rules, 2019. The guidelines are intended to develop the drugs with improved efficacy, safety and reduced toxicity, cost and dose.

8. Private Pathology Labs and Imaging Centres and Regulatory Standards

Pathology labs and imaging centres are the backbone of a healthcare system. The treatment of a disease/injury/illness very much depends on the diagnosis which is done by these laboratories. In nutshell half of the cure is done at the first stage i.e. the proper diagnosis and half depends upon its treatment.

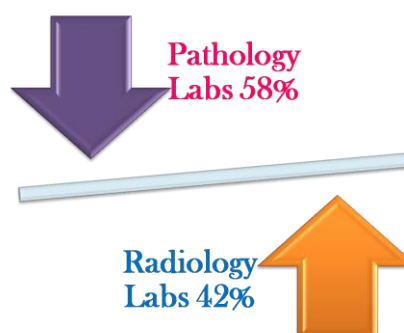


Figure 8: Diagnostic Industry Breakup

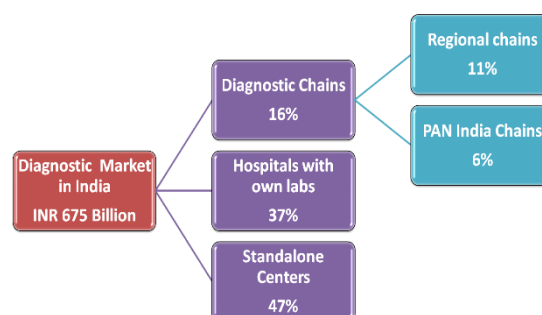


Figure 9: Market Structure of Indian Diagnostic Industry

Private pathology labs and imaging centers plays a very crucial role in Indian healthcare sector as these private labs dominated by their share in health sector and a major portion of Indian population has dependency on these labs for testing and diagnostics. 58% of the total labs are Pathology and 42% are doing radio imaging (figure 8).

Figure 9 reflects the breakup of the diagnostic market in India. These private pathology labs and diagnostic centers are governed by the legal framework of Clinical Establishment Act, 2010 with a motive to provide a minimum standard of healthcare service in India. According to our constitution healthcare is a state subject, therefore state has exclusive powers to select which union law to enforce and which to reject. As of now less than half of the total Indian states have enacted upon this act. In India there are framed guidelines, standards and SOPs which they have to follow to run their labs in standard manner. But it seems only in papers. It is so easy to get all the approvals to run pathology labs that they are growing as mushrooms in India. Anyway, the overall situation of the pathology labs and imaging centers is worst while considering the quality of service provided by these labs and they are far away from the standards [48]. Most of the time we come across the incidents where two or three pathology labs have different results. It is common practices of the pathology labs to provide erroneous diagnostic reports which is a threat to the public health, and the interesting fact is most of them are NABL accredited [49,50]. There are certain standards and guidelines for collecting test samples, their shelf life, transportation conditions etc., if these samples are tested beyond the prescribed shelf life, their reports are useless. All laboratory machines should be calibrated in prescribed time period and cross-checked for efficacy. In India laboratories do not even bother to train the staff properly. They are totally

unaware of the protocol and carry on to process the samples. Even in the laboratories where proper training to the staff is given, nobody bothers to keep an eye whether SOPs are properly being followed or not. This implies that labs are not bound to follow regulatory guidelines and performing unethical practices without any hesitation. Covid -19 pandemic is the recent example, where government authorized ICMR to regulate the guidelines for testing and treatment of the infection by SARS-CoV-2, where ICMR authorized only government labs to perform the testing, afterwards when load became higher other NABL accredited private labs also were given the responsibility of testing. Surprisingly, placing all the rules and guidelines on the haywire false/fake certificates were issued by these laboratories [51–54]. One can imagine how serious matter it was. While government was asking to break the contact chain of corona virus infection, thousands or lacs of fake reports were issued, which means that many infected persons were roaming in public infecting many more. No doubt inefficient testing and unethical practices of these labs was one of the contributory factors to the severity of disease in Second Covid wave. This should be treated as crime but with the down fall of the wave responsible agencies also went to hibernation or started the blame game to shrug off the responsibilities [55]. Nowadays these path labs and imaging centers have become a fancy business with a handsome earning, in spite of that its quality is being deteriorating. These are the loopholes in the system, need to be urgently reviewed and act upon. Otherwise, the system will never grow up to the international quality level and will be failure again and again while fighting against the unprecedented situations like Covid-19. Government has to take some initiatives in form of strict actions or penalties to limit these labs to perform within the standard protocol to maintain the quality of overall healthcare system

preventing deaths due to non-standardize equipments, malpractices and ignorance of the diagnostic labs.

The above discussed segments are interrelated and have interdependency on each other. Like a person cannot have a healthy life if any of the body organ is malfunctioning or not working. Similarly, for any system to work efficiently all of its components need to work together and honestly and on the predefined regulatory guidelines and standards to give a quality service to the public for their benefit. The second most important point is we will not be able to improve the healthcare quality unless we will be independent in this sector. Along with the policies, India needs to invest more and more on biomedical and devices research, developing standards. Several types of medical devices are being used in India as being a huge market for medical products; the development of our own indigenous system will help to boost the economy, as the huge amount which goes to foreign countries will remain in our countries along with opening a huge number of job opportunities for our young talent. Therefore, to achieve the goal of quality healthcare we must work on developing our own medical products, biomedical device and their standards with international traceability.

9. Challenges and Future Direction

India has a robust set of health programs and internationally benchmarked quality standards, but the real challenge lies in implementation—especially in rural areas, workforce training, and reducing out-of-pocket costs. Strengthening monitoring, expanding infrastructure, and improving awareness are critical steps. National Quality Assurance Standards (NQAS) is India's backbone for healthcare quality assurance, ensuring facilities meet international standards. However, The biggest challenge in quality implementation in the Indian healthcare system is the gap between policy design and ground-level

execution, particularly in primary healthcare delivery. Despite ambitious frameworks like the National Health Policy (2017) and Ayushman Bharat, fragmented infrastructure, workforce shortages, and weak accountability mechanisms hinder consistent, equitable, and patient-centered care [56,57]. Primary Health Centres (PHCs), which form the backbone of rural healthcare delivery, are often under-resourced, understaffed, and poorly equipped, leading to diminished community trust and reliance on informal or private providers. Studies highlight that vacancies among doctors, nurses, and laboratory staff remain widespread, with absenteeism further eroding confidence in public facilities. This imbalance is compounded by stark urban–rural disparities, where nearly two-thirds of India's population resides in rural areas but only one-third of health workers serve them. Even initiatives like Health and Wellness Centres under Ayushman Bharat, though promising, risk replicating existing inefficiencies unless systemic flaws in infrastructure, workforce motivation, and accountability are addressed. Quality assurance frameworks such as the National Quality Assurance Standards (NQAS) and Indian Public Health Standards (IPHS) exist, but adherence remains low, with only a fraction of PHCs meeting basic requirements [56]. Certification rates vary widely across states; some have strong uptake, while others lag due to weak governance. Strengthening training, monitoring, and funding mechanisms will be critical to sustaining its impact. A unified monitoring and evaluation framework is also critical. In essence, the challenge is not the absence of policy but the lack of effective implementation mechanisms that ensure reliable service delivery, equitable distribution of resources, and sustained community engagement. Without strengthening primary care infrastructure, institutionalizing a multidisciplinary public health cadre, and enforcing accountability

through robust monitoring, India's healthcare reforms risk remaining aspirational rather than transformative.

The future of healthcare policy implementation in India requires a more integrated and collaborative approach between the central and state governments. Strengthening federal–state coordination is essential to ensure that national health programs are uniformly applied while allowing flexibility for states to adapt them to local contexts. Establishing structured platforms for dialogue, such as joint task forces or intergovernmental councils, could help align priorities and reduce fragmentation in execution [58]. Leveraging digital health technologies, including telemedicine, electronic health records, and AI-driven analytics will further bridge gaps in monitoring and service delivery, particularly in rural and underserved regions. Programs like Ayushman Bharat- Pradhan Mantri Jan Arogya Yojana (PM-JAY) have demonstrated the potential of universal health coverage by providing financial protection to vulnerable families and combining insurance for secondary and tertiary care with strengthened primary healthcare infrastructure [59]. Capacity building at the state level remains a priority. Investments in workforce training, administrative efficiency, and infrastructure development will empower state health departments to implement central policies more effectively. Public–private partnerships (PPP) can complement these efforts by expanding reach, improving infrastructure, and fostering innovation in service delivery.

Future strategies must also emphasize equity and sustainability. The World Health Organization (WHO) underscores that quality of care is fundamental to achieving the Sustainable Development Goals, particularly in reducing maternal and child mortality. Aligning India's healthcare reforms with global frameworks such as Universal Health Coverage (UHC) will

ensure long-term resilience[19]. A comparative Table 1 highlights how different frameworks contribute to healthcare quality in India.

Finally, fixing the accountability for the implementation of quality standards in healthcare, prompt strict penalty and community engagement should be strengthened. Involving civil society, patient advocacy groups, and local communities in policy design and feedback processes will make healthcare more responsive, inclusive, and culturally appropriate. Together, these directions can transform India's healthcare system into one that is not only efficient and equitable but also sustainable and future-ready.

10 Conclusions: The Indian healthcare system stands at a critical juncture where the assurance of quality has become as important as access and affordability. Despite the introduction of ambitious national programs such as the National Health Policy (2017) and Ayushman Bharat, the persistent challenge lies in translating these frameworks into reliable, equitable, and patient-centered care across diverse regions. The COVID-19 pandemic exposed systemic weaknesses, shortages of beds, oxygen, and critical equipment, that underscored the fragility of infrastructure and the urgent need for robust quality assurance mechanisms. A major barrier to quality implementation is the uneven distribution of resources between urban and rural areas. Primary Health Centres, which should serve as the backbone of preventive and promotive care, often remain under-equipped and understaffed. This imbalance is compounded by the shortage of trained medical professionals, inadequate monitoring of standards, and weak accountability mechanisms. Even where policies exist, their execution falters due to fragmented governance and lack of uniform adherence to benchmarks such as the National Quality Assurance Standards (NQAS).

Another pressing issue is the quality of biomedical devices and medical equipment. Reports of faulty ventilators, poorly maintained incubators, and black-market circulation of medical waste highlight how lapses in regulation and enforcement compromise patient safety. The reliance on imported medical devices

In conclusion, India's healthcare system requires a paradigm shift from quantity-driven expansion to quality-centered delivery. Strengthening primary care infrastructure, institutionalizing a public health cadre, enforcing strict biomedical device regulations, and embedding ISO-based quality frameworks are critical steps

Table 1: Comparative Contributions to Healthcare Quality in India

Framework / Program	Scope & Focus	Key Contributions	Challenges / Gaps
WHO Quality Standards	Global benchmarks for patient safety, clinical effectiveness, and equity	Provides universal principles for quality of care; aligns with Sustainable Development Goals (SDGs)	Adaptation to local contexts; resource constraints in low- and middle-income countries
National Health Mission (NHM)	Strengthening primary healthcare and public health systems	Introduced State Health Systems Resource Centres (SHSRCs); improved maternal and child health indicators	Uneven implementation across states; limited monitoring capacity
National Quality Assurance Standards (NQAS)	Accreditation framework for public health facilities	Standardized domains: patient rights, clinical care, infection control, quality management; ISQua-accredited	Requires continuous training and audits; disparities in adoption
Ayushman Bharat – PM-JAY	Universal health coverage combining insurance and primary care	Financial protection for vulnerable families; Health and Wellness Centres for preventive care	Variability in state-level rollout; infrastructure gaps in rural areas
Public–Private Partnerships (PPP)	Collaborative models between government and private sector	Expanded reach, improved infrastructure, and innovation in service delivery	Risk of inequity if not regulated; accountability concerns

further complicates the situation, as indigenous manufacturing often struggles to meet international standards. Harmonization of domestic regulations with ISO frameworks, coupled with strict enforcement of medical device rules, is essential to ensure reliability and restore public trust. The broader implication of these challenges is that poor-quality care not only undermines health outcomes but also erodes confidence in public institutions. Studies have shown that millions of preventable deaths in India are linked not to lack of access but to inadequate quality of care. This reality emphasizes that quality implementation must be treated as a non-negotiable pillar of healthcare reform.

forward. Only by bridging the gap between policy and practice can India achieve sustainable, resilient, and patient-centered healthcare, positioning itself as a global leader in medical excellence.

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Design and Performance Analysis of CPW-Fed Antenna with Strip-Line Feed for Multi-Band C, Ku, and Ka-Band Applications

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Abstract

This paper presents the design, simulation, and performance analysis of a Coplanar Waveguide (CPW)-fed circular microstrip patch antenna with a strip-line feed mechanism, modelled on an FR4 substrate ($\epsilon_r = 4.3$, $\tan\delta = 0.017$, thickness = 1.6 mm) for multi-band C-, Ku-, and Ka-band applications. Two antenna configurations, namely strip in centre and strip on left (proposed), are evaluated along with parametric investigations of substrate material and semi-circular ground slot orientation. The optimised strip-on-left configuration achieves four resonant bands centred at 5.5 GHz, 16.7 GHz, 26.3 GHz, and 34.6 GHz with impedance bandwidths of 1.2 GHz, 1.7 GHz, 2.0 GHz, and 2.5 GHz, respectively. The corresponding return loss values are -22 dB, -53 dB, -24 dB, and -20 dB. Simulated peak gain values of 7.0 dBi, -0.6 dBi, 1.7 dBi, and 0.5 dBi are obtained at the four operating bands, while the Voltage Standing Wave Ratio (VSWR) remains below 2 throughout all resonant frequencies, confirming acceptable impedance matching. Simulated E-plane and H-plane radiation patterns, surface current density distributions, VSWR characteristics, and S-parameter results collectively validate the multi-band performance of the proposed antenna. The compact antenna occupies a footprint of only 20 mm × 20 mm × 1.6 mm and provides simultaneous coverage of frequency bands commonly associated with C-band, Ku-band, and Ka-band wireless communication systems.

Keywords: CPW-fed antenna, circular patch, FR4, C-band, Ku-band, Ka-band, 5G mmWave, strip-line feed, multi-band.

1. Introduction

The rapid expansion of wireless communication systems across microwave and millimetre-wave frequency bands has intensified the demand for compact, multi-band antenna solutions. Modern applications ranging from wireless communication, satellite communication, and emerging millimetre-wave systems and advanced sensing platforms require antennas capable of operating simultaneously across the C, Ku, and Ka bands with acceptable return loss, gain, and radiation characteristics within a single compact element [1], [2]. The C band (4–8 GHz) is extensively used for Wi-Fi hotspots, satellite communication uplinks, and weather radar, while the Ku band (12–18 GHz) supports direct broadcast satellite television, VSAT terminals, and airborne radar systems. The Ka band (26–40 GHz) has emerged as a critical frequency resource for 5G millimetre-wave access, high-throughput satellite internet, and advanced imaging radar platforms, making simultaneous multi-band coverage within a single antenna element highly desirable for system integration and cost reduction. Microstrip patch antennas are widely adopted in these applications owing to their planar profile, compatibility with standard PCB fabrication processes, low cost, and straightforward integration with active microwave circuits [3]. Conventional rectangular or square patch geometries, however, are inherently single-band structures with narrow impedance bandwidth, which limits their applicability in multi-band scenarios. Circular patch geometries provide a practical alternative: their azimuthal symmetry supports multiple degenerate resonant modes that can be individually tuned through controlled perturbation of the patch boundary or the underlying ground plane [4].

FR4 glass-epoxy substrate ($\epsilon_r = 4.3$) remains the most widely used PCB material in commercial antenna designs due to its low manufacturing cost, good mechanical stability, and availability in standard thicknesses. While its higher dielectric loss tangent ($\tan\delta = 0.017$) poses challenges at frequencies above 20 GHz, FR4-based patch antennas have demonstrated competitive performance in the C and Ku bands, and with careful geometric optimisation can achieve acceptable return loss even at lower Ka-band frequencies [5], [9]. For high-volume commercial deployments, the cost advantage of FR4 outweighs its performance limitations compared to premium microwave substrates. The coplanar waveguide (CPW) feed offers a uniplanar architecture that eliminates via holes and back-side ground connections, simplifying fabrication and improving compatibility with monolithic microwave integrated circuits (MMICs). Combined with a strip-line feed element, the CPW configuration provides additional impedance matching flexibility, with strip width and lateral position serving as tunable parameters for controlling resonance frequency and bandwidth across the operating bands [7], [8]. This paper compares two strip positions — centre and left — to identify the configuration that achieves four-band resonance simultaneously. A comparative substrate study is conducted alongside the strip position investigation to characterise how material choice influences resonance frequencies and bandwidths, providing a direct reference for antenna designers selecting between Alumina ($\epsilon_r = 9.9$), Rogers RO ($\epsilon_r = 6.5$), and Rogers RT ($\epsilon_r = 2.2$) alternatives to the FR4 baseline design [11], [12]. Additionally, three semi-circular ground slot orientations (left, right, top) are evaluated for their effect on Ka-band

resonance depth and bandwidth. This paper makes the following contributions: (i) a compact CPW-fed circular patch antenna on FR4 achieving four-band resonance across C, Ku, and Ka bands; (ii) systematic parametric studies of substrate material, strip position, and semi-circular ground slot orientation; (iii) comprehensive result analysis including E/H-plane radiation patterns and gain at all four resonance frequencies, surface current density distributions, and VSWR; and (iv) performance comparison against recently published multi-band designs [6], [10]. The remainder of the paper is organised as follows: Section 2 describes the antenna design methodology. Section 3 presents the parametric studies. Section 4 analyses the simulated results. Section 5 compares with published literature, and Section 6 concludes the paper.

2. Antenna Design Methodology

2.1. Antenna Geometry and Configurations

The proposed antenna consists of a circular radiating patch fed by a CPW-based strip-line mechanism, printed on an FR4 glass-epoxy substrate ($\epsilon_r = 4.3$, $\tan\delta$

$= 0.017$) at a thickness of 1.6 mm. The circular patch geometry was selected to exploit its azimuthal symmetry, which supports multiple degenerate resonant modes that can be independently controlled through strip positioning and ground slot perturbations. A strip-line element bridges the CPW feed gap to the patch periphery, governing impedance transformation and coupling energy into the patch simultaneously across multiple frequency bands. Two configurations are evaluated, differing only in the lateral position of this strip-line element:

- **Strip in Centre:** The strip-line is positioned at the geometric centre of the feed slot, producing symmetric current excitation across the patch.
- **Strip on Left (Proposed):** The strip-line is offset to the left of the feed slot centre, introducing controlled feed asymmetry that generates an additional Ku-band resonance at 16.7 GHz not present in the centre-strip configuration.

Figure 1 illustrates the physical geometry of both antenna configurations. The difference between the two designs is confined to the lateral position of the strip-line element relative to the circular patch centre.

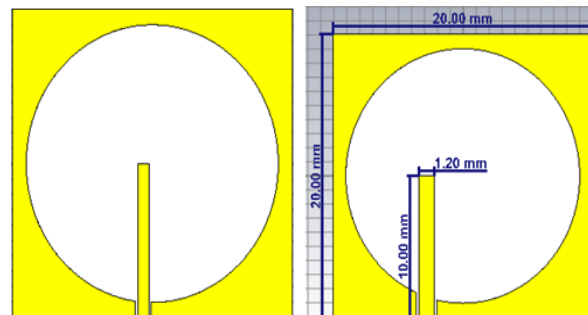


Fig. 1. Simulated geometry of the two antenna configurations evaluated: (a) Strip in Centre (baseline), (b) Strip on Left (proposed design)

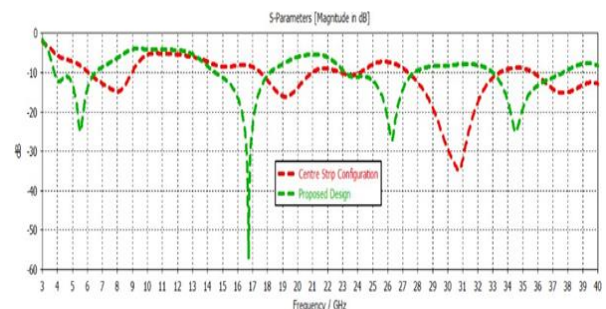


Fig. 2. Simulated S11 response comparison between the Centre Strip configuration and the Strip on Left (Proposed) design across 3–40 GHz, showing the emergence of the Ku-band resonance at 16.7 GHz in the proposed configuration.

3. Parametric Study and Analysis

A systematic parametric study was conducted using CST Microwave Studio (time-domain solver, open-add-space boundary conditions) to evaluate the independent influence of three design variables: substrate material, strip-line position, and semi-circular ground slot orientation. All simulations employ a 50 Ω discrete port excitation and S11 is evaluated across 3–40 GHz to capture all four target bands simultaneously.

3.1. Effect of Substrate Material

The proposed antenna is designed on FR4 (glass/epoxy) substrate with a dielectric constant $\epsilon_r = 4.3$, dissipation factor $\tan\delta = 0.017$, and substrate thickness $h = 1.6$ mm. FR4 is selected as the primary substrate due to its low cost, widespread availability, and demonstrated suitability for multi-band antenna designs operating up to 35 GHz with careful geometric optimisation. For comparative purposes, a parametric substrate study also evaluates Alumina ($\epsilon_r = 9.9$) and Rogers RT ($\epsilon_r = 2.2$) at the same substrate thickness to quantify the performance trade-offs associated with material choice. Table 1 lists the key electrical properties of all three materials evaluated in the parametric study.

Table 1. Electrical properties of substrate materials evaluated in the parametric study. FR4 ($\epsilon_r = 4.3$) is the proposed substrate for the final design

Property	FR4 / Alumina (9.9)	Rogers RO (6.5)	Rogers RT (2.2)
Dielectric Constant (ϵ_r)	4.3 / 9.9	6.5	2.2
Loss Tangent ($\tan\delta$)	0.017 / 0.0003	0.0027	0.0004
Substrate Thickness (mm)	1.6	1.6	1.6

Primary Use	Commercial PCB / Defence	Microwave PCB	mmWave, low-loss
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Figure 3 presents the S11 comparison across the three substrate materials (Alumina at $\epsilon_r = 9.9$, Rogers RO at $\epsilon_r = 6.5$, and Rogers RT at $\epsilon_r = 2.2$) at a constant substrate thickness of 1.6 mm. Higher dielectric constant substrates shift the resonance frequencies toward lower values, consistent with the inverse dependence of resonant frequency on the square root of the effective permittivity. Alumina ($\epsilon_r = 9.9$) produces the most compact electrical structure but with increased mutual coupling between adjacent bands and reduced bandwidth per resonance due to the higher Q-factor. Rogers RT ($\epsilon_r = 2.2$) yields the widest individual resonance bandwidths, particularly beneficial at the Ka-band frequencies above 25 GHz. Rogers RO ($\epsilon_r = 6.5$) offers an intermediate balance between compactness and resonance bandwidth. The FR4 proposed design achieves competitive multi-band performance with the significant advantage of low material cost and wide availability.

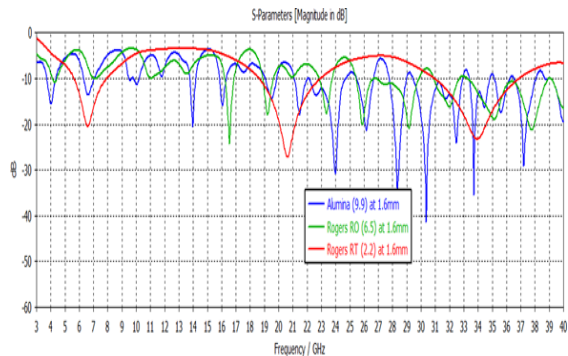


Fig. 3. Simulated S11 comparison for four substrate materials at 1.6 mm thickness: FR4 ($\epsilon_r = 4.3$, proposed), Alumina ($\epsilon_r = 9.9$), Rogers RO ($\epsilon_r = 6.5$), and Rogers RT ($\epsilon_r = 2.2$). Higher permittivity substrates shift resonances to lower frequencies.

3.2. Semi-Circular Ground Slot: Configurations and S-Parameter Performance

A semi-circular notch is introduced into the ground plane to perturb the ground current distribution and activate additional Ka-band resonances. The slot lengthens the effective electrical path seen by the radiating patch without increasing the physical footprint. Three orientations are evaluated systematically: slot entry from the left ground edge, right ground edge, and top ground edge, to determine which configuration yields the deepest Ka-band return loss for the proposed design.

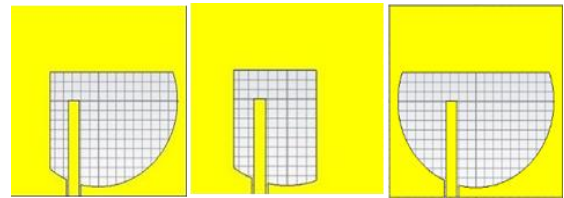


Fig. 4. Simulated antenna geometries showing semi-circular ground slot orientations evaluated: (a) Left-edge slot, (b) Right-edge slot, (c) Top-edge slot. All slots share the same radius and are etched into the FR4 ground plane.

3.2.1. S-Parameter Performance of Ground Slot Orientations

Figure 5 presents the combined S11 results for the three semi-circular ground slot orientations: left, right, and top.. The left-edge slot achieves the deepest return loss while the right and top configurations produce shallower Ka-band resonances of approximately -27 dB and -37 dB respectively. The left-edge slot is selected for the optimised proposed design.

4. Result Analysis of Proposed Antenna

The proposed antenna configuration (strip on left, left semi-circular ground slot, FR4 substrate, 1.6 mm thickness) is characterised

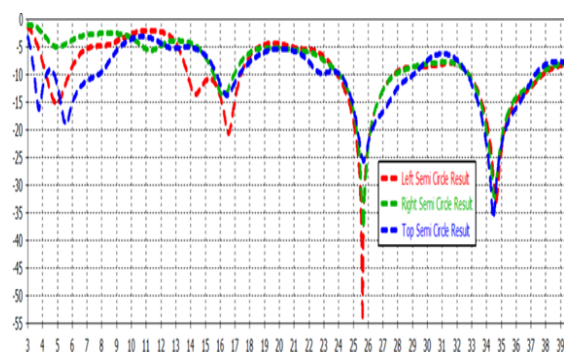


Fig. 5. Simulated S11 comparison for three semi-circular ground slot orientations (left, right, top edge) showing Ka-band resonance sensitivity to slot position. The left-edge configuration achieves the deepest return loss near 25.5 GHz and is selected for the proposed design.

across S-parameter performance, VSWR, antenna gain, radiation patterns, and surface current density distributions at the four resonant frequencies. All results reported in this section are derived from CST Microwave Studio time-domain full-wave simulations.

4.1. S-Parameter Performance.

Table 2. S parameter performance of Centre Strip configuration and Strip on Left (Proposed),

Antenna Design	Band	Centre Freq. (GHz)	Freq. Range (GHz)	BW (GHz)	S11 (dB)	Application
Centre Strip Configuration	1st	5.5	4.8 - 6.0	1.2	-12 dB	Wi-Fi, Satellite Comm.
	2nd	31.0	30.0 - 32.0	2.0	-34 dB	Adv. Radar, High Data Rate
	3rd	34.5	33.5 - 35.5	2.0	-14 dB	Ka Band, High Data Rate
Strip On Left Configuration	1st	5.5	4.8 - 6.0	1.2	-22 dB	Wi-Fi, Satellite Comm.
	2nd	16.7	15.8 - 17.5	1.7	-53 dB	Satellite TV, Radar
	3rd	26.3	25.5 - 27.5	2.0	-24 dB	5G mmWave High Speed
	4th	34.6	33.5 - 36.0	2.5	-20 dB	Adv. Radar

4.2. Comparative Analysis

The comparative S-parameter (S11) analysis between the Centre Strip Configuration and

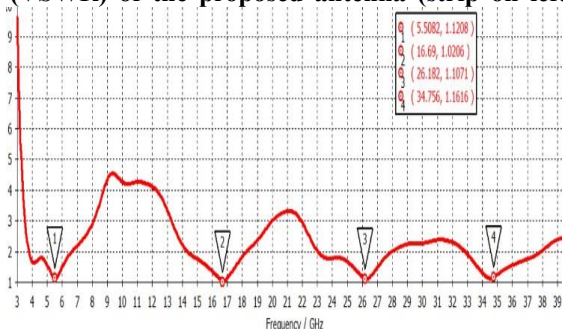
the Proposed Design highlights a significant difference in multi-band performance across the 3–40 GHz frequency range. The Centre Strip Configuration demonstrates moderate performance with three resonant bands: C Band (5.5 GHz, –12 dB), Ka Band (31.0 GHz, –34dB), and upper Ka Band (34.5 GHz, –14 dB). Although the resonance at 31.0 GHz is reasonably deep, the overall coverage remains limited.

In contrast, the Proposed Design outperforms the Centre Strip Configuration across all parameters, operating over four well-defined resonant bands with consistently deeper S11 values: C Band (5.5 GHz, –22 dB), Ku Band (16.7 GHz, –53 dB), Ka Band/5G mm Wave (26.3 GHz, –24 dB), and upper Ka Band (34.6 GHz, –20 dB). Notably, the Proposed Design achieves an exceptional resonance depth of –53 dB at

16.7 GHz, a band entirely absent in the Centre Strip Configuration. Furthermore, it covers one additional operating band with wider bandwidth at the 4th band (2.5 GHz), supporting a broader range of applications including Wi-Fi, Satellite Communications, 5G mm Wave, and Advanced Radar. The strip-on-left configuration is therefore selected as the optimised design for full characterisation.

4.3. VSWR Performance

Fig. 6a. Simulated Voltage Standing Wave Ratio (VSWR) of the proposed antenna (strip on left,



FR4 substrate) across 3–40 GHz. Markers denote local minima at 5.51 GHz (VSWR = 1.12), 16.69 GHz (VSWR = 1.02), 26.18 GHz (VSWR = 1.11),

and 34.76 GHz (VSWR = 1.16), corresponding to the four operating bands.

Figure 6a presents the simulated VSWR of the proposed antenna across the 3–40 GHz simulation range. The VSWR curve exhibits four well-defined local minima that correspond directly to the four resonant bands identified in the S11 analysis. At the first resonance (C-band), the VSWR reaches a minimum of 1.12 at 5.51 GHz, indicating excellent impedance matching. At 16.69 GHz (Ku-band), the VSWR drops to its lowest recorded value of 1.02, approaching the ideal matched condition of unity and consistent with the exceptionally deep S11 of –53 dB at this band. At 26.18 GHz (Ka-band / 5G mm Wave), the VSWR minimum is 1.11, while at the upper Ka-band resonance of 34.76 GHz the VSWR is 1.16. Across all four operating bands, the VSWR remains well below the standard threshold of 2, which conventionally corresponds to a –10 dB return loss and confirms acceptable impedance matching in all intended bands. Between resonances, the VSWR rises above 2, as expected for frequencies outside the antenna's operating bands. The VSWR results are fully consistent with the S-parameter data in Table 2 and collectively confirm that the proposed antenna achieves low-reflection multiband operation across the C, Ku, and Ka frequency ranges.

4.4. Antenna Gain

The simulated peak gain values for the proposed antenna are extracted from CST far-field results using the IEEE convention ($\Phi = 0^\circ$, maximum value). At the C-band resonance of 5.5 GHz, the antenna yields its highest gain of 7.0 dBi, demonstrating acceptable radiation performance within the C-band. The Ku-band resonance at 16.7 GHz produces a gain of –0.6 dBi; while negative, this remains within the suitable for further optimisation through array or

reflector integration where gain is augmented by array or reflector configurations.

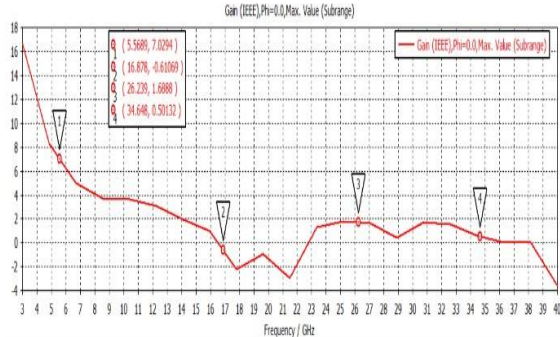


Fig. 6b. Simulated peak gain of the proposed antenna across its four operating bands, plotted using the IEEE convention ($\Phi = 0^\circ$, maximum value), showing 7.0 dBi at 5.5 GHz, -0.6 dBi at 16.7 GHz, 1.7 dBi at 26.3 GHz, and 0.5 dBi at 34.6 GHz.

At 26.3 GHz (Ka-band / 5G mmWave), the gain recovers to 1.7 dBi, and at the upper Ka-band resonance of 34.6 GHz a gain of 0.5 dBi is recorded. Positive gain is sustained at three of the four operating bands, with performance at the 16.7 GHz band attributable to higher-order current distribution that produces multi-lobe radiation rather than broadside concentration. Gain enhancement through array integration or reflector backing is recommended for Ku-band deployment.

4.5. Radiation Pattern Analysis

The simulated far-field E-plane ($\phi = 90^\circ$) and H-plane ($\phi = 0^\circ$) radiation patterns are presented at each of the four resonance frequencies. Patterns are measured at a far-field distance $r = 1$ m and plotted in polar format showing Theta (degrees) versus field magnitude in dB(V/m) for the E-plane and dB(A/m) for the H-plane.

4.5.1. Radiation Pattern at $f = 5.5$ GHz (C-Band)

At the first resonance frequency of 5.5 GHz (C-band), the antenna exhibits a bi-lobed E-

plane pattern with the main lobe directed broadside ($\theta = 0^\circ$), consistent with the fundamental resonant mode of the circular patch. The H-plane pattern shows broad, near-omnidirectional coverage with a slight asymmetry introduced by the left-offset strip-line feed and the left ground slot. Together, the two patterns confirm stable broadside radiation at this band, demonstrating stable broadside radiation characteristics at the C-band resonance.

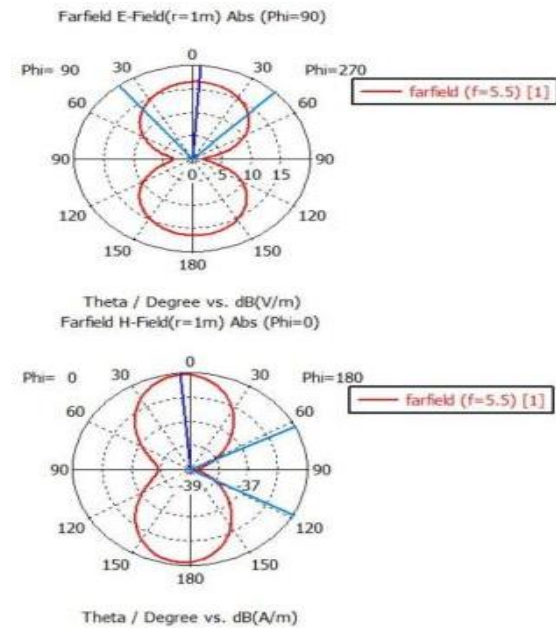


Fig. 7. Simulated far-field radiation patterns of the proposed antenna at $f = 5.5$ GHz (C-band): (a) E-plane ($\phi = 90^\circ$) and (b) H-plane ($\phi = 0^\circ$), showing broadside radiation characteristic of the fundamental resonant mode.

4.5.2. Radiation Pattern at $f = 16.7$ GHz (Ku-Band)

At 16.7 GHz (Ku-band), the radiation pattern transitions to a complex multi-lobe structure in both planes, resulting from higher-order resonant mode excitation on the circular patch. The E-plane shows multiple oblique lobes while the H-plane exhibits a four-lobe clover-leaf distribution, consistent with the deep return loss of approximately -52 dB observed at this

frequency and indicative of strong, efficient feed coupling. For potential Ku-band communication applications, this element can be integrated with a reflector dish or phased array to achieve the required directional gain.

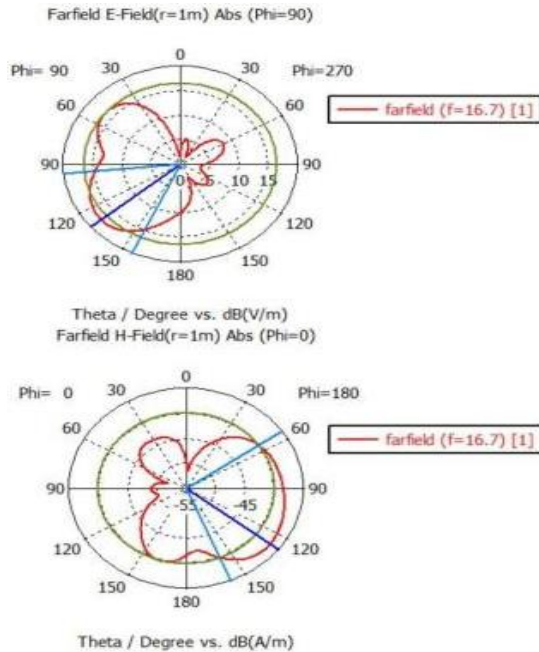


Fig. 8. Simulated far-field radiation patterns at $f = 16.7$ GHz (Ku-band): (a) E-plane ($\phi = 90^\circ$) and (b) H-plane ($\phi = 0^\circ$), exhibiting a higher-order multi-lobe structure consistent with deep impedance matching at this resonance.

4.5.3. Radiation Pattern at $f = 26.3$ GHz (Ka-Band, 5G mmWave)

At 26.3 GHz (Ka-band, 5G mmWave), the E-plane pattern shifts to a predominantly end-fire oriented characteristic with the main lobe directed towards $\theta = 90^\circ$, which is which may be beneficial for certain directional millimetre-wave communication scenarios. The H-plane pattern shows a complex multi-lobe distribution with several side lobes at oblique angles, resulting from the electrically large antenna dimensions at this wavelength. The asymmetric lobe structure is attributable to the asymmetric strip-line and ground slot positioning, which preferentially excites certain azimuthal modes.

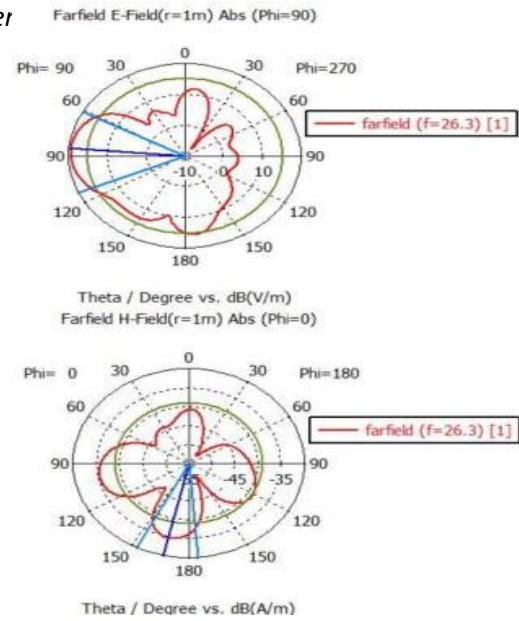


Fig. 9. Simulated far-field radiation patterns at $f = 26.3$ GHz (Ka-band / 5G mmWave): (a) E-plane ($\phi = 90^\circ$) and (b) H-plane ($\phi = 0^\circ$), showing end-fire tendency in the E-plane and complex multi-lobe H-plane distribution at millimetre-wave frequency.

4.5.4. Radiation Pattern at $f = 34.6$ GHz (Ka-Band)

At 34.6 GHz, the highest operating frequency, both E-plane and H-plane patterns become characteristically complex with multiple closely-spaced lobes distributed across a wide angular range. The E-plane shows a broad multi-lobe structure indicating efficient radiation into multiple spatial directions simultaneously. The H-plane pattern exhibits four-to-five lobes with primary lobes directed towards the lower hemisphere, consistent with the ground plane and ground slot contributing significantly to the overall radiation behaviour at this frequency. This diffuse radiation characteristic makes the antenna at 34.6 GHz well-suited for electronically beam-steered advanced radar systems.

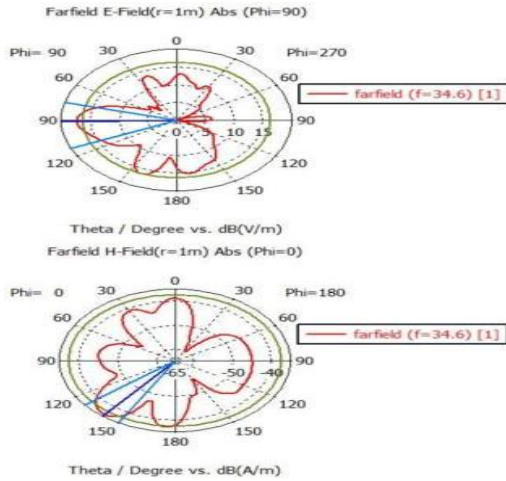


Fig. 10. Simulated far-field radiation patterns at $f = 34.6$ GHz (Ka-band): (a) E-plane ($\phi = 90^\circ$) and (b) H-plane ($\phi = 0^\circ$), showing diffuse multi-lobe radiation at the highest operating frequency, suitable for wide-angle radar coverage.

5. Surface Current Density Analysis

The surface current density distributions on the radiating patch are simulated at all four resonance frequencies to identify the dominant current modes responsible for multi-band operation. High-density regions (red/yellow in the colour scale) indicate areas of strong electromagnetic coupling between the feed structure and the radiating element.

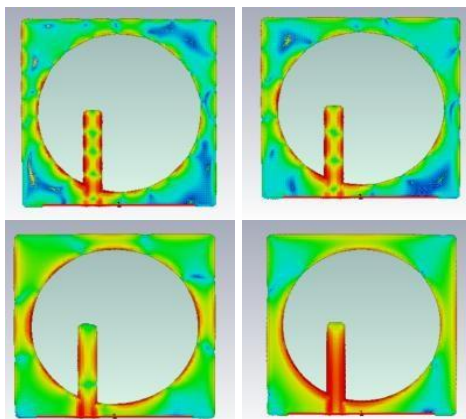


Fig. 11. Simulated surface current density distributions on the proposed antenna at its four resonant frequencies: (a) 5.5 GHz, (b) 16.7 GHz, (c) 26.3 GHz, and (d) 34.6 GHz. Colour scale indicates current magnitude (red = maximum, blue = minimum).

5.1. Surface Current at $f = 5.5$ GHz

At 5.5 GHz (Figure 11), the surface current is strongly concentrated at the bottom edge of the circular patch adjacent to the CPW feed port and strip-line connection. The current flows primarily around the patch perimeter with maximum intensity at the feed-proximal edge, consistent with the fundamental resonant mode of the circular geometry at this frequency.

5.2. Surface Current at $f = 16.7$ GHz

At 16.7 GHz, the current distribution expands around the full patch circumference, with secondary current maxima appearing at approximately 90° and 270° around the perimeter. This multi-nodal current pattern is responsible for the complex multi-lobe radiation observed at the Ku-band resonance and is consistent with higher-order resonant mode excitation.

5.3. Surface Current at $f = 26.3$ GHz

At 26.3 GHz, the surface current distributes more uniformly around the entire patch circumference with current magnitude at the upper half becoming comparable to the lower feed region. The strip-line element shows elevated current density along its full length at this frequency, confirming that the strip acts as a resonant matching element at the Ka-band mmWave frequency. The ground slot edge shows concentrated current consistent with a localised resonance contributing to the 26.3 GHz band.

5.4. Surface Current at $f = 34.6$ GHz

At 34.6 GHz, the surface current exhibits a fragmented multi-modal distribution with localised high-intensity spots at irregular angular positions around the patch perimeter. This pattern is characteristic of very high-order circular modes where multiple simultaneous resonances contribute to the observed return loss minimum, and

suggests a travelling-wave mode behaviour that explains the broad angular spread of the radiation pattern at this frequency.

6. Comparison with Published Literature

Table 3 compares the proposed antenna with representative recently published multi-band antenna designs. The comparison evaluates substrate material, physical size, resonance frequency coverage, and number of simultaneously supported bands.

Table 3 reveals that the proposed design is the only FR4-based entry achieving simultaneous four-band coverage from 5.5 GHz through 34.6 GHz, a 6.3:1 frequency ratio. The single-band Ka-band entries of references [4] and [10] confirm that extending coverage to four simultaneous bands on a low-cost substrate has not been previously demonstrated in the compared literature. The multi-band entries in references [2], [5], and [6] remain below 7 GHz and use physically larger apertures. A further distinguishing feature of the

to 2.5 GHz at 34.6 GHz, which benefits wideband communication systems requiring stable impedance matching across multiple operating bands requiring stable impedance matching across an appreciable instantaneous bandwidth at each operating frequency.

7. Conclusions

This paper has presented the design and comprehensive simulation analysis of a CPW-fed circular patch antenna with strip-line feed, modelled on FR4 substrate and achieving four-band resonance at 5.5 GHz (C-band), 16.7 GHz (Ku-band), 26.3 GHz (Ka-band / 5G mmWave), and 34.6 GHz (Ka-band). The following key conclusions are drawn:

- The proposed configuration (strip on left, left semi-circular ground slot, FR4 at 1.6 mm) achieves four resonance bands with bandwidths of 1.2, 1.7, 2.0, and

2.5 GHz, covering frequency bands associated with C-band, Ku-band, and Ka-

Table 3. Comparison of proposed antenna with recently published multi-band designs

Ref.	Radiator Shape / Structure	Substrate	Size (mm ²)	Resonance Frequencies	Bands	Application
[1]	Slot Antenna	FR4 (4.3)	20×30	3.6 GHz	1	5G sub-6 GHz
[2]	MIMO	FR4 (4.3)	150×70	3.5, 5.0 GHz	2	5G MIMO
[3]	Microstrip Patch	FR4 (4.3)	27×26	4.29, 77 GHz	2	5G/6G
[4]	Reconfigurable mmWave	RT/Duroid	30×23	27 GHz	1	5G mmWave
[5]	Cactus-Shaped	FR4 (4.3)	21×29	3.5, 4.8, 5.8 GHz	3	5G/WLAN
[6]	Two-Port MIMO	RT/Duroid	56.4×36.6	3.4, 4.9, 6.98 GHz	3	5G/6G MIMO
[8]	Slot Antenna	FR4 (4.3)	30×30	4.9 GHz	1	5G sub-6 GHz
[10]	Multi-Slotted	RT/Duroid	53×20	28 GHz	1	5G mmWave
Proposed	Circular Patch	FR4 (4.3)	20×20	5.5, 16.7, 26.3, 34.6 GHz	4	C, Ku, Ka-Band

proposed design is the progressive bandwidth growth from 1.2 GHz at 5.5 GHz

band wireless communication systems.

- The parametric substrate study confirms that Rogers RT ($\epsilon_r = 2.2$) provides the widest Ka-band bandwidth while FR4 offers the best overall cost-performance trade-off for the proposed design.
- The strip-on-left configuration achieves the strongest Ku-band resonance depth (approximately -53 dB at 16.7 GHz) and consistent four-band S11 performance, outperforming the centre-strip baseline. The simulated peak gain values are 7.0 dBi, -0.6 dBi, 1.7 dBi, and 0.5 dBi at the four operating bands, respectively. Furthermore, VSWR values remain below 1.17 across all operating frequencies, satisfying the $VSWR \leq 2$ acceptance criterion and confirming good impedance matching.
- The left-edge semi-circular ground slot produces the deepest Ka-band resonance (approximately -52 dB near 25.5 GHz) and is selected for the optimised design.
- Radiation pattern analysis confirms broadside radiation at 5.5 GHz, higher-order multi-lobe distributions at 16.7 GHz, and progressively complex distributed patterns at the Ka-band frequencies, with spatial complexity increasing with frequency as expected for an electrically larger aperture.

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Ethical Statement

This study does not contain any studies with human or animal subjects performed by any of the authors.

Conflicts of Interest

The authors declare that they have no conflicts of interest to this work.

Data Availability Statement

The data that support the findings of this study are available upon reasonable request from the corresponding author.

Author Contribution Statement

Ujjwal Raghav: Conceptualization, Methodology, Formal analysis, Resources, Data curation, Writing — original draft, Writing — review & editing, Visualization. Kaushal Kumar: Software, Simulation, Validation, Investigation. Manish Kumar, Sandeep Kumar Singh: Supervision, Project administration, Writing — review & editing.

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Enhanced Power Generation in Lithium-Doped Tantalum Oxide Hydroelectric Cell

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Abstract

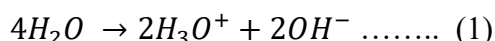
The global green energy demand has led to the development of the Hydroelectric cell (HEC). It is a device that generates electricity through water dissociation on oxygen deficient nanoporous metal oxide surfaces. The dissociation of water produces hydronium and hydroxide ions which undergo electrochemical reactions at the electrodes, generating emf and current. This study investigates the performance of pristine and lithium doped tantalum oxide based HEC. Experimental results demonstrate that doping Ta₂O₅ with lithium significantly enhances current and power output compared to the undoped sample. The pure Ta₂O₅ based HEC produced a short circuit current (I_{sc}) of 0.3 mA and an open circuit voltage (V_{oc}) of 1.23 V compared to the Li doped Ta₂O₅ HEC. It exhibited a substantially higher short circuit current of 2.4 mA and an open circuit voltage of 0.966 V. The doped sample based HEC delivered a power output of ~ 0.25 mW in comparison to the undoped sample which delivered a maximum power output of ~ 0.074 mW. Electrochemical impedance spectroscopy (EIS) revealed that lithium doping reduced the charge transfer resistance and promoted ionic conduction in the doped sample, as evidenced by the extended Warburg diffusion tail in the Nyquist plot. Lithium doping facilitated more efficient water dissociation and ion transport in the sample. The increase power output in the Li doped sample has been attributed to the increased oxygen vacancies, surface defects and nano porosity induced by lithium.

Keywords: Ta₂O₅, Water splitting, Oxygen vacancies, Green energy, HEC.

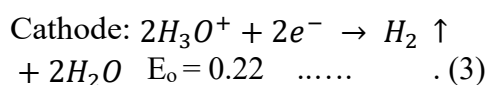
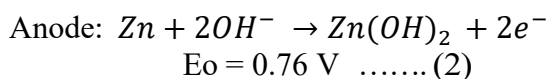
1. Introduction: The fast depletion of fossil fuels and the current climate change scenario have created an urgent need for clean and sustainable energy technologies.

Among emerging technologies, the Hydroelectric cell (HEC) has attracted considerable attention as a green energy device. The nano porous, oxygen deficient

surface of the HEC material spontaneously dissociates water molecules at room temperature without using any acid/alkali or photons [1–4]. Unlike conventional fuel cells or electrolyzers, HECs exploit the simple oxides materials to spontaneously dissociate water molecules on the material surface. Hence HEC offers a pathway for low cost and catalyst free energy generation. The basic principle involves the dissociation of water molecules into H_3O^+ and OH^- ions on the defective surface of the material.



The trapped protons in the nanopores generate strong electric fields of the order of 10^4 V/cm which is sufficient enough to dissociate water molecules in the physisorbed layers over the material surface. The hydroxide ions migrate towards zinc electrode where they are oxidized to form zinc hydroxide. On the other hand, the dissociated hydronium ions in the physisorbed layers migrate towards the silver cathode where they are reduced to hydrogen gas. These electrochemical reactions at electrodes establishes a potential difference across the cell as depicted in the equations below [5–7].



Thus, a Hydroelectric cell delivers an EMF of 0.98 V (0.76V + 0.22 V). The current

generation in Hydroelectric cell critically depends on the defect concentration, importantly the number of oxygen vacancies and the ionic conductivity of the oxide material [8]. Consequently, the enhancement in the defect density and porosity in the oxide material under study directly affect the performance of the Hydroelectric cell with the improved power density.

Tantalum oxide (Ta_2O_5) is a wide bandgap (3.8-4.5 eV) transition metal oxide with excellent chemical stability, environmental inertness and prominent ionic conductivity [9,10]. The open crystal framework and tendency to accommodate dopants in the lattice interstitials make it a potential candidate for water splitting and hence energy production as Hydroelectric cell. However, the pure tantalum oxide is known to have low defect density which limits the dissociation of water on its surface. Lithium doping has been widely reported in metal oxide systems to tailor defect chemistry of the lattice. In case of Ta_2O_5 the substitution of Li^+ for Ta^{5+} creates charge imbalance in the lattice. This charge imbalance is then compensated by the formation of oxygen vacancies. The smaller ionic radius of Li^+ introduces lattice strain that is supposed to increase porosity of the sample and hence the surface area [11]. These structural and chemical modifications are expected to enhance the performance of tantalum oxide based HECs.

Despite the extensive literature on doped metal oxide based HECs, like zinc oxide [12,13], titanium oxide [4], iron oxide [14,15] nickel ferrite [16,17] etc., tantalum oxide based HECs have not been reported so far. The present work addresses this gap by the study of pure and lithium doped tantalum oxide. The hydroelectric cells from both doped and undoped tantalum oxides were fabricated. A comprehensive electrochemical characterization, including voltage-current polarization curves and

electrochemical impedance spectroscopy was performed. The superior performance of the doped sample has been systematically linked to enhanced oxygen vacancy, increased nano porosity and improved ionic conductivity of the lattice arising from lithium doping.

2. Materials and Methods: Synthesis of pure and Li doped tantalum oxide: Pure tantalum oxide was synthesized by the solid-state method. For this Ta_2O_5 was purchased from Thermo Fischer Chemicals (99.9 % purity). 2 g of Ta_2O_5 was hand grinded in a pestle and mortar using acetone solvent, for 30 minutes. Another sample was prepared with 40 wt% lithium doping in Ta_2O_5 . For this, 1.98 g of Li_2CO_3 (Speck pure, 99 % purity) was added to 1.2 g of Ta_2O_5 and it was also hand grinded in a similar manner. After grinding, both samples were presintered at 850 °C for 6 hours. After cooling, the samples were again grinded and pressed in the shape of circular pellets having diameter of 1.2 cm, using a hydraulic press. These pellets were then sintered at 950 °C for 4 hours, and later used for fabricating hydroelectric cells.

2.1 Hydroelectric Cell Fabrication: Hydroelectric cells were assembled by adding a zinc sheet at one face of the pellet as anode, while at the other face silver was comb patterned as cathode. The pristine tantalum oxide sample was labelled as PTO and the lithium doped tantalum oxide

contacts were made at both electrodes for measuring the device's power response.

2.1 Electrochemical Characterization: Voltage-current (V-I) characteristics were recorded using a potentiostat (Keithley 2430 1 kW pulse source meter) by varying the load across the HECs and measuring the voltage drop with increasing cell current. Power ($P = V \times I$) was computed from the measured V-I data. Electrochemical impedance spectroscopy (EIS) was performed using a Wayne-Kerr Impedance Analyzer 6500B over a frequency range of 20 Hz to 120MHz with an AC perturbation amplitude of 25 mV. Nyquist plots were analyzed to extract the series resistance (R_s), charge transfer resistance (R_{ct}) and Warburg diffusion (W).

3. Results and Discussion:

3.1 V-I Polarization Characteristics

Figure 1 represents the V-I polarization curves and corresponding power curves for both pure and doped tantalum oxide based Hydroelectric cells. The pure Ta_2O_5 cell exhibited an open circuit potential (V_{oc}) of 1.23 V and a short circuit current (I_{sc}) of ~0.30 mA. The cell delivered a maximum power output (P_{max}) of approximately 0.074 mW. In contrast, the lithium doped cell delivered an open circuit potential (V_{oc}) of 0.97 V and a substantially increased short circuit current of I_{sc} of ~2.4 mA. The doped cell achieved a P_{max} of approximately 0.25

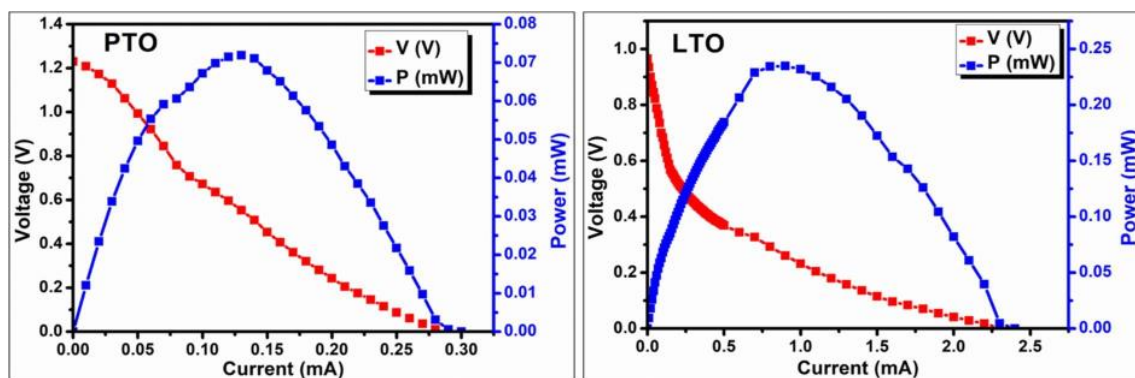


Figure 1: V-I (red) and power-current (blue) characteristics of (left) pure tantalum oxide and (right) lithium doped tantalum oxide based Hydroelectric cells

powder was labelled as LTO. Electrical

mW. Approximately a 3.4 fold increase in

peak power output was obtained upon lithium doping.

The V-I curves for both samples showed the Hydroelectric cell characteristic, reflecting the water dissociation on material surface and electrochemical reactions at the electrode interfaces [18]. The significantly

HECs in the range of 20-120 MHz. The EIS spectra provided a critical insight into the resistance and ionic transport properties of both the samples. The spectra showed significant difference between their electrochemical performances.

The Nyquist plot of pure tantalum oxide

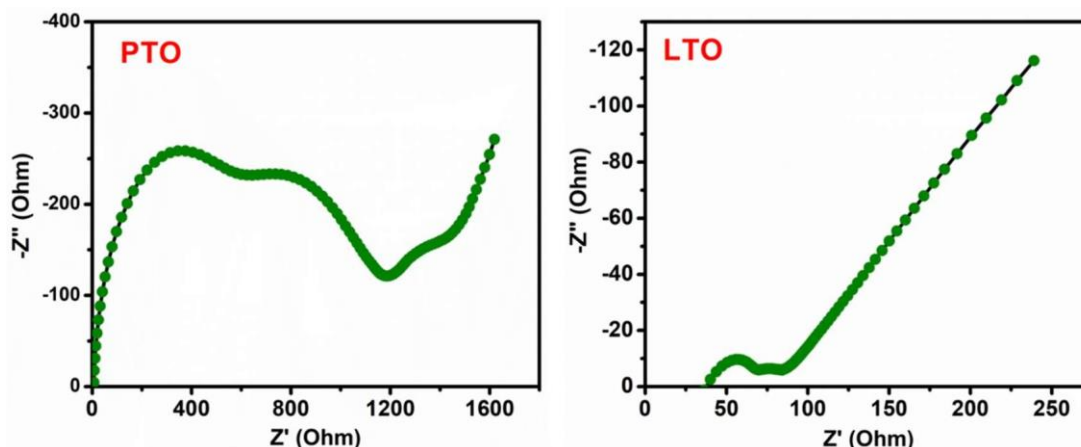


Figure 2: Nyquist plots (EIS) of pure tantalum oxide (at left) and lithium doped tantalum oxide (at right) based Hydroelectric cells, frequency range: 20 Hz to 200 MHz.

higher short circuit current in lithium doped tantalum oxide is indicative of a greatly enhanced water dissociation and ion transport in the material. The slight reduction in open circuit potential of the doped sample in comparison to the pure (~ 0.97 V vs. 1.23 V) was compensated by the gain in current, resulting in the effective improvement in power output. Table 1 summarizes the key performance parameters obtained from both HECs.

Table 1: Current, voltage and power output of pure and lithium doped tantalum oxide based Hydroelectric cells

	Current (mA)	Voltage (V)	Power (mW)
Pure Ta_2O_5	0.3	1.23	0.369
Li doped Ta_2O_5	2.4	0.966	2.318

3.2 Electrochemical Impedance Spectroscopy

Figure 2 represents the Nyquist plots obtained for pure and doped samples based

displayed a broad, depressed semicircular arc spanning approximately 0-1600 Ω along the real impedance axis (Z'), with a peak imaginary impedance ($-Z''$) of about 250 Ω . The shape showed by the pure sample based HEC is characteristic of overlapping RC time constants associated with grain, grain boundary resistance and charge transfer resistance dielectric relaxation within the oxide matrix. The high impedance magnitude at low frequency (~ 1600 Ω) confirmed that the undoped sample offers significant resistance to both electronic and ionic transport. In contrast, the Nyquist spectrum of lithium doped tantalum oxide was dramatically compressed along the Z' axis (0-250 Ω), indicating a significant reduction in total impedance. The small, high frequency semicircle ($Z' \approx 40-90$ Ω) represents grain/grain-boundary resistance and charge transfer processes at the electrode electrolyte interface. The prominent, near linear, low frequency tail extending steeply is representative of Warburg diffusion [19,20]. The Warburg element arises from semi-infinite diffusion of hydronium (H_3O^+) and hydroxide (OH^-)

ions through the nanoporous oxide. Its pronounced character in the doped sample is a direct consequence of the enhanced porosity and interconnected pore network introduced by lithium doping. The steep Warburg tail is consistent with diffusion controlled ion transport within a confined porous structure, indicative of capacitive behavior at the electrode electrolyte interface [21]. The reduced R_s and R_{ct} values in the doped sample, extracted from the high frequency intercept and semicircle diameter respectively, confirmed that lithium doping substantially reduced both bulk resistance and interfacial charge transfer barriers. The lower resistance facilitated faster and more efficient migration of dissociated hydronium and hydroxide ions through the sample pellet leading to 8 fold increase in short circuit current and the ~ 3.4 fold increase in maximum power as observed in the V-I measurements.

Oxygen vacancies are the primary active sites for water adsorption and its chemi-dissociation on material surface [1,22]. The substitution of Li^+ on a Ta^{5+} site introduced negative effective charges that were compensated by the formation of oxygen vacancies. These defect sites strongly adsorbed water molecules and promoted its dissociation into H_3O^+ and OH^- . The higher oxygen vacancy in the doped sample, therefore directly amplified the rate of water splitting and hence, increasing the current generation. Surface defects, including grain boundaries and under coordinated surface Ta sites, introduced additional centers for water adsorption. The nanoporosity of the oxide material is a further critical parameter governing HEC performance [23,24]. During the calcination of the Li-doped precursor, the decomposition of Li_2CO_3 forms Li_2O and CO_2 gas is released that creates a network of nanopores within the Ta_2O_5 lattice. This nanoporous structure dramatically increased the specific surface area available for water interaction, while simultaneously providing ionic diffusion

pathways responsible for the extended Warburg tail in the doped Nyquist spectrum. The combination of higher surface area, greater oxygen vacancy density, and improved ionic conductivity collectively amplifies the overall HEC output in LTO.

4. Conclusions:

This study has demonstrated that lithium doping of tantalum oxide markedly enhances the performance of hydroelectric cells. The LTO HEC delivered a short-circuit current of 2.4 mA and a peak power of ~ 0.25 mW, representing improvements of approximately 8-fold and 3.4-fold respectively over the pristine PTO device. EIS analysis confirmed that lithium doping reduces bulk and charge-transfer resistance and promotes extensive Warburg type ionic diffusion, indicative of a highly porous, ionically conducting oxide matrix. The enhanced performance of LTO is attributed to increased oxygen vacancy defects that act as active sites for water dissociation, and also facilitating faster interfacial charge transfer. The enhanced nano porosity provided a large surface area and efficient ion transport pathways for H_3O^+ and OH^- ion migration. These findings establish Li doped Ta_2O_5 as a promising material for improving water-splitting in hydroelectric cells.

Acknowledgement

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Conflict of Interest

There is

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