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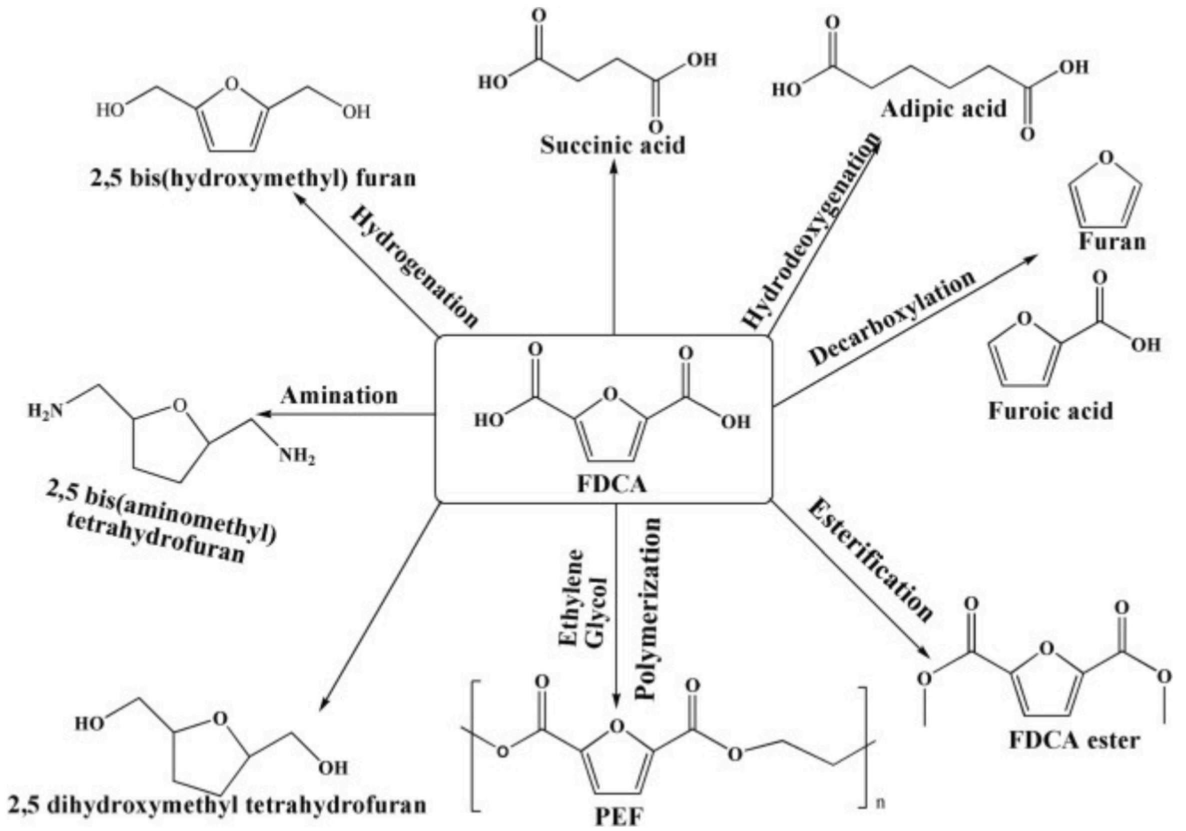
Chemical Formula: $C_6H_4O_5$

Chemical Name: 2,5-Furan Dicarboxylic Acid (FDCA)

Use case:

a. Applications of 2,5-Furandicarboxylic Acid (FDCA):

- 2,5-Furandicarboxylic acid (FDCA) is a bio-based chemical with growing significance in sustainable materials and green chemistry. Some of the major uses include:
    - Chelating Agent: FDCA acts as a strong complexing agent due to presence of two -COOH group and a furan ring and is capable of chelating ions like Ca^{2+}, Cu^{2+}, and Pb^{2+}.
    - Production of Polyesters: FDCA serves as a renewable alternative to terephthalic acid in manufacturing polyesters like polyethylene furanoate (PEF), which exhibits superior barrier properties compared to traditional polyethylene terephthalate (PET).
    - Production of Antibacterial Agents: Derivatives of FDCA, particularly its anilides, have demonstrated significant antibacterial activity, making them potential candidates for antimicrobial applications.
    - Medical Applications: A diluted solution of FDCA in tetrahydrofuran is used for preparing artificial veins for transplantation. It is also used in medicine to remove kidney stones due to its chelating properties.
    - Making Fire Foams: FDCA can be used as an ingredient in manufacturing fire foams due to its chemical stability.
    - Used in Green Chemistry: It is a versatile building block for green materials and biopolymers as it is derived from biomass and hence serves as a renewable alternative to petrochemical-based materials.



b. Alternatives to FDCA:

- There are many alternatives that are used in place of FDCA but most of them are petrochemical-based. Some of these include:
    - Terephthalic Acid: TPA (Terephthalic Acid) is the conventional petrochemical based counterpart to FDCA and is widely used in the production of polyesters. Although, FDCA is costlier than TPA due to higher production cost, TPA is not bio-based, lacking the sustainability benefits of FDCA.
    - Isophthalic Acid (IPA): Similar to TPA, IPA is used in polyester production and lacks sustainability benefits as this is also a petrochemical-based acid.
    - Succinic Acid: This acid can substitute FDCA in the production of polyesters and polyamides, offering a different set of properties. It is derived from biomass and serves as a building block for bioplastics and chemicals, providing a renewable alternative to petrochemical based substances. FDCA possesses an aromatic furan ring, distinguishing it from the aliphatic structure of succinic acid. This aromaticity imparts enhanced thermal and mechanical properties to polymers derived from FDCA, making them more suitable for applications requiring durability and heat resistance.

c. Advantages of FDCA Over Alternatives:

2,5-Furandicarboxylic Acid (FDCA) is considered superior to traditional petrochemical-based compounds like Terephthalic Acid (TPA) and Isophthalic Acid (IPA) due to several key advantages:

1. Renewable Origin & Sustainability
   - Bio-Based Source: FDCA is derived from renewable biomass sources such as fructose or lignocellulose, making it a sustainable alternative to TPA and IPA, which are sourced from non-renewable fossil fuels.
   - Lower Carbon Footprint: Life-cycle assessments have shown that replacing TPA with bio-based FDCA in polymer production can lead to significant reductions in greenhouse gas emissions and non-renewable energy use.

2. Superior Polymer Performance
   - Enhanced Barrier Properties: Polymers like polyethylene furanoate (PEF), synthesized from FDCA, exhibit intrinsically higher gas barrier properties for oxygen, carbon dioxide, and water vapor compared to PET, making them ideal for packaging applications.
   - Higher Thermal Stability: FDCA-derived plastics have superior heat resistance compared to TPA-derived PET, expanding their application range in high-temperature environments.

3. Recyclability & Circular Economy Benefits
   - Easier Recycling Process: FDCA-based plastics, such as PEF, can be more efficiently recycled compared to PET, enhancing their contribution to the circular economy.
   - Reusability in Green Chemistry: FDCA's derivatives can be repurposed into various bio-based chemicals, reducing dependency on petroleum-based feedstocks.
     - FDCA derivative based materials. PEF has better barrier properties, mechanical strength, and recyclability than PET (Polyethylene Terephthalate) which is derived from TPA.

d. Import Status of FDCA in India and Comparison with Terephthalic Acid

2,5-Furandicarboxylic Acid (FDCA) is an emerging bio-based chemical primarily used in the production of sustainable polymers, such as polyethylene furanoate (PEF), which is considered a potential alternative to polyethylene terephthalate (PET). Currently, FDCA is not widely produced or utilized on a commercial scale in India, and specific import data for FDCA is not readily available. This scarcity of data suggests that FDCA imports into India, if any, are minimal and primarily limited to research and development purposes.

In contrast, terephthalic acid (TPA), a key monomer in PET production, is extensively imported into India. According to data from the World Integrated Trade Solution (WITS), India imported approximately 1.59 million metric tons of terephthalic acid and its salts in 2023, valued at around $1.29 billion. The primary exporters to India were:

- China: Approximately 693,000 metric tons, valued at $553.7 million.
- Thailand: Approximately 332,000 metric tons, valued at $268.9 million.
- Other Asian countries: Approximately 311,000 metric tons, valued at $253.6 million.
- South Korea: Approximately 145,000 metric tons, valued at $124.2 million.
- Indonesia: Approximately 87,000 metric tons, valued at $72.6 million.

These figures highlight the significant reliance of India's polymer industry on imported terephthalic acid for PET production. As the industry seeks sustainable alternatives, FDCA presents a promising option due to its potential to replace TPA in polymer applications. However, the transition to FDCA-based polymers like PEF will depend on the development of cost-effective production methods, establishment of supply chains, and market acceptance. For the purpose of this report, we are assuming that FDCA, if produced, would replace TPA. Chemically, 1 mol FDCA can replace 1 mol TPA in PET production. [8]

Production Pathways of FDCA

FDCA is generally produced using two processes:

1. Dehydration of fructose by microwave heating to get HMF and then oxidation of HMF to get FDCA

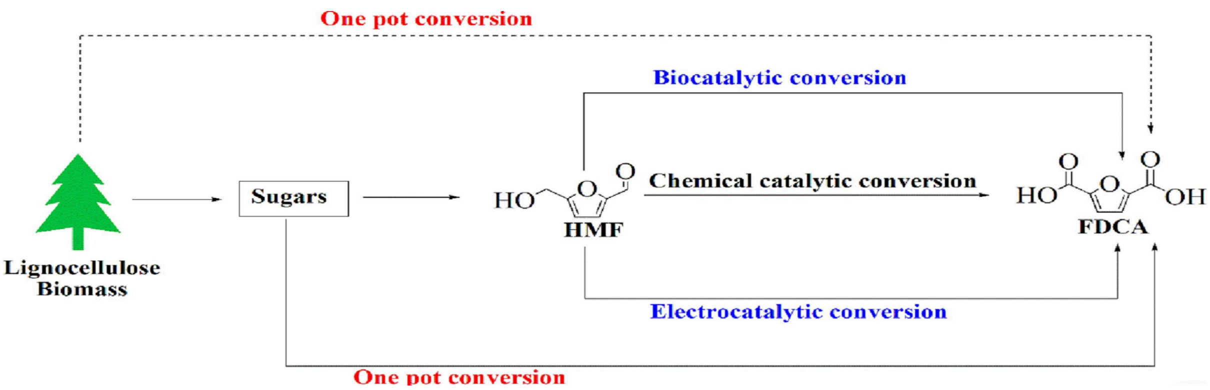


Fig. 1 Overall routes for FDCA production from biorenewable resources. [7].

2. Green Synthesis of 2,5-Furandicarboxylic Acid (FDCA) from Furfural

Economic feasibility:

The most commonly used process for producing 2,5-Furandicarboxylic Acid (FDCA) in industries is the catalytic oxidation of 5-Hydroxymethylfurfural (HMF). This process is favored due to its efficiency, scalability and ability to produce high-quality FDCA with good yields. The use of renewable biomass sources and efficient catalytic systems makes this process environmentally sustainable and cost-effective.

a) Raw Materials Required for FDCA Synthesis (Based on Patent Reports)

The synthesis of 2,5-Furandicarboxylic Acid (FDCA) can follow different chemical routes, each utilizing distinct raw materials. The primary synthesis pathways and their respective input materials, as reported in patent applications, are:

1. Dehydration of Fructose and Oxidation of HMF to FDCA

- **Raw Materials:**
  - **Fructose** – A key starting material obtained from corn syrup or other sugar-rich biomass sources.
  - **Glucose** – Can be converted into fructose via enzymatic or catalytic isomerization.
  - **Lignocellulose** – Derived from plant biomass, can be hydrolyzed to yield fermentable sugars (fructose/glucose).
- **Process Description:**
  - **Fructose dehydration to HMF** using **acid catalysts** ($Sn_2O/\gamma\text{-}Al_2O_3$) in a **biphasic system (DMSO-H_2O)** with **solvent extraction (DCM)**.
  - **HMF oxidation to FDCA** through **HMFCA and FFCA** intermediates using **noble metal catalysts** (AuPd, Pt, Pd) in aqueous media.
  - **Yield: Up to 90% FDCA** under optimized conditions.

2. Oxidation of Furfural and Carboxylation to FDCA

- **Raw Materials:**
  - **Agricultural Waste** – Includes corn stover, wheat straw, and sugarcane bagasse, which serve as feedstocks for furfural production.
  - **Furfural** – An intermediate derived from the acid hydrolysis of hemicellulose in biomass.
  - **Furoic Acid** – An oxidation product of furfural.
- **Process Description:**
  - **Furfural production** from **pentose sugars** using **$SnCl_4$ catalysts** in a **biphasic system**.
  - **Oxidation of furfural to furoic acid** with **Au-based catalysts** in water.
  - **Carboxylation of furoic acid to FDCA** using **Cs/K carbonates and CO_2**.
  - **Overall yield: ~74% FDCA from furfural**.

b) Preliminary Economic Feasibility Analysis: Raw Material, Solvent Costs, and Product Revenue.

Process 1: Fructose → HMF → FDCA

Steps:

1. Fructose to HMF (Dehydration in biphasic DMSO-H_2O system with $Sn_2O/\gamma\text{-}Al_2O_3$ catalyst)
2. HMF to FDCA (Sequential oxidation with noble metal catalysts)

Step 1: Fructose → HMF

- Fructose required: 256.09 kmol (~46,138 kg)
- Fructose price: ₹99/kg [12]
- Raw material cost: 46,138×99 = ₹4,567,662
- Processing cost (35.5% assumption [13]): = ₹2,513,138
- Total Cost for Step 1: 4,567,662+2,513,138=₹7,080,800

Step	Description	Yield (%)	Quantity Needed (kg)	Raw Material Cost (₹) (64.5%)	Processing Cost (₹) (35.5%)	Total Cost (₹)
Fructose → HMF	Acid-catalyzed dehydration in a biphasic system with solid catalyst	55%	256.09 kmol HMF (~46,138 kg)	₹4,567,662	₹2,513,138	₹7,080,800
HMF → FDCA	Oxidation using AuPd catalyst	71%	140.85 kmol HMF (~17,073 kg)	-	-	₹0
Total Cost (Process 1)				₹4,567,662	₹2,513,138	₹7,080,800

Process 1: Fructose → FDCA

- Total Cost (Including Processing): ₹7,080,800
- Total Revenue (100 kmol FDCA = 15,610 kg @ ₹963/kg): ₹15,027,430
- Profit: ₹15,027,430 - ₹7,080,800 = ₹7,946,630
- Profit Margin: 52.9%

Process 2: Biomass (via Furfural) → FDCA (Green Two-Step Process)

Steps:

1. Biomass to Furfural ($SnCl_4$ catalysis in a biphasic system)
2. Furfural to Furoic Acid (Oxidation with Au-based catalyst)
3. Furoic Acid to FDCA (Carboxylation using molten carbonate salts)

Step 1: Biomass (D-Xylose) → Furfural

- D-Xylose required: 190.09 kmol (~28,535 kg)
- Xylose price: ₹150/kg [14]
- Raw material cost: 28,535×150=₹4,280,250
- Processing cost (35.5% assumption): 35.5/64.5×4,280,250=₹2,356,600
- Total Cost for Step 1: 4,280,250+2,356,600=₹6,636,850

Step	Description	Yield (%)	Required Quantity	Raw Material Cost (₹) (64.5%)	Processing Cost (₹) (35.5%)	Total Cost (₹)
Biomass → Furfural	$SnCl_4$ catalysis, biphasic system	71%	Required D-xylose: 190.09 kmol (≈28,535 kg) at ₹150/kg Cost = 28,535 kg × ₹150	₹4,280,250	₹2,356,600	₹6,636,850
Furfural → Furoic Acid	Oxidation with Au-based catalyst	95%	Furfural produced from Step 1: 134.96 kmol (~13,673 kg)	-	-	₹0
Furoic Acid → FDCA	Carboxylation with Cs/K carbonates	78%	Furoic acid produced from Step 2: 128.21 kmol (~15,244 kg)	-	-	₹0
Total Cost (Process 2)				₹4,280,250	₹2,356,600	₹6,636,850

Process 2: Biomass → FDCA

- Total Cost (Including Processing): ₹6,636,850
- Total Revenue: ₹15,027,430
- Profit: ₹15,027,430 - ₹6,636,850 = ₹8,390,580
- Profit Margin: 55.8%

Real-World Use Case in India:

The global FDCA market is projected to grow significantly, with estimates suggesting it could reach approximately US$ 67.96 billion by 2032, exhibiting a compound annual growth rate (CAGR) of 34.20% during the forecast period. [9] This growth is driven by the increasing demand for bio-based plastics and the shift towards renewable resources.

In India, research institutions are actively exploring efficient methods for FDCA production. For instance, the National Chemical Laboratory (NCL) has demonstrated a process for synthesizing 5-hydroxymethylfurfural (HMF), a precursor to FDCA, achieving a Technology Readiness Level 4 (TRL4), indicating successful lab-scale validation. [10] This advancement underscores India's commitment to developing indigenous technologies for sustainable chemical production.

Despite these advancements, large-scale commercial production of FDCA in India has not yet been established. The absence of operational commercial plants for FDCA synthesis highlights the need for further investment and development in this sector.

Addressing challenges such as technological optimization, economic feasibility, and the establishment of a reliable biomass supply chain is crucial for India to fully harness the potential of FDCA in its transition towards a circular economy.

The Gujarat Food and Drug Control Administration (FDCA) has been proactive in promoting research and development within the pharmaceutical sector, which could facilitate advancements in FDCA applications. The FDCA Innovation and Research Cell, for instance, supports collaborations between industry and academia, fostering an environment conducive to the development of sustainable chemicals like FDCA. [11]

Conclusion and Profitability Comment

The market analysis for **2,5-Furandicarboxylic Acid (FDCA)** highlights its potential as a sustainable alternative to **petrochemical-based materials**, particularly in the production of **polyethylene furanoate (PEF)**. FDCA offers significant advantages over traditional alternatives like **terephthalic acid (TPA)**, including **renewable sourcing, reduced carbon footprint, superior polymer properties, and enhanced recyclability**.

From an **economic feasibility perspective**, two production pathways were analyzed:

1. **Fructose → HMF → FDCA**
   - Profit: **₹7,946,630**
   - **Profit Margin:** 52.9%
2. **Biomass (via Furfural) → FDCA**
   - Profit: **₹8,390,580**
   - **Profit Margin: 55.8%**

The **biomass-based method** offers a **greener and potentially more scalable** alternative in the long run. However, **large-scale commercialization remains a challenge** due to **high production costs, limited supply chains, and market acceptance barriers.**The initial estimates suggest that both the methods have similar cost of production

As global demand for bio-based materials grows, **FDCA's profitability is expected to increase**, especially if production efficiencies improve and economies of scale are achieved. **Strategic investments in R&D and infrastructure will be key** to positioning FDCA as a mainstream alternative in India's sustainable chemical industry.

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List the contributions of each author:

- Kanishk Dhariwal contribution : Raw material required for FDCA synthesis. I took raw material from the patent report and briefly explain about them and their use in the process 1 & 2. Preliminary Economic Feasibility take input prices from india mart and do profit analysis for the production of 100 kmol of FDCA. and from a report available online to take total input cost to be 64.5% of total production cost to get good analysis.also do the Real world use case which show that india has a potential market for FDCA due to it's environment friendly characteristics. Find import data of FDCA in india.
- Abhishek Punia : Did research on the application of FDCA using wikipedia and a research journal. Next, Infound the alternatives that can be used in some particular applications and found three alternate chemicals. Then the comparative analysis of FDCA was done with respect to the alternatives. Then I checked the 2 production pathways to prepare FDCA and did an economic feasibility check for both ways and found the process that is economically feasible and profitable.
- Aarnav Gupta : Did research on of cost of raw materials, Scanned through the vendors to get a cost of proposed materials,and cost process .process,provided the feasibility,Real world use cases ,conclusion and profitability
- Rajat : Did the final editing of the report.

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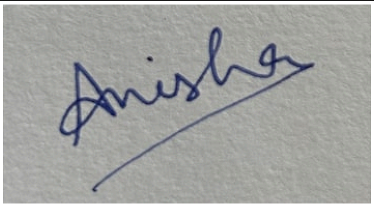
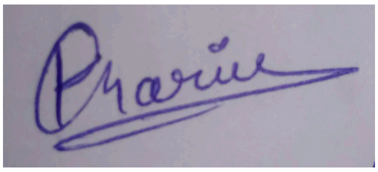
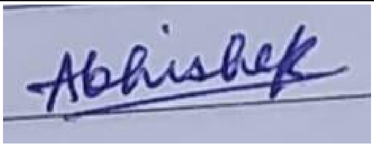
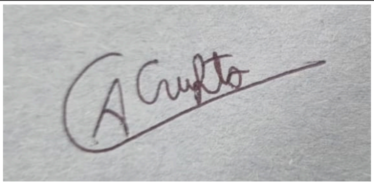
Anisha Nanda (CEO)	230145	
Kanishk Dhariwal	230525	
Abhishek Punia	210044	
Aarnav Gupta	230014	
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