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ValORIZATION OF DISPOSABLE COVID-19 MASK THROUGH THE THERMO-CHEMICAL PROCESS

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HIGHLIGHTS
- A sustainable platform for COVID-19 PPE and CO2 to syngas was studied.
- Chemical composition and thermal stability of face mask waste were identified.
- Ni catalyst promoted syngas production from pyrolysis of disposable face mask.

ABSTRACT

It becomes common to wear a disposable face mask to protect from coronavirus disease 19 (COVID-19) amid this pandemic. However, massive generations of contaminated face mask cause environmental concerns because current disposal processes (i.e., incineration and reclamation) for them release toxic chemicals. The disposable mask is made of different compounds, making it hard to be recycled. In this regard, this work suggests an environmentally benign disposal process, simultaneously achieving the production of valuable fuels from the face mask. To this end, CO2-assisted thermo-chemical process was conducted. The first part of this work determined the major chemical constituents of a disposable mask: polypropylene, polyethylene, nylon, and Fe. In the second part, pyrolysis study was employed to produce syngas and C1-2 hydrocarbons (HCs) from the disposable mask. To enhance syngas and C1-2 HCs formations, multi-stage pyrolysis was used for more C-C and C-H bonds scissions of the disposable mask. Catalytic pyrolysis over Ni/SiO2 further expedited H2 and CH4 formations due to its capability for dehydrogenation. In the presence of CO2, catalytic pyrolysis additionally produced CO, while pyrolysis in N2 did not produce it. Therefore, the thermo-chemical conversion of disposable face mask and CO2 could be an environmentally benign way to remove COVID-19 plastic waste, generating value-added products.

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1. Introduction

Highly contagious coronavirus disease 19 (COVID-19) was identified/characterized in 2019 [1]. World health organization (WHO) manifested COVID-19 outbreak as pandemic on March 2020 [2] because COVID-19 infects over millions of people in all continents [3]. Under these circumstances, non-pharmaceutical intervention to physically cut off COVID-19 contagion by gearing up a personal protective equipment (PPE) (e.g., mask, glove, protective gown, etc.) is mandated in most countries [4-7]. Accordingly, the demands for PPE have been increased [8], which has led to the subsequent generation of plastic wastes [9-11]. Unfortunately, a reliable disposal platform for PPE has

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not been achieved due to several reasons [12]. First of all, most of the disposable face masks used in highly contaminated areas such as medical centers, public transportations, and public places could have high risks of contaminations with coronavirus. In addition, the heterogeneous nature of PPE makes it difficult to establish a reliable recycle platform [13]. Indeed, PPE is manufactured from various polymers (polystyrene, polypropylene, polyethylene, polyvinyl chloride, polyethylene terephthalate, etc.) and metallic compounds [9–11]. Despite that recycling is the best disposal option for PPE, such practice is not easily realized due to difficulty in proper separation [14]. Also, upcycling of PPE cannot be made due to a high bio-hazardous potential [15].

In these contexts, thermal destruction through the thermo-chemical process offers a reliable disposal route for PPE [16,17]. Among the thermo-chemical processes, incinerating PPE is commonly practiced [18], but it suffers from technical incompleteness in terms of air pollution controls (APCs) [19]. At the temperature regimes over the transition state, plastics are melted and volatized [20]. Radical pools created from the thermolysis of polymer, such as polyvinyl chloride (PVC), offer a favorable condition for forming toxic chemicals, such as dioxins [21]. Under these conditions, controlling the stoichiometric ratio of fuel to oxygen is challenging, which leads to a difficult condition for complete oxidation [22,23]. Given that most air pollutants are combustion byproducts, additional unit operations for APCs are required to meet the stringent air quality standard [24,25]. Accordingly, finding a reliable disposal platform for PPE beyond incineration is of great importance [17]. It is desirable to recover energy and valuable chemicals from PPE.

Pyrolysis offers an effective means for recovering energy and chemicals through carbon rearrangement [26]. Specifically, carbonaceous materials made for PPE can turn into different phases of pyrogenic products, including syngas, gaseous/liquid hydrocarbons, and solid residue (char) [27]. Carbon distributions into the three phase pyrolysates are controllable by altering the operational parameters (heating rate, temperature, duration, etc.) [28,29] and adopting catalysts during the process [30]. As compared to the case of lignocellulosic biomass, the formation of char from pyrolysis of plastic waste (e.g., PPE) is negligible [31]. Accordingly, carbon distribution of PPE likely designated into gaseous and liquid pyrolysates [32]. It is readily inferred that valorization of PPE through the pyrolysis process is advantageous over that of lignocellulosic biomass in that the more gaseous/liquid pyrolysates can be obtained. To offer more environmentally benign means to valorize PPE, this study particularly choose carbon dioxide (CO2) as a reaction medium. In short, the mechanistic functionality of CO2 serves a role to alter the compositional modification of gaseous/liquid pyrolysates [34], this study laid great stress on pyrolysis of PPE. More specifically, pyrolysis of a disposable mask from the CO2 environment was mainly conducted as a case study. To reinforce the mechanistic functionality of CO2 during pyrolysis of a disposable mask, earth abundant Ni catalyst was adopted, and all pyrolysates through catalytic pyrolysis were characterized. This catalyst was utilized due to its known catalytic capability for dehydrogenation for H2 production [35,36]. For fundamental study, the main constituents of a disposable mask were determined through analyses of functional groups, organic/inorganic contents, and thermal stability.

2. Materials and methods

2.1. Chemical reagents

Disposable face masks (KF94 grade: the first-class Korean masks that must meet ≥ 94% filtration efficiency of air pollutants) were purchased from a pharmacy store in Seoul, Korea. Prior to pyrolysis studies, the disposable face mask was cut into small pieces and dried at 100 °C overnight to remove moisture. Dichloromethane (> 99.95%), silica support (high purity grade, pore size: 60 Å, particle size: 53–210 μm), low density polyethylene (average MW: 4,000), and isotactic polypropylene (average Mw: 12,000) were obtained from Sigma-Aldrich. Nickel nitrate hexahydrate (> 97.0%) and nitric acid (69.0%) were acquired from Daejung Chemical (Korea). ICP multi-element standard solutions (IV and XVI) were purchased from Merck (Germany). Ultra-high purity (99.999%) N2 and CO2 gases, and N2 balanced H2 (20 vol% H2) gas were provided from Rigas (Korea).

2.2. Characterization of disposable face mask

Prior to pyrolysis study of the disposable face mask, its chemical compositions were identified. As shown in Fig. 1, the face mask was disassembled into filter (layers 1 – 4), nose wire (layer 1 cover and metal frame), and ear strap parts. Each plastic part was analyzed with FT-IR spectroscopy (Thermo Scientific Nicolet 380) to identify its
functional groups, while metal frame in the nose wire was quantified with an ICP-OES (Perkin-Elmer Optima 5300 DV). The detailed procedure for ICP-OES is describe elsewhere \[37\]. To scrutinize the thermolytic profiles of different parts (filter, nose wire, and ear strap) of the disposable face mask, thermo-gravimetric analyses (TGA: Netzsch STA 499) were done under the N2 and CO2 environments, varying thermolysis temperature from 35 to 900 °C with a constant heating rate \(10 °C \text{ min}^{-1}\).

2.3. Catalyst preparation and characterizations

Ni/SiO2 (5 wt% of Ni) was employed as a pyrolysis catalyst in this study. To impregnate Ni metal onto SiO2 support, wetness incipient impregnation method was adapted. Ni precursor was fully dissolved in deionized water, and the precursor solution was added to the SiO2 support dropwise. When the impregnation was done, it was placed in a convection oven overnight at 105 °C, followed by calcination in the air at 600 °C for 5 h. To obtain metal catalyst, the oxidized sample was reduced under 20 vol% of H2 (N2 balanced) at 510 °C for 4 hr with a heating rate of 2 °C min \(^{-1}\). ICP-OES analysis was done to measure the Ni metal loading \((4.98 \pm 0.02 \text{ wt%})\).

2.4. Experimental setups for disposable face mask pyrolysis

A tubular reactor was assembled with cylindrical furnaces for various pyrolysis experiments (one-stage, two-stage, and catalytic pyrolysis). In the experimental setup for one-stage pyrolysis, 1.00 g \(( \pm 0.02)\) of face mask was inserted into the center of tubular reactor, which operated from 35 to 600 °C with a constant heating rate \(10 °C \text{ min}^{-1}\). In the two-stage pyrolysis, additional furnace (the second heating zone) was placed right next to the first heating zone (furnace operating from 200 to 600 °C at 10 °C min \(^{-1}\)). The second heating zone was operated at a constant temperature (600 °C). For catalytic pyrolysis, 5 wt% Ni/SiO2 \((1.00 \pm 0.01 \text{ g})\) was added to the second heating zone in the two-stage pyrolysis setup. During pyrolysis in all the experimental setups, either N2 or CO2 \((100 \text{ mL min}^{-1})\) was flowed through the tubular reactor as a purge gas.

2.5. Product analysis

Gaseous products from face mask pyrolysis were monitored using an on-line micro-GC (3000A, Inficon), directly connected to the tubular reactor. Identification of gaseous products and their quantification were done using a calibration gas mixture (Lot#: 160–401257255-1) made from Inficon. For analysis of condensable hydrocarbons (HCs), a cold solvent trap \((-1 °C)\), filled with dichloromethane, was used to condense them. The compositional matrices of condensed products were analyzed using GC/MS (Agilent 7820A GC and Agilent 5977E MS) and GC/TOF-MS (ALMSCO TOF-MS).

3. Results and discussion

3.1. Identification of the main constituents of face mask

Disposable face masks are manufactured with various plastics (polymers) and inorganic compounds. Given that the disposed face
masks into the environment have no available detailed information on their major constituents, it is required to analyze the types of materials made for them before further treatments. As depicted in the Fig. 1, the disposable face mask was disintegrated into several parts: filter layers 1 – 4, nose wire metal frame, and ear strap. At a glance, it can be realized that filter layers and ear strap are composed of plastics, while nose wire frame is made of metallic compound. Note that plastics are long chain organic carbon-based molecules. Each plastic has their own repeating units, which refer to monomers [38]. To obtain the information on the major repeating units from plastic parts of the face mask, FT-IR was used to characterize functional groups of each part. The resulting FT-IR spectra of plastic parts are shown in the Fig. 2(a) – (c).

The filter layers 1, 3, and 4 showed identical peaks in the two broad ranges from 2838 to 2952 and from 809 to 1456 cm⁻¹, which are characteristic FT-IR peaks of polypropylene (PP) [39]. In contrast, the filter layer 2 had identical peaks at 2915, 2849, 1472, 1377 and 718 with polyethylene (PE) [40]. Ear strap exhibited various peaks with nylon-6 [41]. Nose wire is composed of metal frame and covered by the filter layer 1. The major constituent of the metal frame was Fe (4.58 wt % of total mass of face mask), and the trace amount of other metal species (Zn, Ti, Ca, and Mn) were detected. In Table 1, relative mass portion of plastic and metallic parts of the face mask are summarized with identification of their chemical constituents. The mass portion of different parts of the face mask was measured gravimetrically. In overall, PP (73.33 wt%) and PE (13.77 wt%) are major constituents of the face mask, because they are made for mask filter. Also, nylon (8.27 wt%) and Fe (4.58 wt%) are other main components for ear strap and nose wire frame. To fundamentally observe the thermolytic profiles of the disposal face mask, TGA test was performed before its pyrolysis study. The TGA measurements were conducted under both the N₂ and CO₂ atmospheres between 35 and 900 °C. Thermolytic profiles of the face mask were plotted as residual mass and differential thermogravimetric (DTG) curves in Fig. 3. Because the negligible thermal degradation (mass change) was shown below 200 °C and above 600 °C, the mass loss and DTG curves were selectively described from 200 to 600 °C. Thermolytic patterns of the face mask were compared with those of two major constituents (i.e., PP and PE) of the face mask (Fig. 3(a)). Major thermal degradation of the face mask initiated around 330 °C and ended up at 495 °C. These start and end temperatures were positioned between those of PP and PE. This is plausible because the major constituents of the face mask are PP and PE as defined in the Fig. 1 and Table 1. The residual mass of 5.28 wt% at 600 °C in the N₂ condition indicates the existence of inorganic compounds, which are of Fe primarily, and small amounts of Zn, Ti, Ca, and Mn.

The TGA results of the face mask under the CO₂ atmosphere was also compared in reference to N₂ environment to determine the impact of CO₂ on face mask pyrolysis (Fig. 3(b)). TGA results under the both conditions showed the identical thermolytic patterns, confirming that no additional heterogeneous reactions between CO₂ and the solid face mask were occurred. Note that the Boudouard reaction (BR) is a thermodynamically preferred heterogeneous reaction between gas phase CO₂ and solid carbon at ≥ 710 °C [42]. Since there was negligible amount of solid carbon left at ≥ 500 °C, the BR could not occur according to the TGA study. It should be noted that any gas phase reactions from face mask pyrolysis could not be elucidated due to instrumental limitations of TGA unit. Also, gaseous products evolved from face mask pyrolysis were not able to be clarified with the TGA unit, because TGA study only offers a mass change at the given thermolysis temperature ranges. Thus, further studies to reveal the gaseous and liquid products should be performed to understand the thermolysis mechanism of the face mask and the resulting products from it.

3.2. Non-catalytic pyrolysis of disposable face mask

To identify the gaseous effluents from the mask pyrolysis, experimental setup for a single stage (one-stage) pyrolysis was established. The disposable face mask (1 g) was loaded into the tubular reactor within the temperature-programmed tubular furnace (35 to 600 °C at 10 °C min⁻¹) under both the N₂ and CO₂ environments. This temperature program was chosen to match with that of TGA study to identify the thermolysis mechanism of the face mask. The resulting gaseous effluents (H₂, CH₄, C₂H₆, and C₂H₄) are displayed as a function of pyrolysis temperature in the Fig. 4.

From mask pyrolysis, small quantities (< 0.6 mol%) of H₂ and C₁₂ hydrocarbons (HCs) were detected between 390 and 600 °C under both the N₂ and CO₂ conditions. Also, there was no notable difference shown between them. These results were contrast to the TGA result (Fig. 3), which indicated the substantial thermal degradation of the face mask between 320 and 490 °C. The mass loss of the face mask at this temperature range from the TGA study indicates the evolution of gaseous effluents. In fact, the production of H₂ and C₁₂ HCs from face mask pyrolysis was up to two orders of magnitude lower than that of other lignocellulosic biomass [43–45]. From the FT-IR analyses, it was confirmed that the main constituents of the face mask are PP, PE, and nylon. The repeating units of PP, PE, and nylon are propylene, ethylene, and long-chain amides, respectively. Therefore, it is estimated that volatile fraction of these plastics is indeed higher than that of lignocellulosic biomass [46,47] because the plastics did not produce a char at 600 °C as demonstrated in the TGA study (Fig. 3). However, the concentration of gaseous effluents from mask pyrolysis was lower. Thus, it can be inferred that the formation of long-chain HCs was occurred after face mask pyrolysis using this single-stage setup.

To confirm the presence of the long-chain HCs from one-stage pyrolysis, condensable HCs evolved from mask pyrolysis were collected through a cold solvent trap, filled with a dichloromethane at low temperature (~ 1 °C). The chemical compositions of the condensed gaseous products from one-stage pyrolysis were analyzed using GC-TOF/MS. Fig. 5 and Table 2 represent the compositional matrices of condensable pyrolysates. Major chemical constituents obtained from face mask pyrolysis were C₆₋₄₆ HCs. Both the N₂ and CO₂ conditions showed similar chromatogram patterns. This confirmed that face mask pyrolysis led to thermal degradation of plastics into long-chain condensable HCs, but it did not fully convert long-chain HCs into H₂ and C₁₂ HCs. In addition, the effectiveness of CO₂ was not observed under the one-stage pyrolysis.

To enhance the conversion of condensable HCs into more value-added gaseous products (H₂ and C₁₂ HCs), pyrolysis setup was modified. For more thermal cracking, additional furnace was installed right next to the one-stage pyrolysis setup. The second furnace (second heating zone) operated at 600 °C isothermally, while the first heating zone operated from 35 to 600 °C with a heating rate of 10 °C min⁻¹. The gaseous pyrolysates produced from two-stage pyrolysis are shown in the Fig. 6. From the two-stage pyrolysis the formations of H₂ (3.5 mol%), CH₄ (12.0 mol%), C₂H₆ (4.8 mol%), and C₂H₄ (9.5 mol%) were substantially enhanced from results of one-stage pyrolysis (< 0.6 mol% of H₂ and C₁₂ HCs) under the N₂ condition. This result well agreed with the hypothesis that condensable HCs can be converted into gaseous HCs with additional thermal energy. Considering that chemical structures of

Table 1: Chemical compositions of disposable face mask identified by FT-IR and ICP-OES.

| Parts                         | Chemical compositions | Weight percentage (wt.%) |
|-------------------------------|-----------------------|--------------------------|
| Filter layers 1, 3, 4         | PP                    | 73.33                    |
| Filter layer 2                | PE                    | 13.77                    |
| Ear strap                     | Nylon                 | 4.63 (Fe: 4.58, Zn: 0.02, Ti: 0.01, Ca: 0.01, Mn: 0.01) |
| Nose frame                    | Metals                |                          |
PP, PE, and nylon are mostly composed of C–C and C–H bonds [48], the thermal energy through the second heating zone significantly contributed to the improvement of reaction kinetics for C–C and C–H bonds scissions for the production of gaseous effluents (H2 and C1-2 HCs). The production of C1-2 HCs was likely due to the C–C bond scissions [48], while the production of H2 was attributed to C–H bond scissions [49]. The results of pyrolysis studies of the disposable face mask were identical in both the N2 and CO2 environments. This offers that CO2 can be a viable purge gas for pyrolysis of the plastic waste in the replacement of the conventional purge gas, N2.

3.3. Catalytic pyrolysis of disposable face mask

As discussed in the TGA experiments (Fig. 2 and Table 1), the disposable face mask contained higher than 95 wt% of volatile compounds (PP, PE, and nylon), which are mostly composed of C–C and C–H bonds. The production of C1-2 HCs was likely due to the C–C bond scissions [48], while the production of H2 was attributed to C–H bond scissions [49]. The results of pyrolysis studies of the disposable face mask were identical in both the N2 and CO2 environments. This offers that CO2 can be a viable purge gas for pyrolysis of the plastic waste in the replacement of the conventional purge gas, N2. Fig. 3. (a) Mass loss and DTG curves of face mask, PP, and, low density PE between 200 and 600 °C under the N2 environment, and (b) mass loss and DTG curves of face mask under the N2 and CO2 environments.

Fig. 4. Gas evolution profiles from mask pyrolysis with one-stage setup under the N2/CO2 atmospheres.
catalytic pyrolysis of the face mask in the two-stage setup. Ni catalyst was selected because of its known catalytic performance for C–H bond scissions (dehydrogenation for H₂ production) [36,50,51]. The evolution profiles of gaseous pyrolysates (H₂, CH₄, CO, C₂H₆, and C₂H₄) from catalytic pyrolysis against first heating zone temperature are plotted in Fig. 7. Under the N₂ environment, the performance of catalytic pyrolysis over Ni/SiO₂ was much greater than non-catalytic pyrolysis. In detail, the maximum concentration of H₂ increased from 3.5 to 55.1 mol%, and that of CH₄ increased from 12.0 to 18.2 mol%. In contrast, the concentrations of C₂ HCs were reduced. Thus, it is inferred that C–H and C–C bond scissions of C₂ and longer chain HCs over Ni/SiO₂ catalyst contributed to H₂ and CH₄ formations. The dominant production of H₂ over other HCs indicates that Ni catalyst selectively contributed to C–H bond scissions over C–C bond scissions.

In the CO₂ environment, the similar evolution trends were shown, which are dominant production of H₂ and CH₄ with the reduction of C₂H₆ and C₂H₄ formations (Fig. 7). Nonetheless, concentrations of H₂ and C₁₂ HCs were relatively lower, comparing to the results in the N₂ condition. The most noticeable difference of catalytic pyrolysis under the CO₂ with other pyrolysis setups was CO formation as a major gaseous product. Because of the major constituents of the face mask (i.e., PP, PE, and nylon) have limited quantity of oxygen, the high quantity of CO cannot be expected without the presence of CO₂ as an oxygen source. As discussed in the TGA result, the heterogeneous reaction (i.e., BR) between gaseous CO₂ and solid carbon could not occur at this temperature region. Therefore, there are three possibilities to produce CO in the presence of CO₂ over Ni/SiO₂ catalyst: (1) reverse water-gas-shift (RWGS) reaction (H₂ + CO₂ ↔ CO + H₂O), (2) CO₂ dry reforming (e.g., CH₄ + CO₂ ↔ 2H₂ + 2CO), and (3) gas phase homogeneous reactions (GPRs) between CO₂ and gaseous HCs evolved from the face mask pyrolysis through the second heating zone at 600 °C. The first suggestion is closely related to the presence of both H₂ and CO₂. Indeed, the concentration of H₂ was reduced at ≥ 330 °C in the presence of CO₂, comparing to N₂ condition. This temperature range was overlapped with the temperature window for CO production. In addition, CO₂ dry reforming also could be plausible due to the reduction of CH₄ concentration in the presence of CO₂, comparing to the pyrolysis result in the N₂ condition. Since both the RWGS and CO₂ dry reforming reactions produce CO, consuming H₂ and CH₄, the total molar concentrations of H₂, CO, and CH₄ should be matched when only these two reactions were occurred for CO formation (Fig. 7). However, higher concentrations of gaseous effluents were observed in the CO₂ condition than the N₂ condition (Fig. 7). Thus, it can be inferred that CO formation was not entirely ascribed to the RWGS and CO₂ dry reforming, thereby suggesting additional GPRs between CO₂ and gaseous HCs evolved from face mask pyrolysis. In other words, CO₂ acted as a soft oxidant for catalytic pyrolysis of the face mask over Ni/SiO₂. Therefore, the second highest peak of CO shown at 480 °C was likely ascribed to the GPRs (Fig. 7). Through the catalytic pyrolysis, the cumulative production of gaseous effluents increased 25 times and 165 times higher than two-stage pyrolysis and one-stage pyrolysis, respectively, under the CO₂ condition.

![Fig. 5. GC-TOF/MS results of condensable HCs obtained from mask pyrolysis under the N₂/CO₂ atmospheres.](image)

| Peak Notation | Component | Retention Time | Molecular Weight | Area (CO₂)×10⁻⁶ | Area (N₂)×10⁻⁶ |
|---------------|-----------|----------------|------------------|-----------------|----------------|
| C₄            | 4-methylheptane | 5.222          | 114              | 1.09            | 1.45           |
| C₅            | 2,4-Dimethyl-1-heptene | 6.517          | 126              | 18.54           | 38.19          |
| C₁₂           | 2,4,6-trimethyl-1-nonene (meso form) | 9.804          | 168              | 7.29            | 15.04          |
| C₁₅           | 2,4,6-trimethyl-1-nonene (racemic form) | 9.853          | 168              | 5.38            | 11.50          |
| C₂₁           | 2,4,6,8-tetramethyl-1-undecene (isotactic) | 12.180         | 210              | 47.54           | 58.80          |
| C₂₂           | 2,4,6,8-tetramethyl-1-undecene (heterotactic) | 12.266         | 210              | 17.81           | 21.28          |
| C₂₃           | 2,4,6,8-tetramethyl-1-undecene (syndiotactic) | 12.353         | 210              | 39.56           | 49.43          |
| C₂₆           | 2,4,6,8-tetramethyl-1,10-undecadiene (isotactic) | 12.909         | 222              | 8.66            | 84.17          |
| C₂₇           | 2,4,6,8-tetramethyl-1,10-undecadiene (syndiotactic) | 14.391         | 252              | 18.19           | 22.73          |
| C₃₀           | 2,4,6,8-tetramethyl-1,12-undecadiene (isotactic) | 15.139         | 264              | 14.44           | 20.57          |
| C₃₁           | 2,4,6,8,10,12-hexadecyl-1-pentadecene (isotactic) | 16.588         | 294              | 26.38           | 24.75          |
| C₃₂           | 2,4,6,8,10,12,14-heptadecyl-1,14-pentadecadiene (isotactic) | 17.335         | 306              | 22.86           | 19.36          |
| C₃₄           | 2,4,6,8,10,12,14,18-pentadecyl-1,14-pentadecadiene (isotactic) | 18.713         | 336              | 15.71           | 17.52          |
| C₃₅           | 2,4,6,8,10,12,14,16-octadecyl-1,16-heptadecadiene (isotactic) | 19.429         | 348              | 26.93           | 19.38          |
| C₃₆           | 2,4,6,8,10,12,14,16,18-nonadecyl-1,18-nonadecadiene (isotactic) | 21.378         | 390              | 22.35           | 21.34          |
| C₃₇           | 2,4,6,8,10,12,14,16,18,20-decadecyl-1,20-hexacosadiene (isotactic) | 23.174         | 432              | 24.45           | 27.49          |
| C₃₈           | 2,4,6,8,10,12,14,16,18,20,22,24-dodecaicosyl-1,24-pentacosadiene (isotactic) | 24.831         | 474              | 33.27           | 30.14          |
| C₃₉           | 2,4,6,8,10,12,14,16,18,20,22,24,26-dodecaicosyl-1,26-heptacosadiene (isotactic) | 26.504         | 516              | 32.95           | 34.64          |
| C₄₀           | 2,4,6,8,10,12,14,16,20,22,24,26-tridecamethyl-1,26-heptacosadiene (isotactic) | 28.608         | 558              | 26.77           | 33.42          |
| C₄₁           | 2,4,6,8,10,12,14,16,20,22,24,26,28-tetradecamethyl-1,28-nonacosadiene (isotactic) | 31.884         | 600              | 21.23           | 25.84          |
| C₄₄           | 2,4,6,8,10,12,14,16,20,22,24,26,28,30-undecamethyl-1,30-triacontadiene (isotactic) | 35.802         | 642              | 15.95           | 22.12          |
By switching purge gases of the face mask catalytic pyrolysis between N2 and CO, different H2/CO ratio was achieved from the face mask catalytic pyrolysis (Fig. 7). This immediate control of H2/CO ratios can be technically and industrially beneficial. Both H2 and CO are useful industrial chemicals and fuels to be used as direct fuels and intermediates for the production of more value-added chemicals through well-defined chemical processes. In the chemical processes, the control of H2/CO ratios is crucial to selectively produce desired chemicals such as saturated HCs [52], olefins [52], and alcohols [53].

In sum, this work offered a versatile thermo-chemical process to valorize the disposable COVID-19 face mask. To suggest an environmentally benign process, CO2 was utilized as a reaction medium for pyrolysis of the disposable face mask. Prior to pyrolysis study, chemical constituents of the disposable mask were investigated. Because major compounds of the face mask were plastics (PP, PE, and nylon), its pyrolysis resulted in the production of H2 and various ranges of HCs. To enhance the generations of value-added H2 and C1-2 HCs, multi-stage pyrolysis setup was employed for C-C and C-H bonds scissions of long-chain HCs. Further pyrolysis over Ni/SiO2 catalyst led to substantial conversion of longer chain (≥C2) HCs into H2 and CH4. During catalytic pyrolysis, H2 production was substantially improved under the N2 condition, while significant CO formation was shown under the CO2 environment due to RWGS, CH4 dry reforming, and gas phase reactions of CO2. Thus, H2/CO ratio was controlled in the catalytic pyrolysis when the reaction gas medium was changed. In contrast, CO2 worked as an inert gas for non-catalytic pyrolysis. These findings offer that CO2 can be considered a versatile purge gas and soft oxidant in various thermo-chemical processes, controlling exit gaseous effluents. Formations of syngas and C1-2 HCs from plastic waste (disposable face mask) and greenhouse gas (CO2) can contribute to the reduction of CO2 emission by counterbalancing fossil fuel production. This also could be an environmentally benign and process-efficient way to dispose of COVID-19 plastic waste, simultaneously generating value-added products.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/jcej.2020.126658.
Fig. 7. Gas evolution profiles from mask pyrolysis with 5 wt% Ni/SiO$_2$ catalyst under the N$_2$/CO$_2$ atmospheres.

Fig. 8. Comparison of overall gas production from one-stage pyrolysis, two-stage pyrolysis, and catalytic pyrolysis (5 wt% Ni/SiO$_2$) of the disposal face mask under the CO$_2$ environment.

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