iJRASET
International Journal For Research in Applied Science and Engineering Technology



INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 14 **Issue:** IV **Month of publication:** April 2026

DOI: https://doi.org/10.22214/ijraset.2026.80765

www.ijraset.com

Call: 08813907089 | E-mail ID: ijraset@gmail.com

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 14 Issue IV Apr 2026- Available at www.ijraset.com

Green Advancements in Adipic Acid Synthesis: From Petrochemical Routes to Circular Bioeconomy Strategies

Sanjay Patil[1], R. P. Patil[2]
[1]*Assistant Professor, New Horizon Institute of Technology and Management, Thane, India*
[2]*Assistant Professor, A. C. Patil College of Engineering, Kharghar, Navi Mumbai, India*

Abstract: ***Adipic acid, an important industrial chemical with an annual production of more than 3 million tons can be produced by the nitric acid oxidation of cyclohexane derivatives (KA-oil) . This conventional method uses corrosive reagents and produces significant emissions of nitrous oxide (N_2O). This review looks at innovative, eco-friendly routes for the production of adipic acid. These include advanced catalytic techniques like paired electrolysis and photocatalysis , as well as bio-based pathways using renewable feedstocks including guaiacol, catechol, lignin, and furan derivatives. Under mild conditions, bio-based pathways—especially those using modified Escherichia coli and Pseudomonas putida—show promise for converting aromatics generated from lignin. Moreover, novel photo-electro-catalytic systems and heterogeneous catalytic oxidations with molecular oxygen provide ways to replace nitric acid while preserving or increasing efficiency. This review highlights the transition from petrochemical route to renewable, low-emission pathways and represents important research goals for moving sustainable adipic acid production towards commercial feasibility.***

Keywords: Adipic acid; Green chemistry; Bio-based synthesis; Catalytic oxidation; Photocatalysis; Electrocatalysis; Sustainable processes.

I. INTRODUCTION

Adipic acid (HOOC-$(CH_2)_4$-COOH), a key component in the chemical industry, has an annual manufacturing capacity of more than 3 million metric tons worldwide. About 90% of its use comes from the production of nylon-6,6, which is its main application [1]. The manufacturing of plasticizers, food additives, and polyurethanes are some other important applications. However, a move toward sustainable alternatives has become significant due to the environmental impact of the conventional petrochemical pathway, which is marked by significant emissions of greenhouse gases and generation of toxic waste [2].

N_2O gas has contributed to global warming about three hundred times that of CO_2, and is naturally produced by the oxidation of cyclohexane, which is the basis of the typical industrial procedure [1, 3]. As a result, research has diverged into two primary areas: (i) bio-based routes that leverage renewable biomass and engineered microbial strains, and (ii) advanced catalytic methods that make use of benign oxidants like O_2 or H_2O_2 [2, 4]. Advanced methods such as photocatalytic coupling and paired electrolysis have been developed recently between 2020 and 2026, further separating the generation of adipic acid from traditional nitric acid chemistry [8, 14, 16].

II. MATERIALS AND METHODS

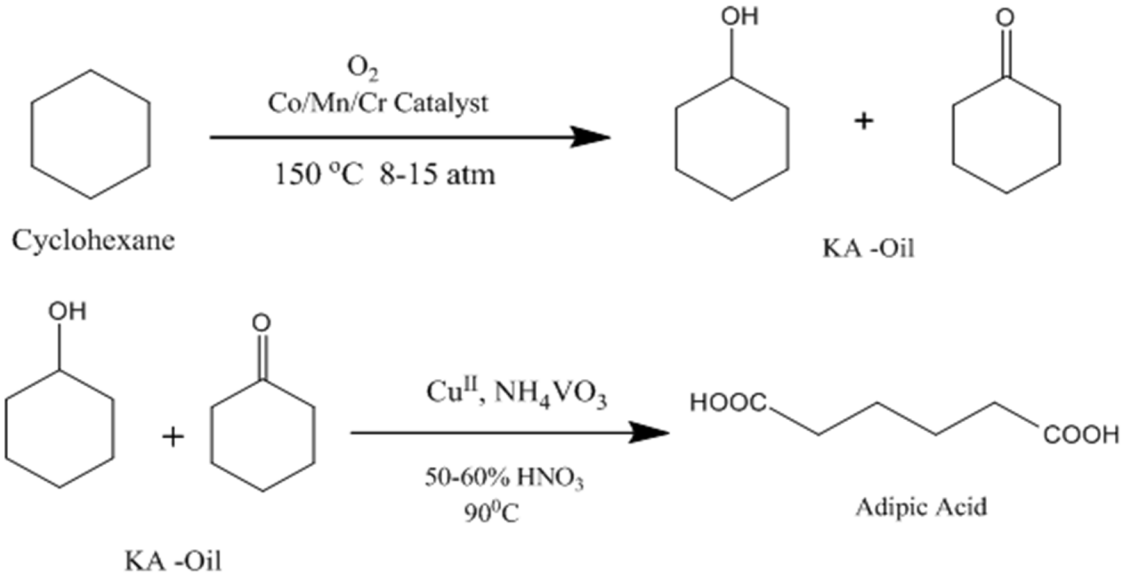
The technical approaches for adipic acid production have undergone tremendous change from corrosive,high-pressure petrochemical synthesis to renewable,mild biotransformations and energy-driven catalytic systems.This section explains the experimental materials and methods from historical benchmarks to cutting-edge research (2020–2026), used in 20 critical references.

A. Traditional Chemical methods (The KA-Oil Route)

This route involves two stage oxidation of cyclohexane. The first step is air-oxidation of cyclohexane , this method uses catalyst such as cobalt or manganese naphthenate at 150–160°C and 8–15 bar of pressure to produce KA-oil (cyclohexanol and cyclohexanone) .This step typically operates at low conversion(4–6%) to maintain selectivity [1, 2]. In the second step the resultant cyclohexanol and cyclohexanone is reacted with concentrated nitric acid (50–60%) oxidation using copper (II) and vanadium (V) catalysts at temperature 60–80°C. This process also produces stoichiometric N_2O and is characterized by high operational severity [1, 3].

©IJRASET: All Rights are Reserved

Figure 1: Conventional route for adipic acid synthesis (KA-oil process)



The main source of industrial N_2O emissions is the nitric acid oxidation stage, which produces about 0.3 kg of N_2O per kg of adipic acid [1].Despite the use of abatement technologies, the process remains energy-intensive and produces acidic waste that require treatment [3]. Cyclohexane raw material is mostly prepared industrially from benzene which is carcinogenic & having significant environmental impact. These issues encourage the search for greener methods that use safer chemicals and renewable raw materials.

B. Greener Pathway

1) Biocatalytic methods

The bio-based approaches makes use of engineered microorganisms, especially *Pseudomonas putida* and *Escherichia coli*.In this method carbon sources include renewable feedstocks like glucose, guaiacol, and catechol are used .Genetic modification can be done by the shikimate pathway or aromatic degradation pathways are installed using Techniques like CRISPR/Cas9 and heterologous gene expression.Fermentation done under fed-batch fermenters, microbes are usually cultivated at 30–37°C under aerobic or micro-aerobic conditions. For example, Suitor et al. (2020) used whole-cell catalysts and engineered E. coli to convert guaiacol in a one-pot system [8]. Separation methods include solvent extraction (e.g., using ethyl acetate),acidification and recrystallization to isolate high-purity adipic acid or its precursors like muconic acid [6, 11].

Bio-based routes make use of renewable feedstocks made from biomass, like sugars and lignocellulosic waste . These pathways are designed to reduce dependence on fossil carbon and eliminate direct N_2O emissions [5, 6].

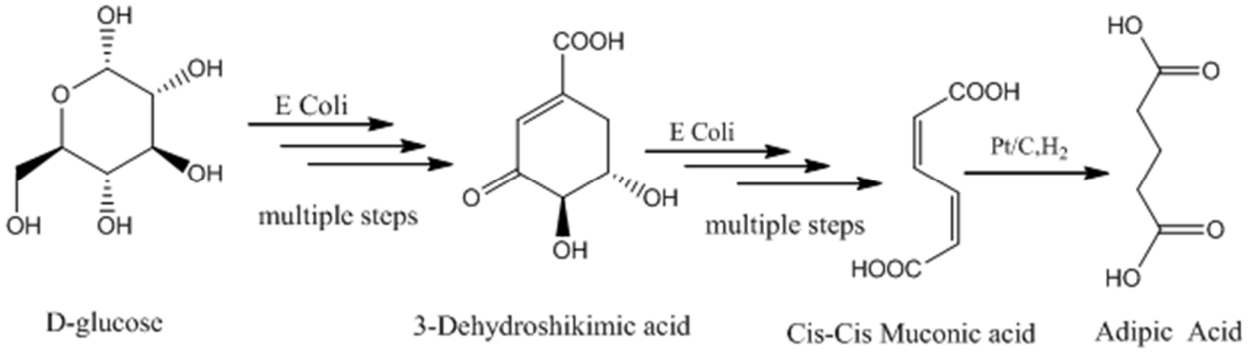
Whole-cell and fermentative biocatalysis

Catalytic hydrogenation after glucose is converted to cis,cis-muconic acid is still a common method [6, 7]. However, current study has focused on lignin-derived aromatics. Suitor et al. (2020) demonstrated a synthesis of adipic acid from green feed stock like guaiacol utilizing a modified Escherichia coli system, accomplishing conversion under mild reaction conditions without the using external reagents [8]. Similarly, Kruyer et al. (2020) used catechol dioxygenase and muconic acid reductase to generate adipic acid from catechol [9].

Pseudomonas putida has also gained popularity due to its durability as an industrial chassis [12, 13]. Lund and Gorwa-Grauslund (2024) described a two-step procedure that converts guaiacol to muconic acid and then to adipic acid using an enoate reductase [11]. Additionally, employing engineered microorganisms to treat oil palm empty fruit bunch lignin has been investigated as a direct use of heterogeneous lignin depolymerization streams to avoid expensive separation procedures [10].

©IJRASET: All Rights are Reserved | SJ Impact Factor 7.538 | ISRA Journal Impact Factor 7.894 |

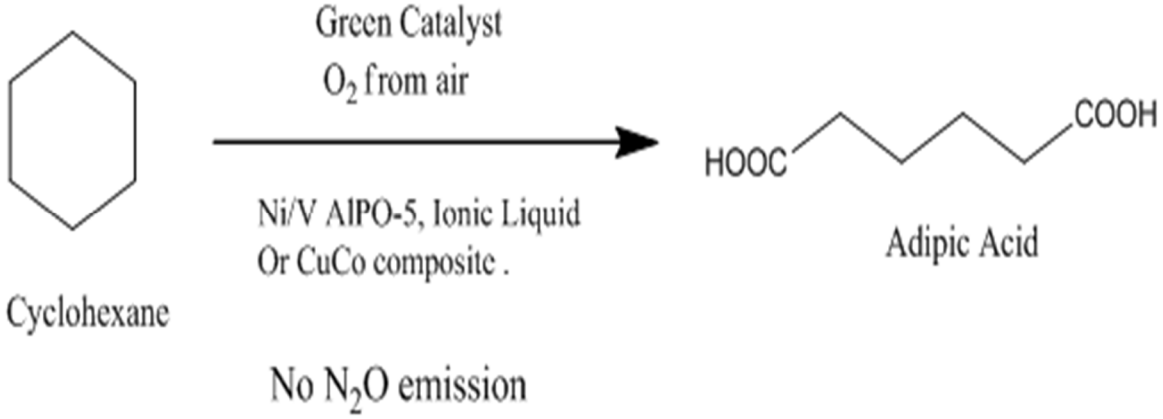
Figure 2: Greener pathways for adipic acid synthesis including bio-based and catalytic routes



2) Aerobic oxidation & Heterogeneous Novel catalyst

Molecular Oxygen (O_2) or hydrogen peroxide (H_2O_2) are used instead of nitric acid in modern catalytic methods. hydrothermal or impregnation methods are used to design catalyst such as Ni/V-incorporated AlPO-5 molecular sieves catalyst achieving approximately 53% selectivity [18], C,N-doped CuCo composites derived from Prussian blue analogues[20], and task-specific metal-based ionic liquids gives around 74% selectivity under aerobic condition [19].Continuous flow micro-reactors or high-pressure batch reactors are mostly used for conducting experiments. O_2-based oxidations use air or pure oxygen at temperatures between 100 and 150°C and pressures between 10 and 50 bar.Quantative analysis of products is performed using gas chromatography or high-performance liquid chromatography [18, 19].

Figure 3: Aerobic oxidation of cyclohexane using novel green catalysts

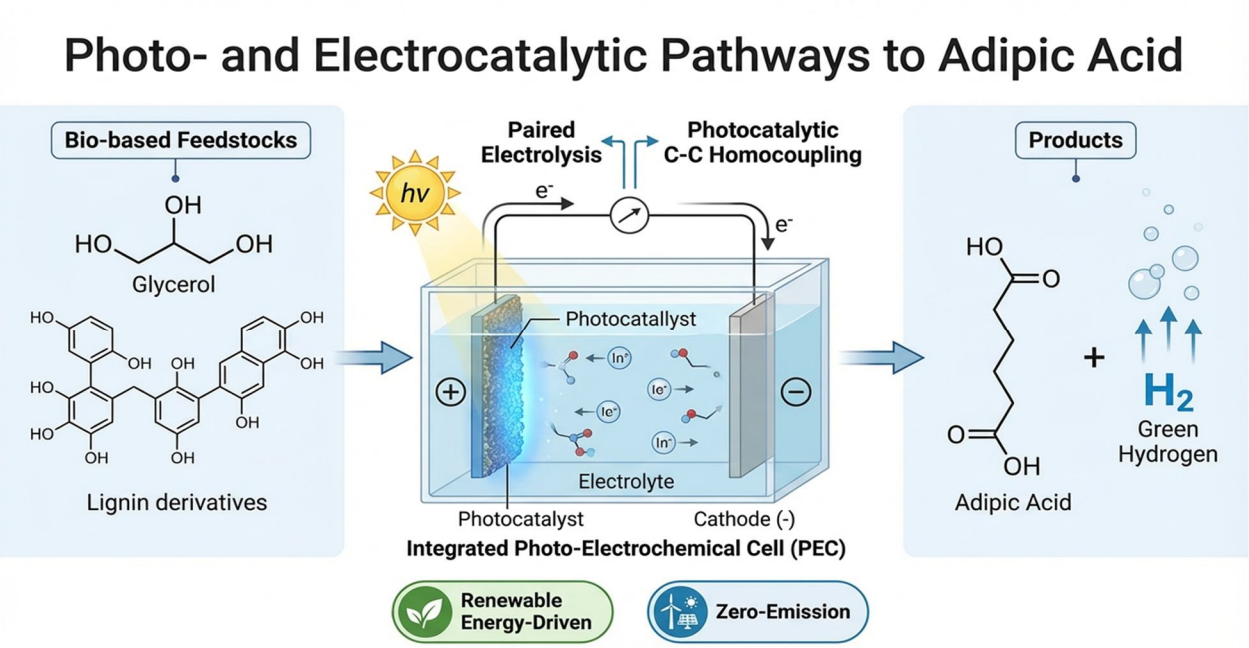


3) Electrochemical and Photochemical methods

Newer methods mostly used light and electricity as an external source of energy for redox reactions taking place at ambient temperature.

- In an electrochemical method, two metal electrodes (such as those based on Pt, Pd, or Cu) are used to perform paired electrolysis in split or undivided flow cells. In order to value lignin phenolics, water as a source of both hydrogen and oxygen in a flow electrolyzer was used by Liu et al. (2024) [14].Liu et al. successfully avoided both H_2 and HNO_3 while obtaining good yields by using bimetallic catalysts in a flow electrolyzer with water and air as redox partners [14]. Furthermore, a selective chemocatalytic route from furan platforms is provided by a one-pot reduction-carbonylation of bio-derived 2-furoic acid [15].
- In the photocatalytic method, semiconductor catalysts (such as Ag-doped TiO_2 or certain Ag cocatalysts) are used in photocatalytic homocoupling from glycerol derivatives utilizing an Ag cocatalyst under UV or visible light irradiation[16]. These systems regularly need certain buffer or alkaline conditions to optimize C–C coupling efficiency[16, 17].Suhadolnik et al. (2020) reported a continuous photo-electro-catalytic process in electrochemistry that incorporates light-driven phases to increase energy efficiency [17].

Figure 4: Emerging photo- and electrocatalytic pathways to adipic acid and green hydrogen



III. CRITICAL DISCUSSION

Adipic acid (AA) synthesis is undergoing a major change, moving away from petrochemical processes toward a more greener, ecofriendly ,sustainable, circular bio-based economy. This section critically studied the evolution of Adipic Acid synthesis, highlights important advances made between 2024 and 2026, and evaluates the successes and limitations of the most significant approaches..In the early stages of research, scientists started focusing on "green" chemistry as a better alternative to the traditional KA-oil process, which required high pressure and was less environmentally friendly. At that time, tools like advanced genetic engineering and modern catalysts were not very developed. Even so, Li and Liu (2005) were among the first to point out the importance of finding ways to synthesize adipic acid without releasing N_2O gas, although their ideas were mostly theoretical rather than practical[5].By 2013, researchers started focusing on using biomass (plant-based materials) to make useful chemicals. Van de Vyver and Roman-Leshkov suggested that muconic acid and furan derivatives could be good starting materials for synthesis of adipic acid [7].There was a major problem at that time—there were no cost effective and efficient catalysts available for the reaction processes like ring-opening and reduction. Because of this problem, later research focused on designing efficient solid (heterogeneous) catalysts to improve the process.

The move toward processes that do not use nitric acid (HNO_3) became stronger after Bart and Cavallaro's 2015 study. They showed that although some technologies can reduce nitrous oxide (N_2O) emissions, they cannot completely remove the need for the oxidizing chemical itself [3].Between 2016 and 2020, there was important progress in making bio-based adipic acid, mainly because of advances in metabolic engineering. During this time, Li and Li (2016) suggested using H_2O_2 hydrogen peroxide as a clean and environmentally friendly oxidant. However, it turned out to be too expensive to produce on a large scale, making it impractical for industry. Because of this, researchers shifted their focus to using molecular oxygen (O_2), which is cheaper and more suitable for large-scale, green production[4].A major shift happened around 2020 with the use of whole-cell biocatalysis, where living cells are used directly to carry out chemical reactions. Kruyer et al. showed that adipic acid–like compounds could be produced from catechol, and Suitor et al. successfully converted guaiacol into adipic acid using *Escherichia coli* [8, 9].Even though these results were promising, there were still problems. The microbes did not produce enough product, and the overall productivity was too low for large-scale industrial use. Because of this limitation, researchers started looking for stronger and more efficient microorganisms. Among these, *Pseudomonas putida* became a popular choice because it is more robust and better suited for industrial applications [12, 13].

At the same time, Suhadolnik et al. (2020) introduced hybrid photo-electro-catalytic systems. These methods were technically new and interesting, but they were not very practical because they were unstable during operation and required expensive equipment, which limited their industrial use [17].

Between 2021 and 2024, researchers improved these methods further and focused more on making processes more efficient and using non-food biomass as raw material. For example, Lang and Li (2021) helped shift attention toward lignin-based feedstocks, which also reduced concerns about using food resources for chemical production [6].By 2024, both biological and electrochemical methods had shown important progress. Lund and Gorwa-Grauslund (2024) developed a two-strain *Pseudomonas putida* system that improved adipic acid production. In another study, Liu et al. (2024) made progress in electrochemical conversion of lignin-derived compounds. In batch conditions, their system gave high yields—about 85% for adipic acid formation and 92% for KA oil production. However, when the process was run continuously, the yield dropped to 38.5%, showing that what works in the lab does not always perform well at industrial scale [11, 14].In a related study, Sikazwe et al. (2024) carried out a techno-economic analysis of bio-based production routes. They found that producing adipic acid through direct fermentation in sugarcane-based systems could lower the selling price by about 33% compared to fossil-based methods, and also reduce greenhouse gas emissions by nearly 79% [21].More recently, research from 2025 to early 2026 has focused on solving remaining biological and catalytic challenges. Ning et al. (2026) improved the metabolic pathway in *Escherichia coli* by fixing key enzyme bottlenecks in the α-ketopimelate pathway, which increased production efficiency [24]. Seibert et al. (2026) showed a new way to convert lignin directly into adipic acid using *Pseudomonas taiwanensis*, effectively channeling lignin-derived compounds into the desired product [23].On the electrochemical side, Cao et al. (2026) developed a new catalyst ($CoFe_2O_4$@CuO/CF) for oxidizing 1,2-cyclohexanediol, which showed high efficiency even at high current levels and solved some power-related issues seen in earlier systems [22]. In another advance, Wang et al. (2026) introduced a tandem Rh-catalyzed process using γ-valerolactone, CO_2, and H_2, achieving up to 89% yield. This method is important because it uses non-aromatic biomass and avoids the problems seen in earlier lignin and furan-based routes [26].

Table 1 shift from petrochemical roots to eco-friendly greener route trade-offs summary

Metric	Petrochemical (KA-Oil)	Bio-based (Fermentation)	Electrocatalytic (paired)
Environmental Impact	High (0.3 kg N_2O/kg AA)	Low (up to 78.7% GHG reduction [21]	Low (Zero direct N_2O)
Economic Viability	Established (Baseline MSP)	Sensitive to titer; potential 33% cost reduction [21]	Low (Zero direct N_2O)
Feedstock Source	Fossil Cyclohexane	Lignin, Glucose, Furanic waste	Lignin-derived phenolics
Technical Success	90%+ Selectivity	Improved titers with P. putida [11, 23]	High Faradaic efficiency (Cao 2026 [22]

Based on the chronological analysis we suggest the following course for adipic acid research and the most recent 2026 discoveries:

IV. FUTURE PERSPECTIVE

It is important to close the yield gap between batch and continuous flow. Scaling high-yield coupled electrolysis and electrocatalytic systems (such $CoFe_2O_4$@CuO/CF) to continuous flow reactors without sacrificing selectivity can be achieved [14, 22]. Efficiency can be increased by utilizing the advantages of both chemical and biological catalysis. Use of heterogeneous catalysts can upgrade intermediates produced by microbes, such as hydrogenated phenols or muconate [23, 25].To attain the titers and productivities required for industrial competitiveness, research should keep working to overcome enzymatic limitations, such as those in the α-ketopimelate pathway [24, 25].A prospective substitute for lignin-based pathways is the expansion of pathways that make use of non-aromatic biomass, such as the tandem Rh-catalyzed hydrocarboxylation of lactones [26].It is important to move away from using food-based sources like glucose and waste materials such as lignocellulosic biomass. This helps prevent issues related to food supply and cost.[6, 21].Measurement of “green and cost-effective processes can be done by Life Cycle Assessment (LCA) and Techno-Economic Analysis (TEA) methods [21].

V. CONCLUSION

Adipic acid is an important chemical used in synthesis of many products, but the conventional method of synthesis, which is as the KA-oil process, gives environmental problems of nitrous oxide emission in large amounts,which is an important greenhouse gas & cyclohexane synthesized from carcinogenic benzene having significant impact on human health.Researchers have developed new routes of synthesis between 2020 and 2026 to find green, ecofriendly & more sustainable pathways that avoid this pollution and avoid the use of carcinogenic benzene as a raw material for synthesis of cyclohexane.Researchers are currently working on two innovative pathways . One path involves biological engineering, where scientists use metabolic processes using bacteria like e-coli —specifically the α-ketopimelate pathway—to teach microorganisms like E coli to produce adipic acid naturally without use of hazardous substances. The other path mainly involves the use of advanced electrical methods such as high-current-density electrocatalysis. This technique uses electricity along with specialized materials, such as $CoFe_2O_4$@CuO/CF, to produce the chemical more efficiently.Another important part of this shift is changing the raw materials for manufacturing . An alternative raw material such as non-edible plant waste can be used as renewable feedstock, such as wood-based lignin or general biomass waste. This modification is a way to a circular economy, where we consider waste is reclaimed into valuable resources.While we are much nearer to a green ,non conventional and low-emission value chain than we were a few years ago, there are still hurdles to clear. Scientists are presently working to overcome major challenges related to scaling up these greener synthesis for large-scale industrial application and increasing the quantity of acid the microorganism can produce, which is essential to make these green methods preferred to traditional methods.

VI. ACKNOWLEDGEMENT

We would like to be grateful to our institute for providing the academic resources & support for this study. We also acknowledge the important work of researchers whose publications greatly supported this study.

Data availability

No primary research results have been included and no new data were generated or analyzed as part of this review.

Conflicts of interest

There are no conflicts of interest.

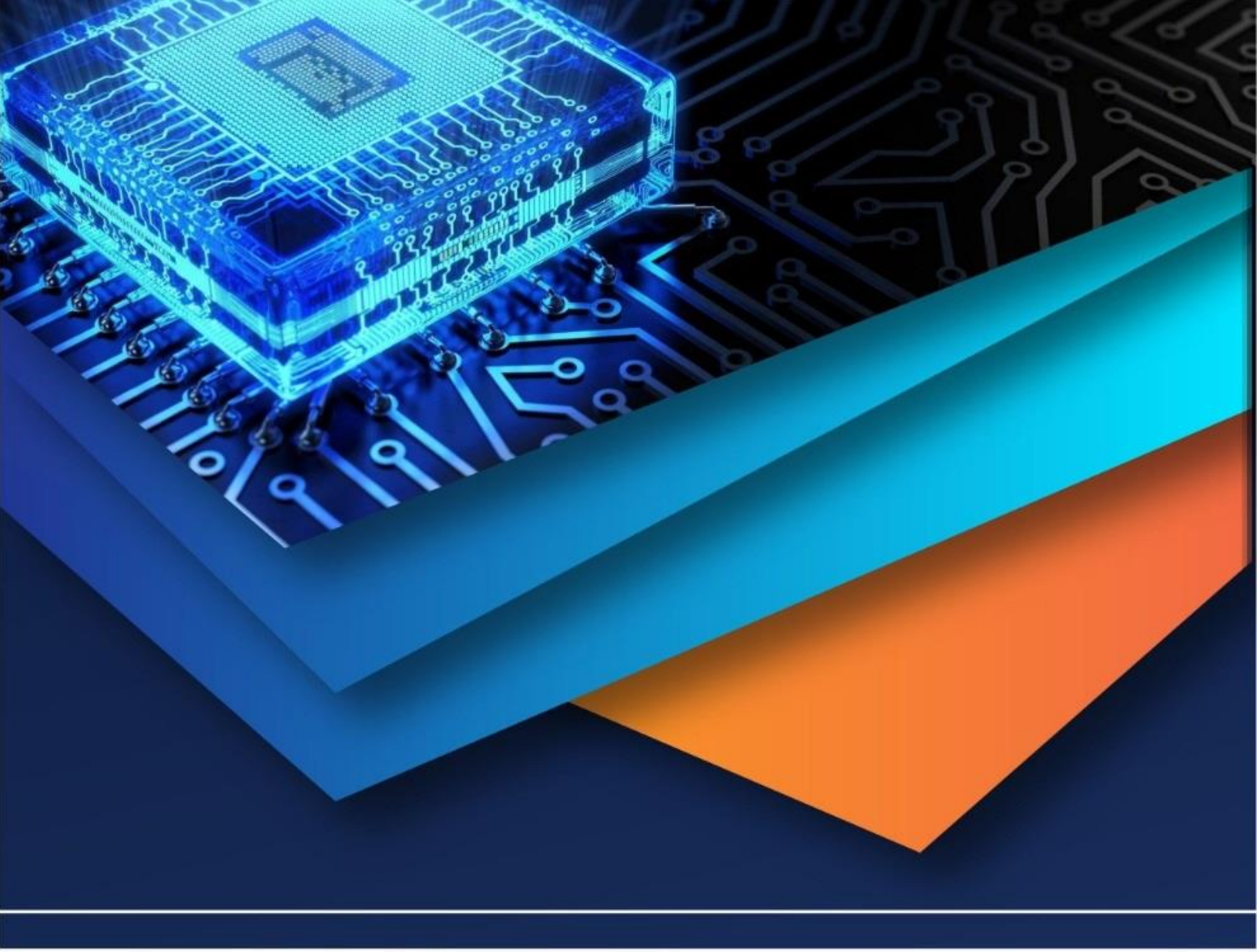
REFERENCES

[1] W. Yan, G. Zhang, and J. Wang, "Recent advances in the synthesis of adipic acid," Front. Chem., vol. 8, p. 185, 2020. DOI: 10.3389/fchem.2020.00185
[2] J. Rios et al., "One-step synthesis of adipic acid from glucose by an engineered Escherichia coli," Green Chem., vol. 23, pp. 3172-3181, 2021. DOI: 10.1039/d1gc00638j
[3] J. C. J. Bart and S. Cavallaro, "Adipic acid: Synthesis, properties and applications," Ind. Eng. Chem. Res., vol. 54, pp. 1-10, 2015. DOI: 10.1021/ie5020734
[4] X. J. Li and H. J. Li, "Green synthesis of adipic acid," Univ. Chem., vol. 31, pp. 1-8, 2016.
[5] H. Y. Li and L. X. Liu, "Study on the synthesis of adipic acid," Hengyang Norm. Univ., vol. 26, pp. 98-101, 2005.
[6] M. Lang and H. Li, "Sustainable routes for the synthesis of renewable adipic acid from biomass derivatives," ChemSusChem, vol. 14, pp. 4376-4385, 2021. DOI: 10.1002/cssc.202101531
[7] S. Van de Vyver and Y. Roman-Leshkov, "Emerging catalytic processes for the production of adipic acid," Catal. Sci. Technol., vol. 3, pp. 1465-1479, 2013. DOI: 10.1039/C3CY20843E
[8] J. T. Suitor, S. Varzandeh, and S. Wallace, "One-Pot Synthesis of Adipic Acid from Guaiacol in Escherichia coli," ACS Synth. Biol., vol. 9, 2020.
[9] N. S. Kruyer et al., "Fully biological production of adipic acid analogs from branched catechols," Sci. Rep., vol. 10, 2020.
[10] T. M. Lo et al., "Biosynthesis of Commodity Chemicals From Oil Palm Empty Fruit Bunch Lignin," Front. Microbiol., vol. 12, 2021.
[11] F. Lund and M. F. Gorwa-Grauslund, "Production of bio-based adipic acid using combination of engineered Pseudomonas putida strains," Sustainable Chemistry for the Environment, vol. 5, 2024.
[12] A. Weimer et al., "Industrial biotechnology of Pseudomonas putida: advances and prospects," Appl. Microbiol. Biotechnol., vol. 104, 2020.
[13] I. Ahmad, "Pseudomonas putida en la biotecnologia industrial: Avances recientes and orientaciones futuras," Salud, Ciencia and Tecnologia, vol. 3, 2023.
[14] F. G. Liu et al., "Sustainable Adipic Acid Production via Paired Electrolysis of Lignin-Derived Phenolic Compounds with Water as Hydrogen and Oxygen Sources," J. Am. Chem. Soc., vol. 146, 2024.
[15] X. Zhang and Y. Wang, "Adipic acid synthesis from bio-derived 2-furoic acid by reduction-carbonylation," Green Chem., vol. 27, 2025.
[16] P. Yang et al., "Preparation of adipic acid from glycerol derivative by photodehalogenative C-C homocoupling," J. Catal., vol. 429, 2024.
[17] L. Suhadolnik et al., "Continuous Photo-Electro-Catalytic Synthesis of Bio-Based Adipic Acid with Reaction Kinetics Modeling," Chem. Eng. Technol., vol. 43, 2020.
[18] T. Raja, "Nitric acid free cyclohexane to adipic acid production using nickel and vanadium incorporated AlPO-5 molecular sieve," Mol. Catal., vol. 546, 2023.
[19] Y. Liu et al., "Highly efficient one-pot aerobic oxidation of cyclohexane to adipic acid using task-specific metal-based ionic liquid," Chem. Eng. Sci., vol. 275, 2023.
[20] S. Wei et al., "Highly enhanced direct catalytic oxidation of cyclohexane to adipic acid by Prussian blue analogues-derived C,N doped CuCo composite catalysts," Chem. Eng. Sci., vol. 284, 2024.

©IJRASET: All Rights are Reserved | SJ Impact Factor 7.538 | ISRA Journal Impact Factor 7.894 |

[21] S. Sikazwe et al., "Techno-economic and life cycle assessment of sugarcane biorefineries for adipic acid production," 2024.
[22] X. Cao et al., "Electrocatalytic oxidation of 1,2-cyclohexanediol to adipic acid with high faradaic efficiency under high current density over a CoFe2O4@CuO/CF catalyst," 2026.
[23] L. Seibert et al., "Biofunneling hydrogenated phenols into adipic acid using recombinant Pseudomonas taiwanensis VLB120," 2026.
[24] Y. Ning et al., "Breaking the bottleneck of the alpha-ketopimelate pathway to boost adipic acid synthesis in Escherichia coli via metabolic and enzymatic engineering," 2026.
[25] M. Zhao et al., "Metabolic Engineering and Synthetic Biology-Driven Strategies to Harness Microbial Production of Adipic Acid: Current Status and Future Direction," 2026.
[26] Wang et al., "Tandem Rh-catalyzed hydrocarboxylation of biomass-derived lactones to diacids," 2026.

©IJRASET: All Rights are Reserved | SJ Impact Factor 7.538 | ISRA Journal Impact Factor 7.894 |



10.22214/IJRASET

45.98

IMPACT FACTOR: 7.129

IMPACT FACTOR: 7.429

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Call : 08813907089 (24*7 Support on Whatsapp)