Bibliometric analysis and an overview of the application of the non-precious materials for pyrolysis reaction of plastic waste

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Table S1 A summary of previous work on employing the title search using keywords such as "pyrolysis," "plastic," "waste," and "catalyst"

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| Title | Year | Findings | Ref. |
| Solar pyrolysis of waste plastics with photothermal catalysts for high-value products | 2022 | The production of hydrogen and jet fuel from plastic by photothermal catalytic pyrolysis provides an environmentally friendly way for high-value recycling of large amount of the waste plastics. | [[1](#_ENREF_1)] |
| Conversion of plastic waste into fuel oil using zeolite catalysts in a bench-scale pyrolysis reactor | 2022 | The pyrolysis oil produced from LDPE by ZSM-5 catalyst possessed a gross calorific value of 41 kJ g−1, almost equal to commercial diesel and fuel oil. | [[2](#_ENREF_2)] |
| Hydrogen production by pyrolysis-nonthermal plasma/catalytic reforming of waste plastic over different catalyst support materials | 2022 | The Ni/MCM-41 and Ni/Y-zeolite enhanced the hydrogen production from the pyrolysis–plasma/catalysis of the plastic. | [[3](#_ENREF_3)] |
| Valorizing plastic toy wastes to flammable gases through CO2-mediated pyrolysis with a co-based catalyst | 2022 | Co catalyst effectively induced chemical bond scissions, leading to substantially enhanced H2 formation. | [[4](#_ENREF_4)] |
| Catalytic pyrolysis of plastic wastes for liquid oils' production using zap usy zeolite as a catalyst | 2022 | The obtained results indicate that the use of ZAP USY zeolite decreased the required activation energy of all plastic waste, which resulted in decreased amounts of solid residue and increased gas production. | [[5](#_ENREF_5)] |
| A structured catalyst of ZSM-5/SiC foam for chemical recycling of waste plastics via catalytic pyrolysis | 2022 | The structured catalyst demonstrated excellent stability in all conditions and great potential to adjust product yield and composition by manipulating these factors, making it a promising catalyst for large scale operation of catalytic pyrolysis of waste plastics. | [[6](#_ENREF_6)] |
| Highly active Ni–Mg–Al catalyst effect on carbon nanotube production from waste biodegradable plastic catalytic pyrolysis | 2022 | The presence of Ni–Mg–Al demonstrated enhanced carbon product stability, reduced carbon defects, a greater carbon graphitization degree, and improved filamentous carbon thermal stability over the NiMg12 catalyst. | [[7](#_ENREF_7)] |
| Upgrading waste plastic derived pyrolysis gas via chemical looping cracking–gasification using Ni–Fe–Al redox catalysts | 2022 | Plausible reaction mechanisms were proposed to interpret the catalytic effects on tuning the morphologies, chemical structure and activity of the coke deposits. | [[8](#_ENREF_8)] |
| The effectiveness of plastic waste pyrolysis reactor with a zeolite catalyst as an appropriate technology in producing kerosene | 2022 | The results of kerosene production from the first, second, and third treatment were 122 ml, 137 ml, and 160 ml respectively. There was a significant difference in the average amount of kerosene produced between every treatment group, the most significant difference is within the third treatment by 35.67. | [[9](#_ENREF_9)] |
| A new sustainable strategy for oil, CH4 and aluminum recovery from metallised food packaging plastics waste using catalytic pyrolysis over ZSM-5 zeolite catalyst | 2022 | At 50 wt.% of ZSM-5, wax was converted into light hydrocarbon oil abundant in flammable compounds. Based on that the catalytic pyrolysis with 50 wt.% ZSM-5 zeolite catalyst is considered to be a promising thermo-chemical technology that can be applied at industrial scale to convert MFPW into oil (21%), gas (66%), Al (8.8%), and Al-free char particles (3.12%). | [[10](#_ENREF_10)] |
| Role of ZSM5 catalyst and char susceptor on the synthesis of chemicals and hydrocarbons from microwave-assisted in-situ catalytic co-pyrolysis of algae and plastic wastes | 2022 | The use of catalyst promoted the excessive cracking of biomass in co-pyrolysis, leading to higher gas and coke residue comparatively. | [[11](#_ENREF_11)] |
| Thermal and catalytic pyrolysis of waste polypropylene plastic using spent FCC catalyst | 2021 | The thermal pyrolysis produced maximum liquid oil (83.3 wt%) with gases (13.2 wt%), and char (3.0 wt%), while the catalytic pyrolysis using 0.1 catalyst to plastic ratio decreased the liquid oil yield (77.6 wt%), and char (2.7 wt%), with an increase in gases (19.7 wt%). | [[12](#_ENREF_12)] |
| Interaction between feedstocks, absorbers and catalysts in the microwave pyrolysis process of waste plastics | 2021 | Adopting continuous heating, reducing the residence time and the amount of activated carbon (AC) can promote wax formation and the maximum yield was 87.75 wt%. | [[13](#_ENREF_13)] |
| Impact of temperature on the activity of Fe-Ni catalysts for pyrolysis and decomposition processing of plastic waste | 2021 | FeNi1 catalyst synthesized by sol–gel method displayed higher activity towards the production of high quality carbon materials than FeNi2 catalyst at any temperature range investigated, due to the porous structure and the uniform dispersion of metal particles. | [[14](#_ENREF_14)] |
| Pyrolysis-catalysis of different waste plastics over Fe/Al2O3 catalyst: High-value hydrogen, liquid fuels, carbon nanotubes and possible reaction mechanisms | 2021 | More, purer and cleaner carbon nanotubes (CNTs) could be obtained from pyrolysis–catalysis of polyolefin (PP and PE), while more amorphous carbon and hydrogen were gathered from PS. | [[15](#_ENREF_15)] |
| Study on the effect of Kankara zeolite-Y-based catalyst on the chemical properties of liquid fuel from mixed waste plastics (MWPs) pyrolysis | 2021 | Combination of zeolite-Y, metakaolin, aluminum hydroxide and sodium silicate from Kankara Kaolin has proven effective in cracking heavy hydrocarbon into lighter liquid product which suggests that the liquid fuel so produced will deposit less sooth upon burning. | [[16](#_ENREF_16)] |
| The synergistic mechanism between coke depositions and gas for H2 production from co-pyrolysis of biomass and plastic wastes via char supported catalyst | 2021 | Appropriate PE ratios (>50%) can exert a positive synergy on gaseous conversion by regulating coke nature during co-pyrolysis of biomass and plastics. Furthermore, coke structure rather than content seems to exert more significant effect. | [[17](#_ENREF_17)] |
| Catalytic cracking of chlorinated heavy wax from pyrolysis of plastic wastes to low carbon-range fuels: Catalyst effect on properties of liquid products and dechlorination | 2021 | Excessive impregnation of Fe, Fe[20]/HY, showed the lowest cracking activity of heavy wax owing to the catalyst having lowest total acid sites. The restored catalytic activity was confirmed by using the regenerated Fe/HY catalyst for the cracking of chlorinated heavy wax. | [[18](#_ENREF_18)] |
| Pyrolysis of low-density polyethylene waste plastics using mixtures of catalysts | 2020 | Using a catalyst (bentonite, kaoline, silica gel and activated charcoal) gave this liquid yield in a shorter time | [[19](#_ENREF_19)] |
| Synthesis of C60 Nanotube from Pyrolysis of Plastic Waste (Polypropylene) with Catalyst | 2020 | The result of XRD and FESEM shows that C60 nanotubes are present in Nano figures, synthesized at 1000 ° C and with pyrolysis temperature 400° C. | [[20](#_ENREF_20)] |
| Selective production of aromatics from waste plastic pyrolysis by using sewage sludge derived char catalyst | 2020 | Principal ash components in sludge char could increase the aromatization degree of chain hydrocarbons and reduce the condensation degree of already formed aromatics. | [[21](#_ENREF_21)] |
| Clean energy from plastic: Production of hydroprocessed waste polypropylene pyrolysis oil utilizing a Ni–Mo/Laponite catalyst | 2020 | The hydroprocessing of polypropylene pyrolysis oil (HPPO-B) provides the opportunity to utilize plastic solid waste (PSW) as a transport fuel. The results of HPPO-B inspire and encourage pursuance of the hydroprocess path for protecting the environment from hazardous PSW. | [[22](#_ENREF_22)] |
| H2 production from co-pyrolysis/gasification of waste plastics and biomass under novel catalyst Ni-CaO-C | 2020 | The high H2 production (86.74 mol% and 115.33 mmol/g) and low CO2 concentration (7.31 mol%) in the gaseous products can be achieved with new catalyst Ni-CaO-C under the optimal operating conditions. | [[23](#_ENREF_23)] |
| CeO2 and La2O3 Promoters in the Steam Reforming of Polyolefinic Waste Plastic Pyrolysis Volatiles on Ni-Based Catalysts | 2020 | The La2O3 incorporation remarkably improved catalyst performance compared to the other two catalysts in terms of conversion (>99%), hydrogen production (34.9%), and coke deposition (2.24 wt %). | [[24](#_ENREF_24)] |
| Bimetallic carbon nanotube encapsulated Fe-Ni catalysts from fast pyrolysis of waste plastics and their oxygen reduction properties | 2020 | The iron-nickel alloy nanoparticles encapsulated in oxidized carbon nanotubes (FeNi-OCNTs) with a Fe/Ni ratio of 1:2 (FeNi-OCNT12) exhibited remarkable electrochemical performance as an ORR catalyst with a positive onset potential of 1.01 V (vs. RHE) and a half-wave potential of 0.87 V (vs. RHE), which were comparable to those of a commercial 20% Pt/C catalyst. | [[25](#_ENREF_25)] |
| Pyrolysis-gasification of wastes plastics for syngas production using metal modified zeolite catalysts under different ratio of nitrogen/oxygen | 2020 | Increasing in both the temperature and oxygen concentration contributed to the formation of n-paraffin. Due to the in-situ hydrogenation, the concentration of multiring aromatics, phenol and other compounds containing oxygen in the pyrolysis oil decreased significantly by Ce/Ni/ZSM-5 and La/Ni/ZSM-5 catalysts. | [[26](#_ENREF_26)] |
| Co-pyrolysis of biomass and plastic waste over zeolite- and sodium-based catalysts for enhanced yields of hydrocarbon products | 2020 | The catalytic presence of sodium prevented coke formation, which has been a major cause of deactivation of zeolite catalysts during co-pyrolysis of biomass and plastics. This finding indicates that the catalyst combination as well as biomass/plastic mixtures used in this work can lead to both high yields of valuable aromatic chemicals and potentially, extended catalyst life time. | [[27](#_ENREF_27)] |
| High temperature pyrolysis of municipal plastic waste using Me/Ni/ZSM-5 catalysts: The effect of metal/nickel ratio | 2020 | Cerium, lanthanum and magnesium showed better performance at a 0.5 ratio. On the other hand, 2.0 Mg:Ni and Mn:Ni ratios showed better properties than others. | [[28](#_ENREF_28)] |
| A lab scale waste to energy conversion study for pyrolysis of plastic with and without catalyst: engine emissions testing study | 2020 | The plastic pyrolysis (bottle) without any catalysts have the highest liquid fraction yield with an average yield of 24% while those with catalyst has lower yield (16–22%). Carry bags with zeolite catalyst yield liquid fraction of 22% at a conversion rate of 47%. | [[29](#_ENREF_29)] |
| The effect of Kankara zeolite-Y-based catalyst on some physical properties of liquid fuel from mixed waste plastics (MWPs) pyrolysis | 2020 | The physical properties obtained in this work for the catalyst that gave the optimum yield (10.49 wt%, 32.42 wt%, 27.09 wt%, and 30 wt%, of zeolite-Y, metakaolin, aluminum hydroxide, and sodium silicate, respectively) are close to that of conventional diesel oil | [[30](#_ENREF_30)] |
| Application of highly stable biochar catalysts for efficient pyrolysis of plastics: a readily accessible potential solution to a global waste crisis | 2020 | The corn stover derived biochar resulted in a liquid yield of about 40 wt% without wax formation. The liquid product comprised about 60% of C8–C16 aliphatic, 20% of mono-aromatic, and 20% of C17–C23 aliphatic hydrocarbons. | [[31](#_ENREF_31)] |
| Catalytic performance and debromination of Fe–Ni bimetallic MCM-41 catalyst for the two-stage pyrolysis of waste computer casing plastic | 2020 | The bimetallic catalysts exhibited remarkable effect on eliminating bromine from pyrolytic oil. Higher amounts of Fe in the catalyst is beneficial for the debromination efficiency. | [[32](#_ENREF_32)] |
| Catalytic pyrolysis of wood-plastic composite waste over activated carbon catalyst for aromatics production: Effect of preparation process of activated carbon | 2020 | When the activated carbon was synthesized using an H3PO4 impregnation ratio of 1:1 and a carbonization temperature of 700 °C, the yield of aromatics reached a maximum of 86.11% and the selectivity of mono-aromatics reached 64.01%. | [[33](#_ENREF_33)] |
| Reduction of polycyclic compounds and biphenyls generated by pyrolysis of industrial plastic waste by using supported metal catalysts: A case study of polyethylene terephthalate treatment | 2020 | The Pt catalyst was more effective to suppress the generation of polycyclic compounds and biphenyl derivatives during the PET pyrolysis than the Pd catalyst at temperatures from 400 to 800 °C. This was likely because the Pt sites catalyzes decyclization reaction and/or free radical mechanism that is dominant in thermal cracking of carbonaceous substances such as PET. | [[34](#_ENREF_34)] |
| Thermal degradation of waste plastics in a two-stage pyrolysis-catalysis reactor over core-shell type catalyst | 2019 | The encapsulation of Ni-Ce core by silica shell could effectively inhibit the sintering of nanoparticles under high temperature conditions. The highest amount of hydrogen production was found when the catalyst: plastic weight ratio was 1.0, and the catalytic reaction temperature was 800 °C. | [[35](#_ENREF_35)] |
| Deformation of virgin HD-PE, PP and waste PP Plastics into green fuel via a Pyrolysis-catalytic using a NiCO3 catalyst | 2019 | Green fuel was analysed by triple quadrupole GC–MS–MS, FT-IR spectroscopy, Perkin-Elmer series-II CHNS/O 24000, ICP, TGA its result founding into five categories as paraffin, cyclic paraffin, alcohols, esters and acetates. Conversion rates of virgin PP, HD-PE and waste PP into liquid green fuels were 87%, 89%, 90%, light gases 12.28%, 10.45%, 9.51% and residues 0.72%, 0.55%, 0.49% recovered from overall production process. | [[36](#_ENREF_36)] |
| Co-feeding effect of waste plastic films on the catalytic pyrolysis of Quercus variabilis over microporous HZSM-5 and HY catalysts | 2019 | Owing to the higher acidity and proper pore structure of HZSM-5, the catalytic co-pyrolysis (CCP) of Quercus (Q). variabilis and waste plastic films (PFs) over HZSM-5 achieved higher aromatic and lower coke formation efficiency than that over HY. | [[37](#_ENREF_37)] |
| High quality H2-rich syngas production from pyrolysis-gasification of biomass and plastic wastes by Ni–Fe@Nanofibers/Porous carbon catalyst | 2019 | The bimetallic Ni–Fe@CNF/PCs catalyst appeared as the optimal catalyst in affording the best compromise between catalytic activity and stability with the existence of the excellent dispersibility of the Fe0.64Ni0.36 alloy nanoparticles and the carbon nanofibers/porous carbon composite structure. | [[38](#_ENREF_38)] |
| Pyrolysis of chlorine contaminated municipal plastic waste: In-situ upgrading of pyrolysis oils by Ni/ZSM-5, Ni/SAPO-11, red mud and Ca(OH)2 containing catalysts | 2019 | ZSM-5 based catalysts showed higher efficiency in aromatization reactions. The change in the olefin content was followed via bromine number and FTIR spectra of pyrolysis oil, which resulted ∼3% and ∼4% decreasing using Ni/ZSM-5 and Ni/SAPO-11 containing catalyst mixtures. | [[39](#_ENREF_39)] |
| Preparation and application of metal loaded ZSM-5 and y-zeolite catalysts for thermo-catalytic pyrolysis of real end of life vehicle plastics waste | 2019 | ZSM-5 and y-zeolite catalysts were loaded by Ce2+, Cu2+, Fe2+, Fe2+, H+, Mg2+, Ni2+, Sn2+ and Zn2+ and the catalytic effects of both parent and metal loaded catalysts were tested by thermogravimetric method. Catalysts can decrease the activation energies of decomposition. Same order of the activation energy decreasing of both ZSM-5 and y-zeolite based catalysts was found: Cu<Ce<Mg<Ni<Fe(III)<Fe(II)<Zn<Sn, however, y-zeolite based catalysts had advanced properties in activation energy decreasing than ZSM-5 based. | [[40](#_ENREF_40)] |
| Kinetic identification of plastic waste pyrolysis on zeolite-based catalysts | 2018 | With the proper selection of pseudocomponents, the lumping approach is appropriate for catalyst evaluation and comparison as well, leading to a better understanding of the previous experimental results and the overall pyrolysis process. | [[41](#_ENREF_41)] |
| Waste HD-PE plastic, deformation into liquid hydrocarbon fuel using pyrolysis-catalytic cracking with a CuCO3 catalyst | 2018 | With the increase of the percentage of the catalyst used, the yield also increased and the yield without the catalyst was less. The liquid hydrocarbon fuel collected had a density of 86 g ml−1. | [[42](#_ENREF_42)] |
| Co-precipitation, impregnation and so-gel preparation of Ni catalysts for pyrolysis-catalytic steam reforming of waste plastics | 2018 | The type of carbon deposited on the Ni/Al-Co catalyst was mainly amorphous type carbon while it was in filamentous form for the impregnation (Ni/Al-Im) and sol-gel (Ni/Al-Sg) prepared catalysts. The maximum H2 yield of 67.00 mmol g1plastic was obtained from pyrolysis-catalytic steam reforming of waste polypropylene with more hydrocarbons in the product gases, while waste polystyrene generated the highest syngas yield of 98.36 mmol g1plastic with more oxygen-containing gases in the produced gases. | [[43](#_ENREF_43)] |
| Microwave-assisted co-pyrolysis of microwave torrefied biomass with waste plastics using ZSM-5 as a catalyst for high quality bio-oil | 2018 | The major chemical compounds of bio-oil were hydrocarbons, ketones, phenols, esters and alcohols (∼80%).Bio-oils with high hydrocarbon content (∼40% in the bio-oil) were obtained in the development of this experiment. | [[44](#_ENREF_44)] |
| Biofuel production from distillers dried grains with solubles (DDGS) co-fed with waste agricultural plastic mulching films via microwave-assisted catalytic fast pyrolysis using microwave absorbent and hierarchical ZSM-5/MCM-41 catalyst | 2018 | Microwave-assisted catalytic fast co-pyrolysis (co-MACFP) of distillers dried grains with solubles (DDGS) and waste agricultural plastic mulching films (WAPMFs) with SiC as microwave absorbent and hierarchical ZSM-5/MCM-41 as catalyst are implemented in a microwave-induced reactor. The total liquid yield and total hydrocarbon carbon yield in bio-oil first increase with the augment of temperature from 500 to 650 °C, and then decrease when temperature continues to rise | [[45](#_ENREF_45)] |
| Catalytic Pyrolysis of Waste Wood Plastic Composite Over H-V-MCM-41 Catalysts | 2017 | By catalytic pyrolysis over H-V-MCM-41, the content of aromatics, furans and hydrocarbons in bio-oil were increased, whereas the content of oxygenates and phenols were reduced. H-V-MCM-41 containing 10 wt.% vanadium showed the highest catalytic activity for the production of mono-aromatics among the H-VMCM-41 catalysts used. | [[46](#_ENREF_46)] |
| Effect of catalyst contact mode and gas atmosphere during catalytic pyrolysis of waste plastics | 2017 | PS produced highest aromatic yields up to 85% whereas PE and PP mainly produced aliphatic hydrocarbons over HZSM-5 zeolite. Hydrogen carrier gas reduced solid residue and also increased the selectivity of single ring aromatics in comparison to inert pyrolysis. | [[47](#_ENREF_47)] |
| Plastic waste to liquid oil through catalytic pyrolysis using natural and synthetic zeolite catalysts | 2017 | Mixing of PS with other plastic wastes lowered the liquid oil yield whereas all mixtures of PP and PE resulted in higher liquid oil yield than the individual plastic feedstocks using both catalysts. | [[48](#_ENREF_48)] |
| Pyrolysis–catalysis of waste plastic using a nickel–stainless-steel mesh catalyst for high-value carbon products | 2017 | The increase in sample-to-catalyst ratio reduced the amount of carbon deposited on the mesh catalyst in terms of g carbon g−1 plastic. The carbons were found to be largely composed of filamentous carbons, with negligible disordered (amorphous) carbons. | [[49](#_ENREF_49)] |
| Fe–Ni–MCM-41 Catalysts for Hydrogen-Rich Syngas Production from Waste Plastics by Pyrolysis–Catalytic Steam Reforming | 2017 | A synergistic effect of iron and nickel was observed, particularly for the (10:10) Fe–Ni–MCM-41 catalyst, where the highest gas yield (95 wt %) and highest H2 production (46.1 mmol g–1plastic) and CO production (31.8 mmol g–1plastic) were shown. | [[50](#_ENREF_50)] |
| Co-production of hydrogen and carbon nanotubes from catalytic pyrolysis of waste plastics on Ni-Fe bimetallic catalyst | 2017 | Catalyst with more Fe loading produced more hydrogen and deposited carbon, due to higher cracking ability and the relatively lower interaction between active sites and support. The presence of Ni in Ni-Fe bimetallic catalyst enhanced the thermal stability and graphitization degree of produced carbons. | [[51](#_ENREF_51)] |
| Effect of growth temperature and feedstock:catalyst ratio on the production of carbon nanotubes and hydrogen from the pyrolysis of waste plastics | 2015 | Conversion of plastic into carbon nanotubes was 29.1 wt.% when 0.5 g LDPE was used, but reduced to 13.1 wt.% with 1.25 g LDPE. | [[52](#_ENREF_52)] |
| Transportation fuels from catalytic co-pyrolysis of plastic wastes with petroleum residues: evaluation of catalysts by thermogravimetric analysis | 2013 | The number of acid sites and catalyst pore size along with impregnation with transition metals such as W/Ni and Ni/Mo are found as the key factors for the energy efficient conversion of polymers and VR to liquid hydrocarbons. | [[53](#_ENREF_53)] |
| Pyrolysis and gasification of landfilled plastic wastes with Ni− Mg− La/Al2O3 catalyst | 2012 | The maximum gas yield, gas calorific value and cold gas efficiency were achieved when the Ni− Mg− La/Al2O3 catalyst was used at 900 °C. | [[54](#_ENREF_54)] |
| Catalytic Pyrolysis of Municipal Plastic Waste to Fuel with Nickel-loaded Silica-alumina Catalysts | 2011 | The gasoline fraction has higher iso-paraffins and a smaller concentration of olefins and aromatics for a lower Si/Al ratio and higher acidity of catalyst | [[55](#_ENREF_55)] |
| Catalytic pyrolysis of plastic wastes with two different types of catalysts: ZSM-5 zeolite and Red Mud | 2011 | Red Mud needs higher temperatures than ZSM-5 zeolite to exert a catalytic effect in pyrolysis, since similar results to those obtained without catalyst are obtained at 440 °C, while at 500 °C a higher yield of gases and a greater proportion of aromatics in the liquids is obtained. | [[56](#_ENREF_56)] |
| Hydrogen-rich gas production from waste plastics by pyrolysis and low-temperature steam reforming over a ruthenium catalyst | 2011 | Because low-temperature steam reforming can be also expected to reduce thermal degradation rates of the catalyst, the pyrolysis-steam reforming process with a Ru catalyst has the potential for use in small-scale production of hydrogen-rich gas from waste plastics that can be used for power generation. | [[57](#_ENREF_57)] |
| Pyrolysis–gasification of plastics, mixed plastics and real-world plastic waste with and without Ni–Mg–Al catalyst | 2010 | Filamentous carbons were observed for the used Ni–Mg–Al catalysts from the pyrolysis–gasification of polypropylene, high density polyethylene, waste plastic and mixed plastics. However, the formation of filamentous carbons on the coked catalyst from the pyrolysis–gasification of polystyrene was low. | [[58](#_ENREF_58)] |
| Pyrolysis of plastic wastes: 2. Effect of catalyst on product yield | 1999 | The presence of PE increases alkane content, whilst PS leads to higher aromatic content in the end product. The alkene formation benefited from the presence of PP. | [[59](#_ENREF_59)] |

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