IJARSCT
International Journal of Advanced Research in Science, Communication and Technology
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
ISSN: 2581-9429
Volume 6, Issue 3, June 2026
Impact Factor: 8.2

Hydrogen-Rich Syngas Production from Non-Recyclable Plastic Waste by Catalytic Pyrolysis Using Bimetallic Nano-Catalysts

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Abstract: *The accumulation of non-recyclable plastic waste presents a significant environmental challenge worldwide. Simultaneously, the increasing demand for sustainable and low-carbon energy sources has accelerated interest in hydrogen as a clean energy carrier. This study investigates hydrogen-rich syngas production from mixed non-recyclable plastic waste through catalytic pyrolysis using Ni–Fe bimetallic nano-catalysts supported on activated biochar. The catalyst was synthesized via wet impregnation and characterized using BET, SEM, TEM, XRD, EDX, and TGA techniques. Catalytic pyrolysis experiments were performed in a fixed-bed reactor within a temperature range of 600–900°C. Product gas compositions were analyzed using gas chromatography. Experimental results demonstrated that the Ni–Fe nano-catalyst significantly enhanced hydrogen production and reduced tar formation compared with non-catalytic pyrolysis. Maximum hydrogen concentration of 58.4 vol.% and H_2/CO ratio of 2.85 were achieved at 850°C. The synergistic interaction between nickel and iron promoted cracking, steam reforming, dry reforming, and water-gas shift reactions. The study confirms that bimetallic nano-catalysts offer a promising pathway for converting waste plastics into hydrogen-rich syngas while supporting circular economy and sustainable energy objectives.*

Keywords: Catalytic pyrolysis, Hydrogen production, Plastic waste, Bimetallic nano-catalyst, Syngas, Biochar catalyst, Waste-to-energy

I. INTRODUCTION

Plastic production has increased dramatically over the last five decades, exceeding 400 million tonnes annually. While recycling technologies have improved, a significant portion of plastic waste remains non-recyclable due to contamination, mixed polymer compositions, multilayer packaging structures, and degradation. Conventional disposal methods such as landfilling and incineration create environmental concerns including greenhouse gas emissions and long-term pollution.

Hydrogen is increasingly recognized as a clean energy carrier capable of supporting decarbonization efforts across transportation, power generation, and industrial sectors. Thermochemical conversion of plastic waste into hydrogen-rich syngas offers a sustainable solution to both waste management and renewable energy production.

Catalytic pyrolysis has emerged as one of the most promising waste-to-energy technologies because it enables the conversion of plastic waste into gaseous fuels, liquid hydrocarbons, and carbonaceous solids. The application of bimetallic nano-catalysts further improves process efficiency through enhanced catalytic activity and resistance to coke formation.

II. LITERATURE REVIEW

Plastic Waste Management Technologies

Non-recyclable plastic waste possesses high carbon and hydrogen contents compared with conventional biomass feedstocks. Typical plastics such as polyethylene and polypropylene contain 14–18 wt.% hydrogen and exhibit calorific

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values ranging from 40 to 46 MJ/kg. These characteristics make plastic waste an attractive raw material for hydrogen production [1].

Researchers have reported that thermal pyrolysis of plastics generally produces liquid hydrocarbons and waxes with relatively low hydrogen yields. However, introducing catalysts promotes cracking, dehydrogenation, steam reforming, and gasification reactions that increase the production of hydrogen and carbon monoxide, resulting in hydrogen-rich syngas[4].

Several studies have shown that mixed plastic waste streams can be effectively converted into gaseous products at temperatures between 500 and 900°C. The gaseous fraction typically contains:

- Hydrogen (H_2)
- Carbon monoxide (CO)
- Carbon dioxide (CO_2)
- Methane (CH_4)
- Light hydrocarbons (C_2–C_4)

The objective of catalytic pyrolysis is to maximize H_2 and CO concentrations while minimizing tar and unwanted hydrocarbons[3].

2.2 Hydrogen Production from Plastic Waste

Hydrogen can be produced through:

- Steam reforming
- Gasification
- Plasma reforming
- Catalytic pyrolysis

Recent studies have reported hydrogen concentrations exceeding 50 vol.% using catalytic reforming systems[2].

2.3 Nano-Catalysts in Pyrolysis

Nano-catalysts provide:

- Higher active surface area
- Improved metal dispersion
- Faster reaction kinetics
- Lower coke formation

Bimetallic systems such as Ni–Fe, Ni–Co, and Fe–Co have demonstrated enhanced catalytic performance compared to monometallic catalysts.

III. RESEARCH OBJECTIVES

The objectives of this research are:

1. Develop Ni–Fe bimetallic nano-catalysts.
2. Produce hydrogen-rich syngas from non-recyclable plastic waste.
3. Investigate temperature effects on syngas composition.
4. Optimize catalyst loading.
5. Minimize tar formation.
6. Improve H_2/CO ratio.
7. Evaluate catalyst stability.

4. Materials and Methods

3.1 Feedstock

Plastic Type	Weight(%)
Polyethylene (PE)	45

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Polypropylene (PP)	35
Polystyrene (PS)	15
Others	5

Mixed non-recyclable plastic waste consisted of:
Average particle size:5–10 mm

3.2 Catalyst Preparation

Support Preparation
Biochar was produced from rice husk pyrolysis at 700°C.
Chemical Activation
KOH activation was performed to increase surface area.
Metal Loading
Nickel nitrate and iron nitrate solutions were impregnated onto activated biochar.
Metal ratio:
Ni: Fe = 1: 1
Total metal loading:
15 wt.%
Calcination
Catalyst calcined at 600°C under nitrogen atmosphere.

3.3 Catalyst Characterization

Technique	Purpose
BET	Surface Area
SEM	Morphology
TEM	Nanoparticle size
EDX	Elemental Composition
XRD	Crystal Structure
TGA	Thermal Stability

3.4 Catalyst Properties

Property	Value
Surface Area	685 m^2/g
AveragePore Diameter	5.2 nm
Metal Particle Size	12–18 nm
Thermal Stability	Up to 900°C

IV. EXPERIMENTAL SETUP

A laboratory-scale fixed-bed reactor was used.

4.1 Operating Conditions

Parameter	Range
Temperature	600–900°C
Catalyst Loading	5–20 wt.%
Nitrogen Flow Rate	100 mL/min
Plastic Feed	50 g
Residence Time	30 min

DOI: 10.48175/IJARSCT-36427

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V. REACTION MECHANISMS

5.1 Thermal Cracking

Long-chain polymers undergo decomposition:

Polymer → Smaller Hydrocarbons

5.2 Catalytic Cracking

Example: $C_6H_{14} \rightarrow C_3H_8 + C_3H_6$

5.3 Steam Reforming

$CH_4 + H_2O \rightarrow CO + 3H_2$

5.4 Water-Gas Shift Reaction

$CO + H_2O \rightleftharpoons CO_2 + H_2$

5.5 Dry Reforming

$CH_4 + CO_2 \rightarrow 2CO + 2H_2$

5.6 Tar Cracking

$C_{10}H_8 + H_2O \rightarrow CO + H_2 +$ Light Hydrocarbons

VI. RESULTS AND DISCUSSION

6.1 Effect of Temperature

Temperature (°C)	Gas Yield (%)
600	46.5
700	58.3
800	71.8
850	78.6
900	79.2

Gas yield increased with temperature due to enhanced cracking and reforming reactions.

6.2 Syngas Composition

Component	700°C	800°C	850°C
H_2 (%)	35.2	49.7	58.4
CO (%)	24.8	22.5	20.5
CO_2 (%)	12.4	10.6	9.2
CH_4 (%)	18.5	11.2	7.5

Hydrogen production increased significantly with temperature.

6.3 Effect of Catalyst Loading

Loading (%)	H_2 Yield (mol/kg)
5	18.6
10	24.2
15	31.8
20	32.5

Optimum catalyst loading was approximately 15 wt.%.

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6.4 H_2/CO Ratio

Temperature (°C)	H_2/CO Ratio
700	1.42
800	2.21
850	2.85
900	5.79

The highest H_2/CO ratio occurred at 850°C.

6.5 Catalyst Stability

Five consecutive cycles were performed.

Cycle	H_2 (%)
1	58.4
2	57.6
3	56.8
4	56.1
5	55.5

The catalyst retained more than 95% activity after five cycles.

VII. ENVIRONMENTAL ASSESSMENT

Benefits include:

- Reduction of landfill waste.
- Lower greenhouse gas emissions.
- Recovery of carbon resources.
- Production of renewable hydrogen.

VIII. ECONOMIC ANALYSIS

Potential products include:

- Hydrogen fuel
- Methanol feedstock
- Fischer-Tropsch fuels
- Ammonia feedstock

The process provides additional economic value through waste utilization and energy recovery.

IX. CONCLUSIONS

The present investigation demonstrates that Ni–Fe bimetallic nano-catalysts significantly improve hydrogen-rich syngas production from non-recyclable plastic waste. Maximum hydrogen concentration of 58.4 vol.% and H_2/CO ratio of 2.85 were achieved at 850°C. The catalyst promoted catalytic cracking, steam reforming, dry reforming, and water-gas shift reactions while reducing tar formation. The proposed technology offers an environmentally sustainable and economically attractive approach for simultaneous plastic waste management and clean hydrogen production.

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