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Production Of Wax From Polypropylene And High-Density Polyethylene Via Thermal And Catalytic Pyrolysis

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***ABSTRACT**: Plastic waste, particularly polyolefin such as polypropylene (PP) and high-density polyethylene (HDPE), represents a major environmental burden. Pyrolysis provides an eco-friendly approach to convert these polymers into useful hydrocarbon products such as wax. This study investigates the production of wax from PP and HDPE through thermal and catalytic pyrolysis using natural bentonite. Experiments were conducted at 450–500 °C in a semi-batch reactor under nitrogen. The results revealed that thermal pyrolysis of HDPE-rich mixtures yielded up to 70 wt% wax, while catalytic pyrolysis enhanced conversion efficiency and reduced reaction time. GC–MS analysis showed that the waxes consist mainly of long-chain aliphatic hydrocarbons (C_4–C_{40}), suitable for lubricants, candles, and coatings. The study demonstrates that bentonite is a promising, low-cost catalyst for converting polyolefin waste into high-value wax products.*

Keywords: Polypropylene, HDPE, Thermal pyrolysis, Catalytic pyrolysis, Bentonite catalyst, Wax yield, Plastic recycling.

1. INTRODUCTION

Plastic pollution has become a critical global challenge, with over 400 million tons produced annually, a large portion of which ends up in landfills or the environment [1]. Polyolefins, particularly polypropylene (PP) and high-density polyethylene (HDPE), constitute a significant fraction due to their extensive use in packaging, consumer goods, and containers [2]. Being non-biodegradable, conventional disposal methods such as landfilling and incineration contribute to environmental damage, greenhouse gas emissions, and resource loss [3]. Consequently, chemical recycling technologies like pyrolysis—which thermally decomposes polymers in the absence of oxygen—have attracted growing attention for converting waste plastics into valuable hydrocarbons [4]. Pyrolysis can produce liquids, waxes, gases, and solid residues, and its ability to tolerate mixed and contaminated feedstocks distinguishes it from mechanical recycling [5]. Among pyrolysis products, waxes—semi-solid hydrocarbons often in the C20–C46 range—have gained interest due to applications in lubricants, candles, cosmetics, coatings, and as feedstock for further cracking [6,7]. Recent research has explored the optimization of operating conditions (temperature, residence time), catalyst type and loading, and feedstock composition to maximize wax yield and tailor its properties [8]. For instance, thermal pyrolysis of LDPE at 500 °C produced a wax yield of 64.5 wt%, while HDPE gave lower yields, with reported densities of 850–880 kg/m³ and calorific values of 45.6–46.2 kJ/g [9]. Thermo-catalytic degradation using calcium bentonite showed that HDPE and LDPE generate waxy oils above 475–500 °C, whereas PP tends to produce viscous liquids unless residence time is limited; catalysts reduced reaction time and modified product distribution [10]. Studies on multilayer film packaging demonstrated that mesoporous catalysts (e.g., Al-MCM-41) with mild acidity could yield up to 60 % wax at 500 °C, while strong acid catalysts (ZSM-5, mordenite) favored gas formation at the expense of wax [11]. Catalytic pyrolysis of single-use polyethylene with acid-modified bentonite achieved 87.5 % liquid hydrocarbon yield, though HDPE/LDPE predominantly produced waxy fractions with a melting point of 38 °C [12]. In contrast, binder-free bentonite pellet catalysts in catalytic pyrolysis suppressed wax formation due to strong cracking, producing oils dominated by aliphatic hydrocarbons from PP, LDPE, and HDPE [13]. Salaudeen et al. reported that adding olivine in fluidized-bed pyrolysis of virgin HDPE at 500 °C increased wax yield from 45.6 % to 66 wt % [14]. Feedstock blends of PP, HDPE, LDPE, and PS with zeolite or bentonite catalysts have shown that bentonite at 500 °C can produce approximately 60 wt % condensable liquid (wax + oils), depending on composition [15].Acid-treated bentonite combined with Ni:Al:Mg composite catalysts achieved 86.4 wt % oil yield for mixed plastic waste, with wax fraction dependent on plastic type [16]. Co-pyrolysis of cooking oil-contaminated PP with activated carbon-metal co-catalysts enhanced wax production, yielding wax with high pour point and stable viscosity [17]. Recent comprehensive reviews comparing thermal and catalytic pyrolysis indicate that PP and HDPE generate waxy products at high temperatures (450–500 °C) under thermal conditions, while catalytic pyrolysis often shifts the distribution toward lighter oils and gases unless mild catalysts are applied [18–21].From this literature, it is evident that feedstock composition, temperature, residence time, and catalyst characteristics (acidity, porosity, structure) are critical for optimizing wax yield and quality [22,23]. In this study, we focus on PP, HDPE, and their blends under thermal and catalytic pyrolysis (with bentonite) to:

1. Quantify wax yield as a function of PP:HDPE ratio, temperature, and catalyst loading.
2. Characterize wax properties (carbon chain distribution, melting point, density, viscosity) under various conditions.
3. Compare catalytic versus thermal processes in terms of yield, reaction time, and energy efficiency.
4. Propose optimal conditions for producing high-quality wax suitable for industrial applications.

2. MATERIALS AND METHODS

2.1 Feedstock Preparation

Polypropylene (PP) and high-density polyethylene (HDPE) wastes were collected from post-consumer packaging and household plastics. The plastics were washed, shredded, and dried at 105 °C for 12 h to remove residual moisture, preventing interference during pyrolysis. The feedstock's were characterized for particle size (1–3 mm) and moisture content (<0.5 wt%). For mixed-feed experiments, PP and HDPE were blended in ratios of 100:0, 70:30, 50:50, 30:70, and 0:100 (wt%).

2.2 Catalyst Preparation

Natural bentonite was pulverized to a particle size of ~100 µm. Acid activation was performed using 1 M H_2SO_4 at 80 °C for 4 h to increase surface acidity and develop mesoporosity, followed by washing with deionized water until neutral pH and drying at 110 °C. The acid-activated bentonite was used at 10 wt% relative to feedstock in catalytic experiments. BET surface area, acidity (via NH_3-TPD), and XRD patterns were measured to confirm catalyst activation.

2.3 Reactor Setup and Experimental Procedure

Pyrolysis experiments were carried out in a stainless-steel semi-batch reactor (500 mL) under continuous nitrogen flow (100 mL/min) to maintain an inert atmosphere. The reactor was equipped with a PID-controlled electric furnace, a thermocouple for accurate temperature measurement, and a cold-trap system for condensate collection.

The feedstock was loaded (50–100 g per run), and heating was applied at 10 °C/min to the desired pyrolysis temperature (450–500 °C). Reaction time was maintained between 20–30 min. Both thermal (no catalyst) and catalytic (with 10 wt% bentonite) pyrolysis runs were conducted for all PP:HDPE ratios. The products were fractionated into wax, liquid, gas, and char by mass balance.

2.4 Product Collection and Analysis

Condensable products were collected using cold traps cooled with ice and dry ice-acetone. Gas yield was estimated by difference. Wax and liquid fractions were separated via filtration and characterized using:

- Fourier Transform Infrared Spectroscopy (FTIR**):** Identification of functional groups.
- Gas Chromatography–Mass Spectrometry (GC–MS): Hydrocarbon chain distribution (C_4–C_{40}).
- Differential Scanning Calorimetry (DSC): Melting point determination.
- Viscosity and density measurements: Using a viscometer and pycnometer at 25 °C.
- Calorific value**:** Using a bomb calorimeter.

These analyses enabled correlation between feed ratio, catalyst presence, and wax properties.

3. RESULTS AND DISCUSSION

3.1 Experimental Conditions

Pyrolysis experiments showed distinct behaviors for PP and HDPE feedstock's. PP alone produced light-brown wax, HDPE yielded yellow, heavier wax, and blends produced intermediate properties. Bentonite catalysis promoted faster conversion and enhanced liquid formation. Table 1 summarizes key experimental conditions and observations

Experiment	Feed (PP:HDPE)	Catalyst	Temp (°C)	Time (min)	Remarks
1	100:0	None	450	23.6	PP – brown wax
2	0:100	None	450	29.0	HDPE – yellow wax
3	50:50	None	450	25.0	Mixed wax
6	100:0	Bentonite	450	26.1	Light wax + liquid
7	0:100	Bentonite	450	25.0	Heavy wax
8	50:50	Bentonite	450	24.0	Medium wax

3.2 Product Yield Distribution (Thermal vs Catalytic)

Thermal Pyrolysis

Thermal pyrolysis of HDPE-rich feedstock's resulted in higher wax yields due to longer polymer chains and higher crystallinity. PP-rich feedstock's tended to produce more gaseous products from shorter-chain cracking. Table 2 shows the distribution of product

Feed (PP:HDPE)	Wax (%)	Liquid (%)	Gas (%)	Char (%)
100:0	64.6	0	25.2	10.2

70:30	67.1	0	26.1	6.8
50:50	66.6	0	25.4	8.0
30:70	68.5	0	24.0	7.5
0:100	70.3	0	23.3	6.4
Catalyst Pyrolysis				
Feed (PP:HDPE)	**Wax (%)**	**Liquid (%)**	**Gas (%)**	**Char (%)**
100:0	38.3	49.0	6.8	5.9
70:30	39.3	47.6	8.2	4.9
50:50	38.7	47.7	7.7	6.0
30:70	37.0	49.5	8.5	5.0
0:100	41.0	48.5	8.7	1.8

3.3 Hydrocarbon Composition of Waxes

GC–MS analysis revealed that PP-derived waxes were enriched in shorter chains (C_4–C_{12}), while HDPE-derived waxes had higher fractions of long chains (C_{23}–C_{40}), suitable for industrial applications like lubricants and candles (Table 4).

Feed (PP:HDPE)	C_4–C_{12}	C_{10}–C_{18}	C_{12}–C_{23}	C_{23}–C_{40}
100:0	32.0	23.1	26.2	18.7
70:30	28.7	23.6	27.4	20.3
50:50	23.5	24.0	29.6	22.8
30:70	22.1	23.9	30.2	23.7
0:100	15.5	25.0	33.5	26.0

FTIR spectra confirmed dominant aliphatic $–CH_2–$ stretching at 2850–2920 cm^{-1}, minimal oxygenated groups, consistent with paraffinic wax standards. Melting points ranged 45–70 °C, densities 0.85–0.88 g/cm^3, and calorific values 45 MJ/kg.

3.4 GRAPHICAL RESULTS

Figure 1. Comparison of wax yield vs PP:HDPE ratio under thermal and catalytic pyrolysis
Thermal runs produce higher wax yields; catalytic runs favor more liquid formation.

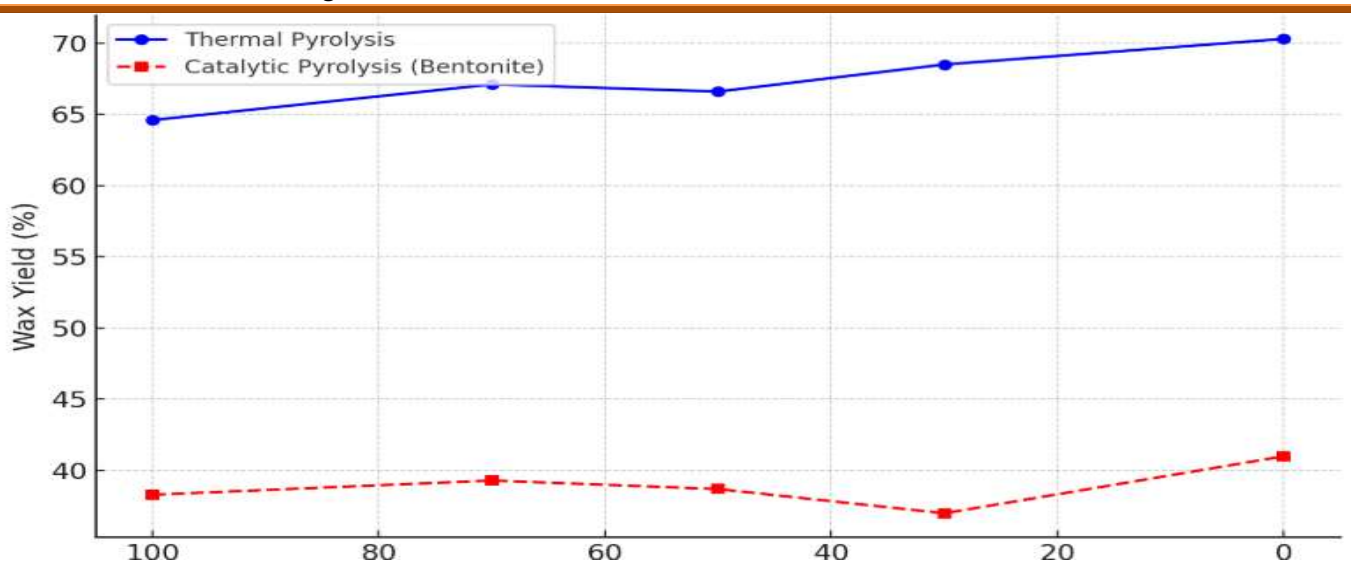
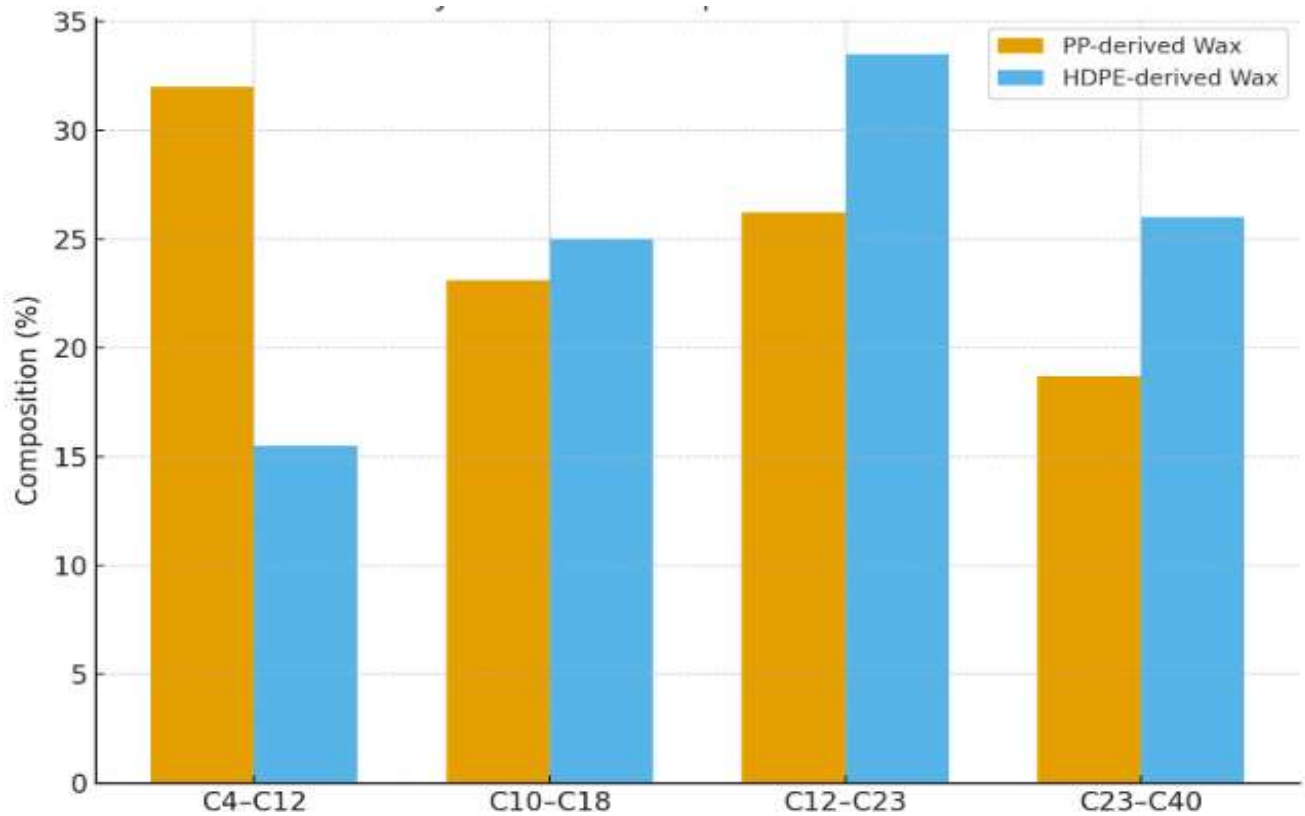


Figure 2. Hydrocarbon composition of PP-derived and HDPE-derived wax
PP produces shorter chains; HDPE favors heavier C_{23}–C_{40} paraffinic hydrocarbons.



3.DISCUSSION

Effect of Feed Ratio: HDPE-rich feedstocks produced heavier wax with longer hydrocarbon chains due to higher crystallinity and polymer chain length. PP-rich feedstocks favored lighter, more volatile fractions. Effect of Catalyst: Bentonite enhanced overall feedstock conversion, decreased char formation, and increased liquid fraction. Wax yield slightly decreased due to secondary cracking of long chains into lighter products. Thermal vs Catalytic Pyrolysis: Thermal runs maximize wax yield (70 wt%), while catalytic runs increase total conversion and improve energy efficiency by reducing char and facilitating secondary reactions. Mild acid catalysts at 450–500 °C optimize wax selectivity. Industrial Relevance: Produced waxes meet standard paraffinic specifications

and are suitable for lubricants, candles, and coatings. HDPE waxes, with heavier hydrocarbon distribution, are ideal for high-melting applications.

4. CONCLUSION

PP and HDPE mixtures can be successfully paralyzed into high-quality wax. Thermal pyrolysis achieved up to 70 wt% wax; catalytic pyrolysis improved overall conversion efficiency and reduced char. HDPE-rich feedstock's yield heavier waxes suitable for industrial applications .Bentonite is a viable, eco-friendly, low-cost catalyst for selective wax production. The produced waxes have favorable physical properties for lubricants, candles, and coating industries.

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