A comprehensive review on different types of fuel cell and its applications

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ABSTRACT

This review article provides an overview of various types of fuel cells that are currently being researched and developed. Fuel cells are electrochemical devices that convert chemical energy directly into electrical energy, making them a promising technology for clean and efficient energy production. The review covers the principles of operation and key characteristics of proton exchange membrane fuel cells (PEMFCs), solid oxide fuel cells (SOFCs), alkaline fuel cells (AFCs), direct methanol fuel cells (DMFCs), and microbial fuel cells (MFCs). The article also discusses the advantages and limitations of each type of fuel cell, as well as the current research and development efforts aimed at improving their performance and reducing their costs. Overall, this review provides a comprehensive understanding of the various types of fuel cells and their potential applications in the field of energy production.

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1. INTRODUCTION

Fuel cells are electrochemical devices that convert the chemical energy of a fuel into electrical energy, with only water and heat as by-products. They are considered one of the most promising technologies for clean and efficient energy production [1]–[3]. It then describes in detail the different types of fuel cells, including polymer electrolyte membrane fuel cells (PEMFCs), solid oxide fuel cells (SOFCs), alkaline fuel cells (AFCs), direct methanol fuel cells (DMFCs), and phosphoric acid fuel cells (PAFCs). For each type of fuel cell, the article provides information on its working principle, vantages, and limitations [4]–[6]. This discusses the applications of fuel cells in various sectors, including transportation, stationary power generation, portable power, and military and aerospace applications. It highlights the benefits of using fuel cells in these sectors, such as reduced emissions, improved efficiency, and increased energy security [7], [8].

In recent years, there has been a significant amount of research and development in the field of fuel cells, leading to the discovery of various types of fuel cells [9]. This literature survey provides an overview of various types of fuel cells, their principles of operation, and their potential applications. They are considered one of the most promising technologies for clean and efficient energy production [10]. PEMFCs are a type of fuel cell that uses a polymer electrolyte membrane to conduct protons from the anode to the cathode. Proton exchange membrane fuel cells (PEMFCs) have a high power density, low operating temperature, and are ideal for portable and transportation applications [11], [12]. In the recent advances in PEMFCs, including the development of new materials, membrane electrode assemblies, and catalysts, and their impact on the performance of PEMFCs.

SOFCs are a type of fuel cell that uses a solid oxide electrolyte to conduct oxygen ions from the cathode to the anode. SOFCs have a high efficiency, can operate at high temperatures, and are ideal for stationary power generation applications [10], [13]. In recent advances in SOFCs, including the development of new materials, cell design, and system integration, and their impact on the performance of SOFCs. AFCs are a type of fuel cell that uses an alkaline electrolyte to conduct hydroxide ions from the cathode to the anode [14]. AFCs have a high efficiency, can use a wide range of fuels, and are ideal for space and underwater applications [15]. The AFCs, including the development of new materials, electrode structures, and catalysts, and their impact on the performance of AFCs [16].

DMFCs are a type of fuel cell that uses methanol as a fuel and a proton exchange membrane as an electrolyte [17], [18]. DMFCs have a high energy density, low operating temperature, and are ideal for portable and transportation applications. Microbial fuel cells (MFCs) are a type of fuel cell that uses microorganisms to generate electrical energy from organic matter [19]. MFCs have a low power density, but can use a wide range of fuels and have potential applications in wastewater treatment and bio-energy production [16]. Recent advances in MFCs, including the development of new materials, electrode designs, and system integration, and their impact on the performance of MFCs [20]. Overall, this literature survey highlights the significant progress made in the development of various types of fuel cells and their potential applications in the field of energy production. Further research is needed to improve their performance and reduce their costs, making them more accessible for commercial applications.

2. CLASSIFICATIONS OF FUEL CELLS

2.1. Proton exchange membrane fuel cells

PEMFCs are a type of fuel cell that uses a polymer electrolyte membrane to conduct protons from the anode to the cathode. PEMFCs have a high power density, low operating temperature, and are ideal for portable and transportation applications [21]. In PEMFCs, hydrogen gas is fed to the anode, where it is split into protons and electrons. The protons are conducted through the polymer electrolyte membrane to the cathode, while the electrons flow through an external circuit, generating electrical power. At the cathode, the protons combine with oxygen to form water [22].

PEMFCs have several advantages, including high efficiency, low emissions, and fast start-up times. They are also lightweight and compact, making them ideal for use in vehicles and portable electronic devices [23]. However, they have some limitations, including high costs and sensitivity to impurities, which can reduce their performance. Research is ongoing to improve the performance and reduce the costs of PEMFCs. This includes the development of new materials, such as alternative catalysts, membranes, and electrode structures, as well as advances in system integration and control strategies [24], [25].

2.2. Solid oxide fuel cells

Solid oxide fuel cells are a type of fuel cell that uses a solid oxide electrolyte to conduct oxygen ions from the cathode to the anode. SOFCs have a high efficiency, can operate at high temperatures, and are ideal for stationary power generation applications. SOFCs are a type of fuel cell that uses a solid oxide electrolyte to conduct oxygen ions from the cathode to the anode. SOFCs have a high efficiency, can operate at high temperatures, and are ideal for stationary power generation applications.

In SOFCs, a fuel gas, such as hydrogen or natural gas, is fed to the anode, where it reacts with oxygen ions from the cathode to produce electricity, heat, and water. The heat generated can be used for cogeneration or other industrial processes, making SOFCs highly efficient. SOFCs have several advantages, including high efficiency, low emissions, and the ability to use a variety of fuels, including biomass and biogas. They also have a long lifespan, with some cells operating for over 10 years. However, they have some limitations, including high operating temperatures, which can lead to thermal stress and reduce their lifespan. These include the development of new materials, such as alternative electrolytes and electrodes, advances in cell and stack design, and improvements in system integration and control strategies [26].

2.3. Alkaline fuel cells

AFCs are a type of fuel cell that uses an alkaline electrolyte, typically potassium hydroxide (KOH), to conduct ions from the anode to the cathode. AFCs have a high efficiency and a long lifespan, but they are typically used in specialized applications such as spacecrafts and submarines due to their sensitivity to carbon dioxide and other impurities. In AFCs, hydrogen gas is fed to the anode, where it is split into protons and electrons. The protons are conducted through the alkaline electrolyte to the cathode, while the electrons flow through an external circuit, generating electrical power. At the cathode, the protons combine with oxygen to form water [27].

AFCs operate at a relatively low temperature compared to other fuel cells, typically around 70 to 90 degrees celsius, but they require high-purity hydrogen and oxygen to operate efficiently. Impurities in the fuel can lead to degradation of the electrolyte and reduced performance. AFCs have several advantages, including high efficiency, fast reaction rates, and a long lifespan. They also have the potential for low costs due to the use of inexpensive materials and the possibility of recycling the electrolyte. However, they have some limitations, including sensitivity to impurities and the need for high-purity reactants.

2.4. Direct methanol fuel cells

DMFCs are a type of fuel cell that uses methanol as the fuel and a proton exchange membrane (PEM) as the electrolyte. DMFCs have a high energy density, are easy to handle and store, and have the potential to be used in portable electronic devices. In DMFCs, methanol is fed to the anode, where it is oxidized by a catalyst to produce protons, electrons, and carbon dioxide. The protons are conducted through the PEM to the cathode, while the electrons flow through an external circuit, generating electrical power. At the cathode, oxygen is reduced to form water. The overall reaction in a DMFC can be expressed as (1):

$$CH3OH + 1.5O2 \rightarrow CO2 + 2H2O \quad (1)$$

DMFCs have several advantages, including high energy density, low emissions, and ease of handling and storage. They also have a relatively simple design, with no need for an external reformer to convert the fuel into hydrogen [28]. However, they have some limitations, including low efficiency and slow reaction rates, which can reduce their performance. Research is ongoing to improve the performance and reduce the costs of DMFCs. This includes the development of new materials, such as alternative catalysts and membranes, and advances in system integration and control strategies. One approach is to improve the performance of the catalysts used in DMFCs, which can increase the rate of the methanol oxidation reaction and improve the efficiency of the cell. Another approach is to optimize the design of the fuel cell, such as the flow channels and the membrane electrode assembly, to improve the performance and reduce the costs of the cell [29].

2.5. Microbial fuel cells

MFCs that uses microorganisms to generate electricity by oxidizing organic matter. MFCs have the potential to be used for wastewater treatment, bio-energy production, and other applications that involve the use of organic matter. In MFCs, microorganisms, typically bacteria are attached to an electrode surface or suspended in a solution between two electrodes. The microorganisms oxidize organic matter, such as wastewater or organic waste, and transfer electrons to the anode, where they are collected and conducted through an external circuit to the cathode, generating electrical power. At the cathode, oxygen is reduced to form water. The overall reaction in an MFC can be expressed as (2):

$$Organic\ matter + O2 \rightarrow CO2 + H2O + electricity \quad (2)$$

MFCs have several advantages, including the ability to use a variety of organic matter as fuel, low emissions, and the potential for wastewater treatment and energy recovery. They also have a relatively simple design, with no need for expensive catalysts or high-purity reactants. However, they have some limitations, including low efficiency and slow reaction rates, which can reduce their performance.

Research is ongoing to improve the performance and reduce the costs of MFCs. This includes the development of new materials, such as alternative electrodes and membranes, and advances in system integration and control strategies. One approach is to improve the performance of the microbial communities used in MFCs, such as through the use of genetically modified bacteria or the addition of co-cultures to improve electron transfer. Another approach is to optimize the design of the MFC, such as the geometry and spacing of the electrodes, to improve the performance and reduce the costs of the cell.

3. RESULTS AND DISCUSSION

Fuel cells are a promising technology for generating electricity in a clean and efficient manner. Different types of fuel cells have been developed over the years, each with its own unique features and operating characteristics. In this analysis, we compare the performance of seven types of fuel cells based on their operating conditions, fuel, efficiency, power density, and cost, which is discussed in Table 1.

PEMFCs have high power density and efficiency, and are suitable for low-temperature applications. However, they are expensive due to the use of platinum catalysts, and the durability of the membranes can be a challenge. SOFCs have high efficiency and can use a variety of fuels, including natural gas and biogas. They are suitable for high-temperature applications, but can be expensive and require complex manufacturing processes.

Table 1. Comparison of different types of fuel cells

Type of fuel cell	Electrolyte	Operating temperature (°C)	Fuel	Efficiency (%)	Power density (W/cm²)	Cost
PEMFC	Polymer electrolyte membrane	60-100	Hydrogen	Up to 60	Up to 4	High
SOFC	Ceramic electrolyte	500-1000	Hydrogen, natural gas, biogas	Up to 60	Up to 1.5	High
AFC	Alkaline electrolyte	70-90	Hydrogen	Up to 70	Up to 0.5	High
DMFC	Polymer electrolyte membrane	60-120	Methanol	Up to 40	Up to 0.5	Moderate
PAFC	Phosphoric acid electrolyte	150-200	Hydrogen, natural gas, and biogas	Up to 50	Up to 0.5	Moderate
Molten carbonate fuel cell (MCFC)	Molten carbonate electrolyte	600-700	Natural gas and biogas	Up to 50	Up to 1	High
MFC	Organic matter	Room temperature	Organic matter	Up to 80	Up to 0.05	Low

AFCs have high efficiency and can use hydrogen as a fuel. They operate at low temperatures, but the alkaline electrolyte can be corrosive and require careful handling. DMFCs use methanol as a fuel and have moderate efficiency and power density. They can operate at low temperatures and are suitable for portable applications, but can suffer from methanol crossover and poisoning of the catalyst. PAFCs have moderate efficiency and can use a variety of fuels, including natural gas and biogas. They operate at moderate temperatures, but are expensive and can require maintenance due to the use of phosphoric acid electrolyte.

MCFCs can use natural gas and biogas as fuel and have high efficiency. They operate at high temperatures and can generate electricity from waste heat. However, they can be expensive due to the use of high-temperature materials. MFCs use organic matter as a fuel and have high potential for generating electricity from waste streams. They operate at room temperature and have low power density and efficiency, but ongoing research aims to improve their performance.

Overall, each type of fuel cell has its own advantages and disadvantages, and the choice of fuel cell depends on the specific application and operating conditions. Ongoing research is focused on improving the performance and durability of fuel cells to make them more cost-effective and commercially viable. The fuel cell includes various applications like:

a. Transportation: fuel cells are increasingly being used in transportation, particularly in cars, buses, and trucks. They offer high efficiency and low emissions, making them an attractive alternative to traditional internal combustion engines. Hydrogen fuel cell vehicles are already on the market, and ongoing research is focused on improving their performance, reducing costs, and increasing the availability of hydrogen fuelling infrastructure.
b. Stationary power generation: fuel cells can also be used for stationary power generation, providing electricity and heat for residential and commercial buildings, hospitals, and data centres. They are highly efficient and reliable, and can operate independently of the grid, making them ideal for remote locations or in areas with unreliable power supply.
c. Portable devices: fuel cells are increasingly being used in portable devices such as laptops, smart phones, and camping equipment. They offer longer runtimes than traditional batteries and can be recharged quickly.
d. Military applications: fuel cells are used in various military applications, such as in submarines and unmanned aerial vehicles (UAVs). They offer high energy density and longer runtime compared to traditional batteries, making them suitable for long-duration missions.
e. Marine applications: fuel cells are also being used in marine applications such as ships and submarines, as they offer high efficiency and low emissions, reducing the environmental impact of marine transportation.

f. Medical applications: fuel cells are being explored for medical applications such as implantable devices and portable medical equipment. They offer long runtimes and high reliability, making them suitable for use in critical medical applications.

In summary, fuel cells have a diverse range of applications across various sectors, offering high efficiency, low emissions, and reliable power generation. Ongoing research and development efforts are focused on improving their performance, reducing costs, and increasing their commercial viability, to accelerate their adoption as a clean energy technology.

4. CONCLUSION

Fuel cells have emerged as a promising technology for generating clean energy. The different types of fuel cells discussed in this review, including proton exchange membrane fuel cells, solid oxide fuel cells, alkaline fuel cells, direct methanol fuel cells, phosphoric acid fuel cells, molten carbonate fuel cells, and microbial fuel cells, each have unique advantages and disadvantages that make them suitable for specific applications and operating conditions. The applications of fuel cells are diverse and expanding, ranging from transportation to stationary power generation, to portable devices, and even in the field of medicine. They offer a viable alternative to traditional fossil fuel-based power generation, reducing greenhouse gas emissions, and helping to mitigate climate change. However, the widespread adoption of fuel cells is still limited by challenges such as cost, durability, and scalability. Further research and development efforts are needed to improve the performance and reduce the cost of fuel cells, and to increase their commercial viability.

REFERENCES

[1] N. de Miguel, R. O. Cebolla, B. Acosta, P. Moretto, F. Harskamp, and C. Bonato, "Compressed hydrogen tanks for on-board application: Thermal behaviour during cycling," *International Journal of Hydrogen Energy*, vol. 40, no. 19, pp. 6449–6458, May 2015, doi: 10.1016/j.ijhydene.2015.03.035.

[2] O. Dumont, A. Parthoens, R. Dickes, and V. Lemort, "Experimental investigation and optimal performance assessment of four volumetric expanders (scroll, screw, piston and roots) tested in a small-scale organic Rankine cycle system," *Energy*, vol. 165, pp. 1119–1127, Dec. 2018, doi: 10.1016/j.energy.2018.06.182.

[3] B. Somaiah and V. Agarwal, "Distributed Maximum Power Extraction From Fuel Cell Stack Arrays Using Dedicated Power Converters in Series and Parallel Configuration," *IEEE Transactions on Energy Conversion*, vol. 31, no. 4, pp. 1442–1451, Dec. 2016, doi: 10.1109/TEC.2016.2557803.

[4] M. Forouzesh, Y. P. Siwakoti, S. A. Gorji, F. Blaabjerg, and B. Lehman, "Step-Up DC–DC Converters: A Comprehensive Review of Voltage-Boosting Techniques, Topologies, and Applications," *IEEE Transactions on Power Electronics*, vol. 32, no. 12, pp. 9143–9178, Dec. 2017, doi: 10.1109/TPEL.2017.2652318.

[5] V. F. Pires, A. Cordeiro, D. Foito, and J. F. Silva, "High Step-Up DC–DC Converter for Fuel Cell Vehicles Based on Merged Quadratic Boost–Ćuk," *IEEE Transactions on Vehicular Technology*, vol. 68, no. 8, pp. 7521–7530, Aug. 2019, doi: 10.1109/TVT.2019.2921851.

[6] S. B. Mahajan, P. Sanjeevikumar, P. Wheeler, F. Blaabjerg, M. Rivera, and R. Kulkarni, "X-Y converter family: A new breed of buck boost converter for high step-up renewable energy applications," in *2016 IEEE International Conference on Automatica (ICA-ACCA)*, IEEE, Oct. 2016, pp. 1–8, doi: 10.1109/ICA-ACCA.2016.7778458.

[7] C. G. Zogogianni, E. C. Tatakis, and M. S. Vekic, "Non-Isolated Reduced Redundant Power Processing DC/DC Converters: A Systematic Study of Topologies With Wide Voltage Ratio for High-Power Applications," *IEEE Transactions on Power Electronics*, vol. 34, no. 9, pp. 8491–8502, Sep. 2019, doi: 10.1109/TPEL.2018.2889294.

[8] R. Panigrahi, S. K. Mishra, and A. Joshi, "Synthesizing a Family of Converters for a Specified Conversion Ratio Using Flux Balance Principle," *IEEE Transactions on Industrial Electronics*, vol. 68, no. 5, pp. 3854–3864, May 2021, doi: 10.1109/TIE.2020.2984450.

[9] T. Jahnke *et al.*, "Performance and degradation of Proton Exchange Membrane Fuel Cells: State of the art in modeling from atomistic to system scale," *Journal of Power Sources*, vol. 304, pp. 207–233, Feb. 2016, doi: 10.1016/j.jpowsour.2015.11.041.

[10] A. Chapman, K. Itaoka, H. Farabi-Asl, Y. Fujii, and M. Nakahara, "Societal penetration of hydrogen into the future energy system: Impacts of policy, technology and carbon targets," *International Journal of Hydrogen Energy*, vol. 45, no. 7, pp. 3883–3898, Feb. 2020, doi: 10.1016/j.ijhydene.2019.12.112.

[11] H. Homayouni, J. DeVaal, F. Golnaraghi, and J. Wang, "Voltage Reduction Technique for Use With Electrochemical Impedance Spectroscopy in High-Voltage Fuel Cell and Battery Systems," *IEEE Transactions on Transportation Electrification*, vol. 4, no. 2, pp. 418–431, Jun. 2018, doi: 10.1109/TTE.2018.2806090.

[12] J. Liu *et al.*, "PEMFC Residual Life Prediction Using Sparse Autoencoder-Based Deep Neural Network," *IEEE Transactions on Transportation Electrification*, vol. 5, no. 4, pp. 1279–1293, Dec. 2019, doi: 10.1109/TTE.2019.2946065.

[13] B. Tanç, H. T. Arat, E. Baltacıoğlu, and K. Aydın, "Overview of the next quarter century vision of hydrogen fuel cell electric vehicles," *International Journal of Hydrogen Energy*, vol. 44, no. 20, pp. 10120–10128, Apr. 2019, doi: 10.1016/j.ijhydene.2018.10.112.

[14] R. S. Gemmen, "Analysis for the Effect of Inverter Ripple Current on Fuel Cell Operating Condition," *Journal of Fluids Engineering*, vol. 125, no. 3, pp. 576–585, May 2003, doi: 10.1115/1.1567307.

[15] M. Bressel, M. Hilairet, D. Hissel, and B. O. Bouamama, "Remaining Useful Life Prediction and Uncertainty Quantification of Proton Exchange Membrane Fuel Cell Under Variable Load," *IEEE Transactions on Industrial Electronics*, vol. 63, no. 4, pp. 2569–2577, Apr. 2016, doi: 10.1109/TIE.2016.2519328.

[16] S. G. Fernandez *et al.*, "Unmanned and autonomous ground vehicle," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 9, no. 5, pp. 4466–4472, Oct. 2019, doi: 10.11591/ijece.v9i5.pp4466-4472.

[17] L. Barelli, G. Bidini, and A. Ottaviano, "Solid oxide fuel cell modelling: Electrochemical performance and thermal management during load-following operation," *Energy*, vol. 115, pp. 107–119, Nov. 2016, doi: 10.1016/j.energy.2016.08.107.
[18] A. Hagen, R. Barfod, P. V. Hendriksen, Y.-L. Liu, and S. Ramousse, "Degradation of Anode Supported SOFCs as a Function of Temperature and Current Load," *Journal of The Electrochemical Society*, vol. 153, no. 6, pp. A1165–A1171, 2006, doi: 10.1149/1.2193400.
[19] G. Dotelli, R. Ferrero, P. G. Stampino, S. Latorrata, and S. Toscani, "PEM Fuel Cell Drying and Flooding Diagnosis With Signals Injected by a Power Converter," *IEEE Transactions on Instrumentation and Measurement*, vol. 64, no. 8, pp. 2064–2071, Aug. 2015, doi: 10.1109/TIM.2015.2406051.
[20] Q.-A. Huang, R. Hui, B. Wang, and J. Zhang, "A review of AC impedance modeling and validation in SOFC diagnosis," *Electrochimica Acta*, vol. 52, no. 28, pp. 8144–8164, Nov. 2007, doi: 10.1016/j.electacta.2007.05.071.
[21] S. M. R. Niya and M. Hoorfar, "Study of proton exchange membrane fuel cells using electrochemical impedance spectroscopy technique – A review," *Journal of Power Sources*, vol. 240, pp. 281–293, Oct. 2013, doi: 10.1016/j.jpowsour.2013.04.011.
[22] X. Yuan, H. Wang, J. Colinsun, and J. Zhang, "AC impedance technique in PEM fuel cell diagnosis—A review," *International Journal of Hydrogen Energy*, vol. 32, no. 17, pp. 4365–4380, Dec. 2007, doi: 10.1016/j.ijhydene.2007.05.036.
[23] R. Palanisamy, R. Sahasrabuddhe, M. K. Hiteshkumar, and J. A. Puranik, "A new energy regeneration system for A BLDC motor driven electric vehicle," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 11, no. 4, pp. 2986–2993, Aug. 2021, doi: 10.11591/ijece.v11i4.pp2986-2993.
[24] Y. Zhang, H. Liu, J. Li, M. Sumner, and C. Xia, "DC–DC Boost Converter With a Wide Input Range and High Voltage Gain for Fuel Cell Vehicles," *IEEE Transactions on Power Electronics*, vol. 34, no. 5, pp. 4100–4111, May 2019, doi: 10.1109/TPEL.2018.2858443.
[25] P. Ramasamy *et al.*, "Implementation of multicarrier PWM based 7-level Z-source cascaded H-bridge inverter," *International Journal of Power Electronics and Drive Systems (IJPEDS)*, vol. 13, no. 1, pp. 322–329, Mar. 2022, doi: 10.11591/ijpeds.v13.i1.pp322-329.
[26] J. Li and J. Liu, "A Novel Buck–Boost Converter With Low Electric Stress on Components," *IEEE Transactions on Industrial Electronics*, vol. 66, no. 4, pp. 2703–2713, Apr. 2019, doi: 10.1109/TIE.2018.2847646.
[27] X. Liu, H. Li, and Z. Wang, "A Fuel Cell Power Conditioning System With Low-Frequency Ripple-Free Input Current Using a Control-Oriented Power Pulsation Decoupling Strategy," *IEEE Transactions on Power Electronics*, vol. 29, no. 1, pp. 159–169, Jan. 2014, doi: 10.1109/TPEL.2013.2251004.
[28] X. Zhao, L. Zhang, R. Born, and J.-S. Lai, "Solution of input double-line frequency ripple rejection for high-efficiency high-power density string inverter in photovoltaic application," in *2016 IEEE Applied Power Electronics Conference and Exposition (APEC)*, IEEE, Mar. 2016, pp. 1148–1154, doi: 10.1109/APEC.2016.7468014.
[29] P. Ramasamy *et al.*, "Simulation of 3D-space vector modulation for neutral point clamped inverters," *Bulletin of Electrical Engineering and Informatics*, vol. 12, no. 2, pp. 719–726, Apr. 2023, doi: 10.11591/eei.v12i2.4502.

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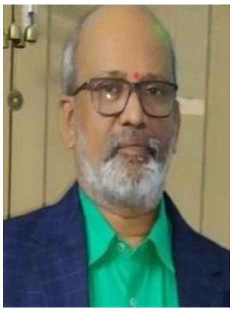

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