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Review

Thermochemical Conversion of Automotive Paint Sludge: A Review

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Abstract

Automotive paint sludge (APS) is a hazardous and non-biodegradable waste generated during the painting process in the automotive sector. Approximately 40% of paint sprayed on automotive parts ends up as waste, resulting in huge amounts of APS generated every year. Its complex composition, which includes heavy metals and other toxic substances, poses significant environmental and health risks if not properly managed. Conventional disposal methods are increasingly unsustainable, necessitating for alternative approached that enable both waste reduction and resource recovery. This review explores existing literature on the thermochemical conversion of APS, with attention on combustion, incineration, pyrolysis and gasification. The paper looks at process performance, operational challenges, product distribution, and environmental implications, while identifying key knowledge gaps and emerging research directions. Thermochemical conversion technologies show potential for APS valorization via the production of syngas, liquid fuels, and char, alongside significant waste volume reduction. However, the high moisture content of APS presents serious difficulties, as it can lead to incomplete combustion, increased hazardous emissions, and the generation of heavy metal-contaminated ash requiring disposal. Mitigation strategies like pre-drying and advanced emission control systems are effective but energy-intensive and economically burdensome. Emerging approaches, particularly co-gasification and co-pyrolysis with high-calorific feedstocks, show promise in overcoming these challenges through synergistic interactions. Thermochemical conversion offers a viable route for sustainable APS management, enabling resource recovery and energy generation while lowering environmental impacts. However, technical and economic constraints associated with feedstock properties and process requirements limit its standalone application. Future research should focus on scale-up feasibility to support the transition of APS thermochemical conversion technologies from laboratory to industrial application, while considering environmental and economic requirements.

Keywords: automotive paint sludge; thermochemical conversion; energy recovery; pyrolysis; gasification

1. Introduction

The automotive industry continues to grow in response to rising global mobility demands, driven by rapid economic growth and industrialization across both developed and emerging regions. High vehicle ownership and production rates in the European Union (EU), the United States (USA), Australia, Japan, and South Africa (SA), is evidence to this ongoing trend [1]. Japan had about 488 vehicles per 1,000 people over similar recent years and Australia around 578 per 1,000 [2]. Across EU, many countries report ownership levels exceeding 520 vehicles per 1,000 people, and SA's ownership rate stands notably higher than the African average at approximately 176 vehicles per 1,000 people

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[2–4]. As a result, this growth has led to a parallel rise in waste generation, along with an increased need for the reduction of waste production and improvement in the recycling process, thus reducing landfill use [5].

There are four main stages in the production process of automobiles, which are stamping, welding, painting and assembly [6]. The painting stage plays an important role in providing both aesthetic quality and corrosion protection to vehicle bodies. Automotive paints consist of four distinct layers: the primer, primer surfacer, base coat and clear coat. The primer, which is the bottom layer is responsible for strong adhesion between the coat and the vehicle body. Above this layer, the primer surfacer provides mechanical strength and improves resistance to corrosion and environmental degradation. The base coat imparts colour and visual appeal, incorporating pigments, alumina platelets, and mica particles uniformly dispersed within a polymeric binder. The clear coat functions as a protective barrier, protecting the underlying coatings from ultraviolet (UV) radiation, oxidation and physical wear. Each layer has a distinct purpose and chemical composition based on the type of car, make, and the year of production [7–9].

Throughout these operations, the industry makes use of huge amounts of natural resources such as water, fossil fuels and natural metals, all the while producing various forms of waste products, which include liquid, solid and gaseous waste streams, either hazardous or non-hazardous wastes [10,11]. An estimated 5% of the world's industrial waste comes from this industry, with OEMs (original equipment manufacturers) contributing approximately 56 kg of waste per automobile, of which 12.5% is considered hazardous [12,13]. Hazardous wastes arise at multiple stages of production, as shown in Figure 1 [11]. Hazardous wastes arise at multiple stages of production, as shown in Figure 1 [11]. Among these, the painting process is the main source of hazardous waste due to the generation of paint residues, solvents and automotive paint sludge (APS), which constitutes the largest hazardous fraction. APS is classified under the EU (European Union) waste code 080113*, which refers to waste paints and varnishes containing organic solvents or other hazardous substances, with the asterisk (*) indicating that the waste is considered hazardous [11].

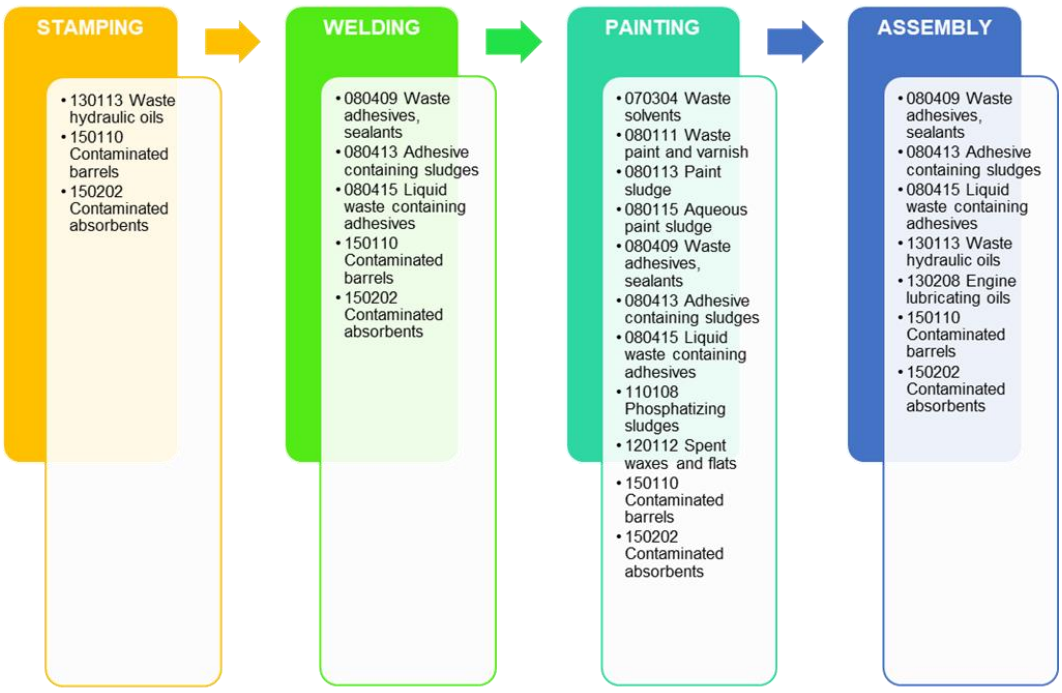

Figure 1. Points of hazardous waste formation during the production of automobiles [Adopted from 11].

In large automobile manufacturing plants, vehicle bodies are painted within enclosed paint spray booths where automated spray systems are used to apply successive paint layers uniformly. Even with this automation, the general transfer efficiency of the process is pretty low. About 40–50%

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of the sprayed paint does not reach the automotive surface and escapes into the surrounding air as fine mist or overspray [14,15]. The overspray is normally caught by water curtains or wet scrubbing systems, producing a mixture of water and paint particles. The mixture is then transported by suction systems to sludge pits to recover water through solid-liquid separation. Automotive paint sludge is the semisolid substance that is left over after the water recovery process [14]. Studies have reported that on average automotive manufacturing plants generally generate between 1.5 and 5.0 kilograms of paint sludge per vehicle produced [16,17]

Most countries still manage automotive paint sludge by dewatering, followed by landfilling or incineration. These practices carry significant risks to the environmental and human health because they contribute to soil, groundwater and air pollution [18]. Though the waste management hierarchy prioritizes recycling, recovery and reuse over waste disposal, these methods remain considerably unexploited for APS. Besides, landfilling is becoming increasingly costly and needs long-term environmental monitoring. Therefore, a move from conventional disposal to more efficient and sustainable treatment technologies is necessary, and thermochemical conversion is amongst these processes [18].

While incineration and landfilling remain the dominant strategies for managing APS, they have serious negative effects on the environment [18]. Incineration and co combustion of paint sludge can produce toxic emissions including polychlorinated dibenzo p dioxins, dibenzofurans, polycyclic aromatic hydrocarbons and heavy metals, which pose threats to air quality and human health, and may result in hazardous ash residues requiring careful control and disposal [11,19,20]. This has driven the exploration of alternative treatment methods [18].

Reuse in primers and sealants, integration into building materials like asphalt and concrete, and biological stabilization through composting or bioleaching are some of the ways that APS recycling has been explored [14]. The heterogeneous composition of APS often requires process-specific reagents and pre-treatment steps, while integration into construction materials is generally limited to low substitution levels (generally ≤ 5 wt.% in cementitious systems, though up to ~20 wt.% replacement has been reported for bituminous binders) due to reductions in mechanical strength [21–23]. Unlike conventional biosolids or wastewater treatment sludge, which consist mostly of biodegradable organic matter and nutrients which can be useful for agricultural activities [24,25], APS is made up of synthetic polymers, solvents and heavy metals that make its reuse difficult [16]. The typical method of treating biosolids is biological degradation [26], while APS necessitates physico-chemical treatments such as coagulation, flocculation and dewatering. APS resistance to biological degradation is further complicated by the presence of inorganic components and cross-linked polymers [11,14,24]. Biological treatments involve the use of microorganisms along with nutrients or amendments such as composting agents, bulking materials (e.g., sawdust or straw), or bioleaching microorganisms, frequently result in dilution effects rather than complete contaminant removal [14,27].

These alternative treatment methods require exact sludge composition control and are limited in application, as contaminants are often immobilized rather than fully degraded. Together with the challenges faced with incineration and landfilling, this propels the need for more sustainable and integrated treatment approaches that enable both energy recovery and complete pollutant destruction, and minimal impact to the environment.

Recovering valuable metals and nutrients, limiting the release of VOCs, and reducing the volume of waste can be made possible by energy recovery from APS, through thermochemical conversion processes. For example, [19] showed that pyrolysis of APS produced a gas fraction rich in methane, carbon monoxide, and ammonia and a liquid fraction containing hydrocarbons like styrene and toluene, illustrating both effective breakdown of VOC precursors and recovery of energy-rich chemical products. In addition to reducing VOC emissions, 28displayed that the chemical looping gasification process for oil-based APS produced syngas, which is combustible and mostly constituted of hydrogen (3.88%), carbon monoxide (1.69%), and methane (0.87%). A 2020 study by [20]. on the co-combustion of paint sludge and lignite showed higher heat output and helped immobilize

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hazardous metals in ash, which decreased volume and generated energy. Earlier work by [29] converted APS by pyrolysis into useful ceramic materials along with recoverable liquid hydrocarbons and off-gases, further demonstrating multi-product energy and material recovery potential from APS. While thermochemical technologies have been developed for other wastes, such as municipal solid waste and different biomass residues, including food and agricultural wastes (as common targets for bio-oil, syngas, and biochar production), APS poses particular difficulties due to its complex chemical properties, high moisture content, and heterogeneous composition [30–32].

This review focuses on the recent advances in research and development in gasification and pyrolysis of the sludge and seeks to identify the difficulties and challenges involved and thus identify a potential gap to be explored that can contribute toward finding a permanent solution to this waste.

2. Characteristics of APS

Automotive paint sludge comes in two main types, solvent-based and water-based, depending on the paint type used [19]. Water-based paint is mostly used for base coats, whereas solvent-based ones are common for clear coats [17]. Lately, water-based paints have gained popularity because they release fewer VOCs than solvent-based options [17,33]. Solvent-based paint sludge generally exhibits a higher calorific value, and its solvent fraction can be recovered through distillation, contrary, no widely established recycling route currently exists for water-based paint sludge. As a result, solvent-based sludge is often mixed with water-based sludge and co-processed in cement kilns as a supplementary fuel [19]. Even with some differences, both sludge types are characterized by high carbon content and complex chemical compositions that makes their management hard [19].

The chemical makeup of APS differs according to the formulation of the paint and application process. Basically, APS is largely constituted by water and organic solvents along with uncured polymer resins, pigments, curing agents, flotation additives and other minor formulation ingredients [14]. Researchers generally characterize APS using physicochemical parameters such as moisture content, ash content, organic matter, pH, hardness, calorific value and heavy metal concentration [34]. Relevant data from literature is shown in Table 1 below. For example, [35] studied paint sludge collected from Toyota manufacturing facility in Ramnagar, Bangalore, India, after mechanical dewatering. The sludge sample contained 29.9 wt. % moisture (as received), 75.2 wt.% volatile matter, 2.1 wt.% fixed carbon and 22.7 wt.% ash. The ash was mostly TiO_2 (53%) and Al_2O_3 (18%), which reflects the common use of white-pigmented coatings. On a dry basis, APS normally holds 70 - 90 wt.% organic matter, mostly originating from uncured polymeric binders, monomers and residual solvents, resulting in a higher heating value (HHV) in the range of 4,000 - 6,000 kcal/kg (17 - 25 MJ/kg) (Ruffino et al., 2023), which is comparable to lignocellulosic biomass, which typically has an HHV in the range of 17 - 21 MJ/kg [36]. This indicates its potential for energy recovery through incineration or thermochemical conversion processes such as pyrolysis or co-processing in cement kilns [14,17,34].

In addition, APS demonstrates solubility in organic solvents such as xylene and thinner waste, but is largely insoluble in water, hexane, or alcohol. This property offers potential for in-plant recycling or material recovery, particularly of primer materials, which have been reported to be up to 15% cheaper than virgin primers when recovered from sludge residues [34]. Clearcoat sludge is mostly organic binders and solvents, resulting in low ash content (e.g., 4.84 wt.% on dry basis) and greater HHV of 26.57 MJ/kg [37]. Basecoat and primer sludges are composed of inorganic pigments and fillers, leading to higher ash (36.17 wt.% for basecoat, 60.24 wt.% for primer) and lower HHV (18.64 MJ/kg and 9.88 MJ/kg, respectively) [37]. These differences come from clearcoat's emphasis on gloss without pigments, versus coloured layers use of inorganics for opacity and adhesion. Basecoat and primer sludges also show elevated metals like Ti, Cr, Co and Cu, because of pigments (e.g., TiO2), anticorrosives, and fillers. Clearcoat has far lower metal amounts, confirming its minimal inorganic content. Such metals accumulate as oxides, increasing ash and reducing energy density [37,38]. APS is extremely sticky and difficult to handle because of the presence of uncured paint resins, which cure and form a film when heated. To make APS management easier, detackification chemical agents are often added to the sludge [14].

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Overall, the presence of heavy metals, VOCs and other toxic organic substances in APS make it an extremely hazardous waste, as summarized in Table 1. These substances have the ability to cause long-lasting environmental effects and serious health and safety hazards, including toxicity, reactivity, corrosivity, flammability and potential carcinogenic effects [19,39]. Due to its high total organic carbon and dissolved organic carbon contents, APS is unsuitable for direct landfill disposal, as leachate may contaminate soil and groundwater if improperly managed [34]. The non-biodegradable nitrogen-containing polymers also make its degradation process and long-term environmental stability even more hard [19].

2.1. Thermogravimetric Analysis

Thermogravimetric analysis (TGA) is a thermal characterization technique used to evaluate the thermal stability and decomposition behaviour of materials by measuring changes in their mass as a function of temperature or time under a controlled atmosphere. It provides important information on moisture content, volatile matter release, thermal degradation stages and residual ash formation. TGA is widely extensively used in the characterization of solid wastes and fuels, including biomass, plastics, and industrial wastes, to determine their suitability for thermochemical conversion processes such as pyrolysis, gasification and combustion [40–42]. For complex industrial residues such as APS, TGA is particularly useful for understanding the degradation behaviour of the organic binders, solvents, and polymeric resins that constitute a significant fraction of the sludge [19,37].

According to [43], APS shows stages of thermal decomposition at 471 °C, 596 °C, and 767 °C, which can be associated with the breakdown of volatile chemicals and organic resin compounds. A mass loss of 20% was observed while heating up to 1200 °C. The pigment-rich nature of APS was reflected in the residual, which was mainly composed of inorganic oxides such as TiO_2, AlO_3, and BaO. [44] evaluated APS's suitability for microwave-assisted pyrolysis and energy recovery using thermal, FTIR, and proximate analytical techniques. The sludge had a heating value of 22.3 MJ/kg and comprised 38.3% moisture, 28.8% ash, 22.2% volatile matter, and 10.7% fixed carbon. FTIR analysis revealed strong hydrocarbon-related functional groups from organic resins and binders, while water-related peaks reflected the high moisture content. Thermal analysis revealed that APS melts and degrades between 260 and 500 °C, which is consistent with the breakdown of polymeric paint components. Microwave pyrolysis converted most of the organic matter into gases and condensable liquids. The product yields were 64.7% gas, 26.1% aqueous, 0.27% liquid oil, and 8.9% solid residue. The authors also noted that the inherent moisture in APS can enhance microwave absorption, suggesting that APS may be treated by microwave pyrolysis without the requirement of extensive pre-drying. The study of Tian et al., 2023 compared solvent-based and water-based APS using TG-FTIR and Py-GC/MS, observing that both sludge types began significant weight loss near 200 °C. Primary mass loss occurs between 130–560°C for solvent-based APS and 109–548°C for water-based APS, with peaks linked to H2O, CO2, CH4, NH3, phenols, and CO release detected by TG-FTIR. The activation energies vary between 165-179 kJ/mol, with order-based nucleation models. The products include hydrocarbons (47%), oxygenated compounds (43%), and other species like nitrogen-containing compounds, e.g., melamine. The results of Py-GC/MS show the energy-rich volatiles.

Thermogravimetric analysis of polyurethane paint sludge by [45] shows that the pyrolysis process occurs in distinct thermal degradation stages depending on the paint type. Based on the study, waterborne polyurethane paint sludge has a decomposition process that occurs in two stages. The first stage is when volatiles are released, which happens between 200-325 °C, while the second stage is when major decomposition takes place between 330-500 °C, during which significant weight loss is observed due to the breakdown of large organic molecules into smaller gaseous compounds. In contrast, oily polyurethane paint sludge decomposes in four stages, beginning at approximately 200 °C and extending up to 790 °C, with the final stage corresponding to the pyrolysis of fixed carbon residues. During thermal decomposition, a variety of gaseous and condensable products are produced. The major gaseous products include CH_4, CO_2, CO, and water vapour, along with hydrocarbons such as alkanes, olefins, and aromatic compounds. The high percentage of volatile

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matter, around 97.81% for waterborne paint sludge, suggests that the major part of the material will be transformed into gaseous or liquid forms during the pyrolysis process. Furthermore, the paint sludge has a calorific value of roughly 18.84 MJ/kg, which is close to that of low-grade coals [34,46].

[28] investigated the thermal behaviour of oil-based APS during chemical looping gasification using Red mud as an oxygen carrier. Thermogravimetric–differential thermal analysis (TG–DTA) showed that APS decomposes through several stages. The first stage, at temperatures below 270 °C, refers to the evaporation of free and bound moisture. The second stage, in the range of 270 to 480 °C represents low-temperature pyrolysis, where large organic molecules in the paint resins undergo chain scission reactions to form smaller hydrocarbons and release CO_2. In the following stage of high-temperature pyrolysis, the curve in the TG graph is stable, with most of the volatile compounds already evaporated and a mass loss of about 93 wt.%. In this stage, compounds of tar and gaseous organic molecules undergo decomposition to form substantial amounts of CH_4 and CO_2, with a portion of the methane gas undergoing a second stage of decomposition to form H_2 and CO. In the last stage, which is a chemical looping gasification reaction, CH_4 and CO_2 react with red mud oxygen carrier, and CO_2 reacts with the remaining carbon The metal oxides Fe_2O_3 and Al_2O_3 in the red mud facilitate the reaction, producing H_2 and CO gas and thus showing the suitability of APS as a fuel in a gasification process [28].

Recent work by [37] gives a comprehensive thermal decomposition characterization of five APS streams, producing data that is relevant to pyrolysis and gasification. Using TG/DTG analysis under both nitrogen and air atmospheres across multiple heating rates, the authors found that APS decomposes in three stages: moisture and VOC removal (30-220 °C), devolatilization and resin cracking (220-550 °C) and carbonization of inorganics (550-800 °C). Clear coat and base coat sludges displayed the highest volatile content, greatest mass loss during devolatilization, higher heating values and pyrolysis activation energies of 126-140 kJ/mol which is comparable to that of lignocellulosic biomass, confirming their potential as feedstocks for thermochemical conversion processes. Whereas primer and electrocoat sludges were found to contain more than 50 wt.% ash and displayed limited mass loss, indicating restricted energy recovery potential but strong catalytic potential due to their metal oxide content, which could act as in situ catalysts, accelerating char conversion and tar cracking during cogasification or copyrolysis with carbonaceous materials. Phosphate coat sludge, with only 3.17 wt% volatiles, 73.46% ash and the lowest HHV of 0.611 MJ/kg, decomposed very little and was thus not a strong candidate for thermal treatment and more suitable for metal recovery or civil engineering uses like cement/aggregate replacement. The kinetic evaluation exhibited activation energies in the range of 74-140 kJ/mol for primary decomposition, with higher second-stage values reflecting the stability of cross-linked paint resins. The compositional differences between APS types influence drying requirements, devolatilization behaviour, tar formation and ash-related issues during thermochemical conversion.

In addition to single-feedstock studies, the thermochemical behaviour of APS has also been investigated in mixed-waste systems. [47] analyzed a hazardous waste mixture consisting of paint slag and tar slag using TGA and observed a three-stage pyrolysis process. The first stage, which ranges between 40 °C and 105 °C, involved evaporation of moisture. The main pyrolysis stage involved a significant gas evolution. The thermogravimetric analysis indicated that three main decomposition peaks occurred at 302 °C, 752 °C, and 1079 °C. These peaks indicated that successive degradation reactions of organic compounds occurred. Similarly, [48] used the thermogravimetric technique to examine the thermal breakdown properties of APS during co-pyrolysis with sewage sludge. The authors reported that 10% char residue is produced following co-pyrolysis and APS heating value of 18.6 MJ kg^{-1}. They also discovered that when sewage sludge is co-pyrolyzed with APS, changes in TG curves indicated that synergistic effects occurred. These effects enhanced the formation of H_2 and CO gases. These effects were attributed to catalytic reactions that occurred because of the metal oxide compounds present in ash. These compounds acted as a catalyst. These findings suggest that APS can participate effectively in co-pyrolysis systems, which may lead to

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increased gas yields through the occurrence of catalytic reactions caused by the metal oxides contained in the sludge ash.

The thermal behavior of APS displays characteristics that fall between those of biomass and synthetic polymers when compared to other common waste-derived fuels. Lignocellulosic biomass typically decomposes over a range of 200-500 °C, with specific peaks related to the degradation of hemicellulose, cellulose, and lignin, with 10-20% char residue typically produced because of the presence of lignin in the biomass [49–51]. Due to their high volatile matter content and low ash content, synthetic polymers, such as plastics like polyethylene (PE), polypropylene (PP), and polystyrene (PS), have a single peak associated with plastic degradation that usually occurs over a range of 350-500 °C with minimal residue formed [42,49,51,52]. Tyres are primarily composed of natural rubber and synthetic rubbers such as styrene–butadiene rubber and butadiene rubber. TGA studies show that pyrolysis occurs in stages, beginning with additive volatilization at 200–320 °C, followed by natural rubber degradation at 320–400 °C, and decomposition of styrene–butadiene and butadiene rubbers at 400–520 °C, with only minor mass loss above 520 °C, indicating that pyrolysis is largely complete by ~500 °C [53,54]. Significant char residues are produced, often 30–40%, as a result of the presence of carbon black and mineral fillers [51]. APS therefore demonstrates intermediate behaviour: it begins losing mass at relatively low temperatures due to moisture release similar to biomass, while its main devolatilization range overlaps with both biomass and plastics. However, APS typically produces moderate char yields due to its inorganic pigment content.

The aforementioned studies show that APS has thermally degradable organic components that produce combustible gases, condensable hydrocarbons and inorganic-rich char during thermal treatment. The single-feedstock TGA studies such as those by [43,44] and [19] has a thermal decomposition behaviour primarily consisting of moisture evaporation (30-220°C) followed by devolatilization (220-550°C) of organic paint resins and the formation of gaseous hydrocarbons during pyrolysis. The organic matter decompose to form energy carriers, whereas the inorganic pigments remain as residues with potential catalytic activity, supporting the use of APS in thermochemical conversion processes such as pyrolysis, gasification and co-processing. The thermal decomposition profile of APS, characterized by a main DTG region between approximately 200 and 550 °C and moderate char formation, compares favourably with other waste-derived fuels. These similarities in thermal behaviour indicate that APS can act as a viable feedstock for energy recovery. Co-treatment with other wastes can improve thermochemical conversion performance. While single-feedstock APS decomposition is largely governed by its intrinsic composition and which in turn produces moderate gas yields because of the presence of inorganic components (ash) and high moisture, co-processing with other wastes can promote synergistic reactions that enhance gas formation and overall energy recovery.

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Table 1. Characterization of APS (adapted from Ruffino et al., 2023).

Characteristic	Unit	Kalani et al., 2025					Abu Bakar et al., 2022	Yaganeh et al., 2022	Gadhekar et al., 2019	Rosli et al., 2018	Salihoglu et al., 2018	Yenikaya et al., 2018	Dalmazzo et al., 2017		Januri et al., 2015	Tian et al., 2015	Gautam et al.,2010
		C	PR	B	E	P							WBB	C			
Moisture content	%						29.9	70.65	54.5	2.4	63.4 ± 0.29	63.4	50.9	60.8	2.4	-	29.9
Ash (dry basis)	%	4.84	60.24	36.17	51.28	73.46	22.7	-	24.83	2.9	-	-	5.5	-	2.9	-	22.7
Volatile matter (dry basis)	%						75.2	-	75.66	75.9	72.6 ± 6.28	-	72.4	94.5	75.9	-	75.2
Fixed carbon (dry basis)	%	54.70	22.81	37.75	30.78	3.17	2.1	-	-	3.2	-	-	-	-	3.2	-	2.1
Calorific value	MJ/kg	26.57	9.88	18.64	14.70	0.611	-	-	23.87	22.6	7.68	-	17.91	20.17	22.6	-	18.13
pH	-	-	-	-	-	-	-	-	7.6	-	9.4	9.44	-	-	-	-	-
Fe	mg/kg	459	887	4817	18750	15483	6.6	0.43 (%) (Fe_2O_3)	-	-	-	-	0.268	0.08	-	-	6.2(%) (Fe_2O_3)
Al	mg/kg	17301	10274	26983	22484	10086	19.1	18.0 (%) (Al_2O_3)	-	-	-	-	1.02	-	-	-	18.0(%) (Al_2O_3)
Ti	mg/kg	18	106	238	88	3	56.2	54.2 (%) (TiO_2)	-	-	-	-	6.81 (%)	0.0044 (%)	-	-	53.0(%) (TiO_2)
Si	mg/kg	688	526	961	658	7487.79	7.2	2.15 (%) (SiO_2)	-	-	-	-	-	-	-	-	6.8(%) (SiO_2)
Ba	mg/kg	277	22973	1244	4796	181	9.0	-	-	-	-	6.4	6.57	41.7	-	6210	8.5(%) (BaO)

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P	mg/kg	121	211	856	51228	52216	0.4	-	-	-	-	-	-	-	-	0.19 (g/kg)	0.4(%) (P_2O_2)
Na	mg/kg	2523	323	1112	1465	6642	0.2	-	-	-	-	-	-	-	-	-	0.2(%) (Na_2O)
K	mg/kg	32	33	656	5382	23049	0.2	-	-	-	-	-	-	-	-	0.34 (g/kg)	0.4(%) (K_2O)
Ca	mg/kg	2171	4339	1794	12507	8266	0.4	2.30 (%) (CaO)	-	-	-	-	-	-	-	1.28 (g/kg)	0.4 (%) (CaO)
Mg	mg/kg	1232	255	1791	1126	201	0.4	0.66 (%) (MgO)	-	-	-	-	-	-	-	2.02 (g/kg)	0.14 (%) (MgO)
Cl	mg/kg	0.32	0.21 (%)	0.083 (%)	0.16 (%)	0.083 (%)	0.14	-	-	-	-	440	-	-	-	-	-
Co	mg/kg	0.0(%) (Co_3O_4)	0.011(%) (Co_3O_4)	0.0(%) (Co_3O_4)	0.0(%) (Co_3O_4)	0.00(%) (Co_3O_4)	-	-	-	-	-		144	0.847	-	4.80	-
Cr	mg/kg	65	109	199	192	185	-	106 (%)	-	-	152.2		228	9.17	-	38.1	-
Cu	mg/kg	3	104	70	422	10	-	-	-	-	-	<1	171	7.07	-	47.5	-
Ni	mg/kg	10	9	22	35	3	-	16.2 (%)	-	-	10.7	<0.5	18.3	5.21	-	42.4	-
Pb	mg/kg	-	-	-	-	-	-	15.2 (%)	-	-	10.5	-	17.0	9.85	-	<0.003	-
Zn	mg/kg	0.016(%) (ZnO)	0.016(%) (ZnO)	0.0107(%) (ZnO)	2.17(%) (ZnO)	1.84(%) (ZnO)	-	-	0.12		-	<1	172	186	-	28.1	-

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3. Overview of Other Recycling Processes

Automotive paint sludge contains significant organic (solvents, resins) and inorganic (pigments, additives) materials and thus offers a lot of recoverable energy potential [55]. However just like sewage sludge, it comes with difficulties like high moisture, ash and heavy metals. Energy recovery from APS can be achieved through biological or thermochemical pathways, each accompanied by inherent trade-offs.

Anaerobic digestion (AD) is a main biological method, which is considered a relatively cost-effective management option for paint sludge, enabling the reduction of organic contaminant release while simultaneously generating biogas [16,56]. Traditional AD has low uptake in paint sludge treatment because paint solvents and resins inhibit microorganisms activity [57]. Nonetheless, recent studies suggest some potential. For example, [16] added biochar into a mesophilic AD reactor (APS mixed with conventional sludge) and found that it greatly improved the biogas yield. The optimum blend (3:1 APS: sludge with 26 g/L biochar) produced ~530 mL biogas (about 50% methane) within one month. This showed that APS can be used as a feedstock for biogas production given that conditions are optimized. Similarly, vermicomposting (mixing APS with other biosolids) has been tested; one study found it could immobilize Cr^{6+} (reducing it from 5 to 0.2 mg/kg) by coprocessing paint sludge with sewage sludge [58]. Even so, biological routes generally yield limited energy compared to sludge with only biodegradable organics, and residual heavy metals remain in the digestate/compost [59].

4. Thermochemical Conversion

Thermochemical conversion refers to a group of heat-driven processes that transform solid or liquid waste materials into valuable products such as syngas, oil, char, or directly into energy in the form of heat and electricity. These processes take place by means of chemical decomposition of organic matter under controlled temperature and oxygen conditions. Based on the extent of oxidation and reaction environment, thermochemical conversion can be widely categorized into incineration (combustion), pyrolysis, gasification, and co-gasification [60,61].

Thermochemical methods are particularly suitable for treating carbon-rich and high-calorific wastes such as APS, which is characterized by its high organic and hydrocarbon content. In comparison to biological or physicochemical treatments, thermochemical processes can achieve volume reduction, energy recovery, and detoxification of hazardous compounds in a single step [14,17,31].

Moisture content is a critical parameter in thermochemical conversion processes, as excessive moisture can negatively impact process efficiency and product quality [56]. Fresh APS is extremely wet, having an average water content of about 90%. Most thermal treatment methods therefore start with mechanical dewatering, that is typically carried out through filter presses or centrifuges, which can decrease moisture content from around 90% to 80–70% [14]. This is followed by thermal drying, which can further reduce the moisture content to below 5 -15%, thereby significantly improving process efficiency [14,24].

In low oxygen or no oxygen processes such as gasification and pyrolysis, high moisture content can be a drawback. It can restrict devolatilization and slow reaction kinetics, which can lower the yield and energy quality of the combustible gases or syngas produced [63]. For example, in a patented process by [64], APS is first dried under vacuum at temperatures below 200 °C to evaporate water and low-boiling solvents prior to pyrolysis taking place. This resulted in obtaining equal amount of gaseous, liquid and solid fractions (approximately 1:1:1 by weight) with the gaseous fraction rich in hydrocarbon compounds. Without such pretreatment, the latent heat of water vaporization greatly reduces process efficiency. On the other hand, [65] performed pyrolysis of wet paint sludge and reported product distributions of 25–37% gas, 34–63% liquid, and 25–37% solid (depending on resin type), with only 30–40% char recovery because of energy losses associated with

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moisture evaporation. The moisture content of APS also directly influences the hydrogen-to-carbon (H/C) ratio of the reacting system, which plays an important role in determining product distribution and quality. Water or steam levels in moderation are known to promote favourable reactions such as steam reforming of volatiles, char gasification, water-gas reactions and water-gas shift reactions. This has the effect of enriching hydrogen formation and enhancing gas quality in gasification and reforming-based processes. But when moisture exceeds the optimal threshold, the heat-sink effect takes over and cancels out those benefits, lowering the energy content of product gases and reducing the overall gasification efficiency [56].

In combustion systems, elevated moisture content decreases flame temperature and combustion efficiency, leading to increased auxiliary fuel requirements and higher emissions per unit of useful energy recovered. Certain co-processing approaches (e.g. cement-kiln feed), APS is mixed with dry fuels or treated chemically (e.g. with desulfurizers) to enable safer combustion without extensive drying [35]. Bearing a high organic carbon content, APS is commonly incinerated as hazardous waste or co-fired in cement kilns as refuse-derived fuel. Even after mechanical dewatering, APS typically still it contains more than 60 wt% moisture, which severely limits the suitability of this feedstock for thermochemical conversion and its acceptability as refuse-derived fuel in cement kilns. The high moisture content increases combustion instability, reduces thermal efficiency, and restricts kiln feed rates to below 5% of clinker capacity due to risks of incomplete burnout and elevated carbon monoxide (CO) emissions. Thus, for improving handling and storage and for increasing downstream conversion efficiency, thermal pre-drying is a necessity. Conventional heating, hot gas drying, or microwave irradiation has been commonly used to reduce moisture before incineration, pyrolysis, quasi-pyrolysis, gasification, or co-firing. In particular, microwave irradiation can offer the additional advantage of rapid volumetric heating and enhanced bound-water release due to dipolar interaction [66]. Overall, sufficient thermal pre-treatment is normally a prerequisite for the effective thermochemical processing of APS [66]. Energy and cost for drying remain a significant issue, with, advanced drying (microwave, superheated steam) proposed but rarely demonstrated at industrial scale.

4.1. Incineration

[67], reviewed the disposal and recycling pathways for hazardous paint wastes generated by the automotive and engineering industries, reporting incineration as the dominant option for paint sludge management. It was pointed out that paint waste has a high calorific value, making it suitable as a supplementary fuel. However, its incineration presents risks of heavy-metal emissions, toxic ash and potential dioxin formation, drawing attention to the regulatory problems associated with direct combustion, i.e., incineration without prior treatment, stabilization, or material recovery. Several recycling alternatives, such as incorporation into road materials, coloured concrete and sealant formulations were also presented. These approaches were found to be technically feasible, simple, financially viable and offering environmentally beneficial reuse pathway. Their use is however limited by regulatory requirements, emissions concerns (e.g., VOCs), variability in sludge composition, logistical challenges, and limited large-scale implementation, making their feasibility largely site-specific [67]. The study did not examine thermochemical pathways such as pyrolysis or gasification, nor did it provide emission data or combustion performance metrics. Such analysis would have enable a more robust comparison between conventional incineration and emerging thermochemical processes.

Direct incineration also known as combustion or burning of APS is generally done only in specialized systems [60]. Sludge is burned in a provided chamber with excess air, mainly producing carbon dioxide and water, leaving behind a mineral residue in the form of ash. The carbon dioxide generated is normally released with the flue gas into the atmosphere, although some facilities may implement emission control measures or carbon capture technologies to reduce its environmental impact [68]. The ash needs to either be properly disposed of or, whenever possible, reused as a raw material in the production process of construction products [**Error! Reference source not found.**].

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The main product which is heat must be immediately utilized for power production as storage is not practical [69]. However, when incineration is considered as a treatment option, technology and cost become major limitations. For incineration to be economically viable, the process must operate autothermically, meaning enough water must be removed through mechanical dewatering so that the sludge can sustain combustion without needing auxiliary fuel [70]. There are still some difficulties in the management of emissions and ash. Particulate matter, VOCs, acidic gases and other pollutants emitted during incineration must be captured or reduced as part of emission control, and the ash must be appropriately managed to minimize environmental damage [69,71].

The most common commercial incineration route is co-processing in cement kilns. Paint sludge is fed into a cement rotary kiln along with raw materials; it effectively burns at ~1400 - 2000 °C, integrating its inorganics into the clinker and using its organic part as fuel. Cement co-processing of APS is already a commercial practice in some regions as Muniz et al., 2003 noted. Industrial trials, conducted at a Toyota supplier in collaboration with ACC Cement in India by [35], have demonstrated that cement kilns provide the high temperatures and long residence times required for the complete destruction of organic components in paint sludge. They also showed that cement kiln co-processing can effectively absorb both the energy and mineral value of the waste without forming harmful emissions, as the combustion products are treated within the kiln's existing pollution control systems. In this sense, cement kiln co-processing functions as a waste-to-energy incineration system, simultaneously achieving hazardous waste destruction and energy recovery while avoiding the creation of residual ash. In contrast, conventional incineration and landfilling are generally regarded as less sustainable options, with cement kiln co-processing ranking higher in the waste management hierarchy due to its combined material and energy recovery benefits.

A study by [72] investigated particulate formation and trace-element behaviour during the combustion of recovered paint solids (RPS) and coal, both individually and in co-combustion. The RPS, generated from automobile paint-booth overspray had a heating value of about 24.92 MJ/kg and was characterized by high volatile matter (76.5% wt), substantial moisture content (46.3% wt) and elevated chlorine levels (3419 ppm) relative to coal, which has a heating value of about 28.04 MJ/kg, lower volatile matter (48.3% wt), lower moisture content (27.7% wt), and significantly lower chlorine levels (10 ppm). Combustion experiments were performed in a laboratory-scale tubular furnace at 1200 °C for both RPS alone and for mixtures with sub-bituminous coal. Co-combustion significantly increased the formation of submicrometer particles (geometric mean = 24.5 nm), contributed to more reducing local conditions and the formation of volatile chlorine species. Trace element partitioning also shifted: arsenic, chromium and lead exhibited greater volatilization and enrichment in fine-mode ash, whereas mercury was fully volatilized and showed a 62 % increase in oxidized $HgCl_2$ under co-combustion. This study points out the energy recovery potential of RPS thermal treatment while emphasizing the need for emission control measures to manage increased fine particle and trace metal emissions.

4.2. Pyrolysis

Pyrolysis is commonly used for sludge treatment because it offers advantages like efficient processing, volume reduction and the recovery of valuable products [73]. By definition, pyrolysis is an endothermic process in which solid waste is thermally broken down into gaseous, liquid, and solid intermediates in the absence of oxygen. It is normally carried out at temperatures between 250°C to 800°C, depending on the type of feedstock and pyrolysis method such as slow pyrolysis, fast pyrolysis, and flash pyrolysis [74–76]. Pyrolysis methods differ mainly in heating rate and residence time. Slow pyrolysis operates at low heating rates (around 5 - 7 °C/min) and long residence times (over 1 hour), favouring char production. In contrast, fast pyrolysis uses high heating rates (>100 °C/min) at moderate temperatures (400 - 600 °C) and short residence times (0.5 - 2 s) to maximize oil yield [74]. Flash pyrolysis is an extreme form of fast pyrolysis that involves very high heating rates and short residence times (<1 s), producing up to 60–75 wt% oil. But before it can be used as a fuel

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for transportation, this oil must be upgraded because it has a lower energy content and less desirable properties than traditional fossil fuels [77].

The liquid product, alternatively referred to as pyrolysis oil, is a heterogeneous mixture that contains considerable amount of oxygen and alkaline properties. Through catalytic cracking, hydrodeoxygenation and other upgrading processes, this oil can be additionally refined into fuels like gasoline, diesel, and jet fuel or into important chemicals like phenols, organic acids, and aromatic compounds [78,79]. The solid residue (char) may be used as a fuel or applied to soil to act as an enhancer or used as an adsorbent to remove contaminants such as heavy metals, dyes and organic pollutants from water and air [76,80]. Producer gas, pyro gas, or syngas are some of the common names utilized to describe the gaseous pyrolysis product. It is mostly composed of hydrogen, carbon monoxide, methane, carbon dioxide and other light hydrocarbons, and it can be used as a combustible fuel for heat and power generation or further processed as a feedstock for chemical synthesis and fuel production [81,82]. Despite its advantages, conventional sludge pyrolysis can face limitations, like the poor application performance of the resulting residues, which is mostly due to high concentrations of heavy metals, residual organic contaminants, low nutrient value, and inconsistent physical properties, restricting their use in soil amendment, adsorption, or other beneficial applications. Moreover, the low volatiles and high ash content of the feedstock can reduce the yield and quality of the gaseous and liquid products [54,83,84].

[29] showed one of the earliest thermochemical valorization routes for APS through pyrolysis under controlled nitrogen atmospheres. APS, obtained from Ford Motor Company plant was first dried (initial moisture content not specified) and pyrolyzed at 600 °C for 2 hours in a quartz tube reactor with nitrogen purged to achieve an inert environment. The process generated 36.5 wt % off-gases, 28.4 wt % liquid hydrocarbons, and 35.1 wt % solid char. The solid residue consisted mainly of calcium titanate ($CaTiO_3$), barium titanate ($BaTiO_3$), titanium dioxide (TiO_2), amorphous alumina (Al_2O_3) and carbon. Titanium nitride (TiN) was formed by sintering at 1000 °C in ammonia. The produced materials were further utilized as reinforcing additives by blending them with aluminum powder to fabricate metal matrix composites and by incorporating them as 20 wt % fillers in polypropylene. In the latter case, the impact strength remained comparable to talc-filled polypropylene (0.4 ft-lb/in), while Young's modulus increased from 2164 MPa for unreinforced polypropylene to 3108 MPa with the APS-derived filler. This work showed that APS can be transformed into low-cost, composition-tolerant ceramic composites suitable for "low-tech" reinforcement applications such as in the fabrication of metal matrix composites (MMCs) and reinforced plastic components, providing a viable alternative to conventional disposal and demonstrating the potential for value-added utilization of APS.

Another study by Muniz et al., 2003 showed that pyrolysis "deactivates" APS by destroying organics and providing substantial reduction in the quantity of the solids. The authors studied the deactivation of paint sludge containing alkyd, latex, and polyurethane resins utilizing batch pyrolysis at temperatures between 450 and 650 °C. The process resulted in major mass reductions ranging from 70% to 96%, depending on the type of resin. The gaseous products, were made up mostly of light hydrocarbons (methane, ethane, ethylene and propane), showed high calorific value, indicating potential for energy recovery. Liquid fractions consisted predominantly of aromatic and aliphatic hydrocarbons and could be reused as solvents or fuel. The study demonstrated that higher temperatures and shorter reaction times favoured improved energy efficiency, while reaction time had limited influence on the solid residue reduction. Although conducted in a batch reactor at laboratory scale, this work provides foundational evidence supporting pyrolysis as an effective thermal treatment method for automotive paint sludge.

The pyrolysis behavior of solvent-based (OAPS) and water-based (WAPS) automobile paint sludge is compared in an experimental study by [27] using thermogravimetric–Fourier transform infrared (TG-FTIR), pyrolysis–gas chromatography–mass spectrometry (Py-GC/MS), and iso-conversional kinetic models including Flynn–Wall–Ozawa (FWO) and Kissinger–Akahira–Sunose (KAS). The authors identified three pyrolysis stages, with the main devolatilization taking place in

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the second stage. The activation energies for OAPS (179.09 kJ/mol via FWO; 168.28 kJ/mol via KAS) were a little higher than those for WAPS (175.90 kJ/mol via FWO; 164.80 kJ/mol via KAS), suggesting that OAPS requires more energy for thermal decomposition and is therefore more thermally stable. Gas evolution analysis indicated that CH_4, CO_2, and NH_3 were the dominant gaseous products for both sludges, while Py-GC/MS showed that OAPS pyrolysis primarily produced hydrocarbons (47.2%), whereas WAPS produced a higher proportion of oxygenated compounds (42.7%). The results from the proximate and ultimate analysis showed that OAPS contains high volatile matter (96.36%) and a relatively high heating value (29.67 MJ/kg) compared to WAPS (72.41% and 20.93 MJ/kg, respectively), leading to a massive mass loss during pyrolysis (≈93% for OAPS), with notable compounds like styrene and melamine detected among the decomposition products. OAPS (1.74%) had a far lower ash content than WAPS (25.04%). These results imply that OAPS is more suitable for energy recovery due to its higher calorific value and hydrocarbon-rich products, whereas WAPS, with its higher oxygenated compound content and ash fraction, may be more suited for chemical recovery but with lower fuel quality.

In a fixed bed reactor, [86] investigated the pyrolysis of paint sludge at 1000–1400 °C under nitrogen. They proved that paint sludge can be converted into carbon black with a maximum yield of 25.1 wt.% and a high percentage of carbon, more than 96%. They concluded that the formation of graphitized carbon structures and spherical carbon black particles is enhanced at high temperatures.

4.2.1. Catalytic and Microwave Assisted Pyrolysis

Thermal (non-catalytic) pyrolysis uses only heat as a driver for the degradation of organic materials. This needs higher temperatures as well as longer residence times (Lyu et al., 2024). Catalytic pyrolysis, however, employs catalysts to lower activation energies, enabling lower temperatures, faster rates and targeted products while suppressing nitrogenous pollutants like NH_3 and HCN [87–89]. Catalysts boost gas yields, produce narrower-boiling liquids with superior fuel properties, and drive deoxygenation/aromatization for stable, low-oxygen oils [87].

In comparison to traditional pyrolysis, which relies on external heating through conduction and convection [81], microwave-assisted pyrolysis uses electromagnetic radiation to heat the material internally and volumetrically. This allows for more uniform and rapid heating, improving heat transfer within the feedstock. As a result, microwave-assisted pyrolysis can handle wet materials more effectively, since water absorbs microwave energy and promotes internal heating, decreasing the need for extensive pre-drying. In addition, the enhanced heating efficiency facilitates more effective breakdown of hydrocarbon chains compared to conventional pyrolysis [81,90]. [91] applied microwave pyrolysis at 600–1000 Watts for 10–45 minutes to APS char impregnated with 5 M potassium hydroxide (KOH), using a KOH-to-char ratio of 1:3. As a result, carbonization and pore formation occurred under a nitrogen flow. Higher power and longer irradiation (e.g., 1000 W, 45 min) yield higher carbon content (up to 89 wt %), surface area (434 m^2/g) and pore volume (0.290 cm^3/g), though mesopore-dominated (2.67 nm). The yield of the activated APS char reduced with power and time because of volatile removal, improving porosity but falling short of supercapacitor standards (>1000 m^2/g). However, Idris et al., 2020 did not evaluate the electrochemical performance of the AC in a real supercapacitor or compare it to commercial carbons. If they had built actual cells and tested cycling stability, the outcome would indicate whether APS-derived AC meets device requirements. [92], looked into AC as a microwave absorber (MWA) for the pyrolysis of APS. 200 g of APS was pyrolyzed at 600 W for 30 minutes under N_2 after being mixed with 10, 15, 20, and 25 weight percent AC. They found that, in the absence of AC, the gas phase accounted for 75.5% of the pyrolysis product distribution. Adding 10 % AC shifted the balance to obtain 79.61% liquid phase, giving the highest oil yield of 9.9 g. The 25 % AC sample produced the greatest liquid of 84.91 %, however the liquid was mostly aqueous, indicating a limited yield of the desired organic oil fraction. Solid-char yields changed only slightly across loadings, ranging from 7.89% to 11.35% of the original APS, indicating that the application of microwave absorbers primarily affects the liquid and gas fractions rather than the solid residue. The authors conclude that 10 % AC is optimal for maximizing oil recovery from

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APS. [44] used microwave-assisted pyrolysis on APS collected from a Malaysian automotive plant, which contained 38 % water and had a calorific value of 22.3 MJ/kg. A modified commercial microwave (250 mL min^{-1} N_2 purge, 150 mL min^{-1} carrier) was utilized while varying three sample weight loading, microwave power, and radiation time. The optimum conditions for maximizing liquid hydrocarbon oil were 200 g loading, 1000 W power and 30 min radiation, yielding 0.1 g (0.27 % of the feed) liquid oil. Under these conditions the product distribution was 8.9 % solid char, 0.27 % liquid oil, 26.13 % aqueous phase and 64.7 % gas. Yields plateaued beyond 30 min, indicating longer residence does not improve recovery and may increase cost. Microwave-assisted pyrolysis can efficiently turn high moisture APS into usable oil and gas while using water as a built-in heating medium, making it a viable alternative to conventional hazardous waste disposal.

4.2.2. Co-Pyrolysis

To overcome issues faced with single feedstock pyrolysis such as low energy content, high ash or contaminant levels, unfavorable product distribution, and poor char quality, recent research has heavily focused on co-pyrolysis of sludge with biomass or other additives. Because sludge and biomass differ in ash content, volatile matter, and elemental composition, synergistic effects can arise during co-processing, improving product quality and enhancing overall resource utilization [73].

Work by [48]]investigated the co-pyrolysis of sewage sludge (SS) and APS, focused at optimizing the disposal of sewage sludge in cement kiln systems. The study was conducted utilizing thermogravimetric analysis (TGA) coupled with thermogravimetric-mass spectrometry (TGA-MS). The authors first characterized the individual pyrolysis behaviours and showed that APS possesses low moisture of 2.17%, high ash content of 54.22%, and a calorific value of 18.58 MJ/kg, while SS exhibited high moisture of 54%, low ash of 8.47%, and a slightly higher calorific value of 18.81 MJ/kg, highlighting the complementary properties of the two feedstocks for co-pyrolysis. They found that co-pyrolysis had both synergistic and antagonistic effects. Synergistic effects were mostly caused by hydrogen free radicals in sewage sludge and catalytic iron components in paint sludge ash, enhancing gas production, including compounds such as CH_4, CO and C_6H_6. Antagonistic effects arised from changes in the physical form during mixing, leading to film formation that prevents volatile release and raises coke yield while reducing tar output. The study identified an optimal blend ratio of 60% SS and 40% APS that maximizes synergistic benefits while reducing antagonistic effects. According to the kinetic results, the activation energy required for co-pyrolysis is higher than that needed for individual pyrolysis processes. And thermodynamics imply that the process of co-pyrolysis is not spontaneous. Evolved gas analysis also confirms increased production of methane, carbon monoxide and other small hydrocarbons in the presence of APS, related to the catalytic role of iron and improved radical reactions. Overall, this study adds on the understanding of co-pyrolysis mechanisms, providing valuable guidance for sustainable energy recovery and hazardous waste management in cement plants.

[86] employed thermogravimetric analysis and kinetic modelling to evaluate the co-pyrolysis of paint sludge, oil sludge, waste printed circuit boards (PCBs) and penicillin fermentation residue. Their results found that paint sludge/PCBs/penicillin decomposed at 150-550°C (volatile-rich), while oil sludge broke down at 550-900°C. The paint sludge/penicillin blend showed the strongest synergy, driven by mutual volatile, lowering activation energies and enhancing pyrolysis performance, whereas oil sludge/paint showed antagonism. Selecting the right waste blend is key in optimizing hazardous waste co-pyrolysis. Although insightful, additional validation under continuous reactor settings and life-cycle assessment are required to determine whether large-scale adoption is feasible.

4.3. Gasification

Sludge gasification is a thermochemical process that converts dried sludge into syngas and ash at high temperatures, usually around 1000 °C, using gasifying agents like air, steam, oxygen, carbon dioxide, or combinations of them [70,93]. With pure oxygen as the oxidizing agent, it can run at even higher temperatures (1400–1700 °C) and pressures (0.6–2.6 MPa) [70]. The process releases thermal

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energy, which can be used for power generation or process heat [70]. Syngas, also known as synthesis gas, is a combustible mixture made up of carbon monoxide, hydrogen, methane, as well as heavier hydrocarbon species like tars and lighter hydrocarbons like ethane and propane [93]. Syngas can be made from nearly any hydrocarbon-based feedstock, including natural gas, coal and organic waste, via reactions with steam, oxygen, or carbon dioxide [100,101]. The produced syngas composition and quality is controlled by the feedstock properties, the chosen gasifying agents, reactor configuration, catalytic influences, and operating conditions [93].

Gasification takes place through four major sequential stages, which are drying, pyrolysis, oxidation and reduction [74]. Each stage assists to breaking down complex hydrocarbons into simpler gaseous components through a series of reactions [94,95]. During the drying stage, moisture is removed from the feedstock and turned into steam. This steam can contribute to the thermal decomposition of the material into syngas. In the pyrolysis stage, the carbonaceous materials of the feedstock begin to decompose into a carbon-rich char and volatile species in the absence of oxygen [93]. The process then goes to the oxidation stage, where partial combustion of the feedstock with a gasifying agent, results in the production of carbon dioxide and water, while also releasing heat that sustains the overall reaction. Finally, in the reduction stage, high-temperature chemical reactions occur in an oxygen limited environment, turning the remaining char and intermediate gases into syngas. These include the Boudouard reaction, steam reforming, the water-gas shift reaction and methanation. Majority of these reactions are endothermic and require the supply of energy, except for methanation, which is exothermic [94–96].

APS gasification remains underexplored, as evidenced by the identification of a single relevant study [53], indicating a clear gap in the literature. On the other hand, the gasification of other industrial sludges, particularly municipal sewage sludge, has been broadly studied. Comprehensive reviews of sewage sludge gasification were published by [56 and 97]. Different reactor types, including fixed-bed, bubbling fluidized-bed, circulating fluidized-bed, as well as auger and rotary kiln reactors, were explored. They showed that gas yield and tar formation are significantly impacted by reactor design [56,97]. Fluidized-bed and circulating fluidized-bed reactors provide high gas output and clean syngas, whereas downdraft fixed-bed reactors produce low-tar syngas but may face slag and pressure issues. Auger reactors yield high-quality gas with low tar, whereas rotary kilns and plasma reactors can improve tar removal but suffer from low heat transfer or high energy demand, respectively [56,97]. Catalytic processes were also studied using metal oxides like CaO, Fe_2O_3 and Ni-based catalysts to enhance hydrogen production and decrease tar formation during sludge pyrolysis and gasification [56,97].

The chemical looping gasification (CLG) of oil-based wet APS (OWAPS) was explored as an alternative to conventional thermal treatments by [53]. Unlike traditional gasification, which directly reacts feedstock with the gasifying agent which can be air, oxygen, or steam, CLG uses a solid oxygen carrier to supply lattice oxygen, generating reactive oxygen species (ROS) that selectively improve CH_4 cracking and CO_2 reduction while minimizing direct combustion [53,98,99]. Red-mud (RM) containing 30.5 % Fe_2O_3 and 21.2 % Al_2O_3 was used as an inexpensive iron-based oxygen carrier (OC) by Yang et al., 2024. Optimal conditions were obtained at 1000 °C for 60 min using carrier-gas flow of 2.4 L/h and an RM-OC : APS mass ratio of 2 : 1 yielding flammable-gas concentrations of 3.88 % H_2, 1.69 % CO and 0.87 % CH_4. These corresponded to gas productions of 0.37, 0.16 and 0.09 L/g APS respectively. The mechanistic analysis links these results to lattice-oxygen migration from Fe_2O_3 to the reaction zone, where ROS drive CH_4 dehydrogenation and CO_2 reduction. Gas concentrations were diluted by a large N_2 sweep, so the reported yields underestimate the actual production potential in a larger reactor. The performance declined when the RM-OC addition ratio exceeded 2 : 1, indicating structural collapse of the carrier at higher loadings. Only OWAPS was examined, leaving other APS types untested. While the RM-OC showed good regeneration over ten cycles, a modest decrease in gas output was observed, suggesting potential long-term deactivation.

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5. Gaps in Knowledge

Despite the increasing interest in thermochemical valorization of APS, there are still several knowledge gaps that limit the development of scalable and economically viable processes. Firstly, although some studies, like the ones carried out by [37] and Tian et al., 2023, have given some useful insights into APS composition and thermochemical behaviour, APS composition can vary significantly depending on paint systems (e.g., electrocoat, primer, basecoat and clearcoat) and manufacturing processes. These variations lead to differences in polymeric binders, pigments, solvents and inorganic fillers. Most available studies still rely on a limited number of samples, making it difficult to generalize thermochemical behaviour and predict product yields or pollutant formation across different APS sources. Majority of APS studies are restricted to thermogravimetric analysis or small batch reactors, whereas continuous reactor systems commonly used for other feedstocks (e.g., fluidized-bed or rotary kiln reactors) remain largely unexplored. Experimental studies using continuous or pilot-scale reactors are needed to evaluate heat transfer, residence time and gas–solid interactions under realistic operating conditions. Catalytic upgrading strategies are rarely examined for APS, even with their proven effectiveness in biomass and sewage sludge thermochemical conversion for enhancing hydrogen production and reducing tar formation. In addition, co-processing strategies with complementary feedstocks such as biomass, plastics, or waste tyres remain underexplored, even though such approaches have demonstrated synergistic effects in other thermochemical systems. Finally, most APS studies focus on basic product distribution (gas, liquid, char) without detailed analysis of downstream applications, limited attention has been given to product upgrading, potential applications of char and liquid products, and comprehensive techno-economic and life-cycle assessments. Addressing these gaps is essential to advance APS thermochemical conversion from laboratory-scale studies toward practical industrial applications, and determine whether these processes can compete with established waste management options and to identify the most promising process configurations.

6. Conclusions and Future Prospects

At present, there isn't a particular treatment method that dominates the management of APS. Biological treatment routes (anaerobic digestion or composting) remain experimental, with only limited industrial or academic trials reported, and need careful management of toxic constituents that may inhibit biological activity [16]. Studies on the pyrolysis of APS were primarily conducted mostly on laboratory scale without any economic evaluation, according to [14]. Less than ten additional studies appeared from 2023 to 2026, identified via ScienceDirect and Google Scholar have specifically investigated the pyrolysis of paint sludge during this period. These recent works have mainly focused on improving the fundamental understanding of APS pyrolysis kinetics and product formation.

Latest advances include Thermogravimetric/ Derivative Thermogravimetric (TGA/DTG) and pyrolysis-gas chromatography/mass spectrometry (Py-GC/MS) characterization of multi-stage decomposition and gas evolution patterns across APS types (electrocoat, primer, basecoat, clearcoat) [27,37]. High-temperature pyrolysis processes aim to produce value-added char and carbon black [Jiang et al., 2025; 86], whereas co-pyrolysis with sewage sludge, oil sludge, and fermentation residues exhibits both antagonistic and synergistic interactions affecting gas formation and volatiles release [Zhou et al., 2024; 86]. All of the processes are still based at lab-scale. A single study on CLG of wet oil-based APS using red mud oxygen carrier was identified, therefore making research on APS gasification even more limited [28]. In practice, cement-kiln co-processing, with its proven technology and real-world commercial use, serves as the closest approximation to an industrial baseline disposal route [35], while other thermochemical conversion methods are still mostly limited to laboratory scale [16].

Choosing the best recovery method needs balancing energy or material recovery potential against environmental impact, operational complexity and cost. Similar to sewage sludge, thermochemical conversion of APS offers clear advantages over landfilling by reducing significant

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waste volumes and showing potential for energy recovery. Pyrolysis can destroy organic contaminants and pathogens while decreasing solid residues by up to approximately 96% by weight [14]. Gasification produces syngas that may be employed as a fuel for heat and/or electric production and as a feedstock for synthesis of various chemicals. Syngas serves as a vital intermediate in the production of ammonia, methanol, hydrogen, and synthetic hydrocarbon fuels. It also plays a key role in the Fischer-Tropsch (FT) process, where it is used to produce (i) synthetic crude oil, (ii) lubricants, and (iii) hydrocarbon-based fuels [100and 101]. However, because of its high moisture and ash contents, as well as the presence of heavy metals and chlorine, APS gasification is anticipated to suffer from low syngas quality and increased gas-cleaning demands, necessitating energy-intensive drying and extensive gas-cleaning, as seen in sludge gasification systems [11,34]. While high moisture content of APS is normally viewed as a drawback for thermochemical conversion processes, it can potentially act as an in-situ gasifying agent in co-gasification systems. The inherent moisture content of the APS could supply the oxygen needed for oxygen-deficient feedstock materials, driving water-gas shift reactions that produce carbon monoxide, which is a component of syngas [40 and 97]. However, it is still poorly understood how APS moisture affects gas composition, reaction mechanisms, and the overall process efficiency. In co-pyrolysis or co-gasification systems with other wastes (e.g., biomass or plastics), the mineral-rich components of APS could potentially act as in situ catalysts, promoting tar cracking and improving gas quality without the need for external catalysts. However, APS is a complex material, and its different fractions exhibit distinct thermochemical behaviours. While organic-rich fractions may be suitable for energy recovery, ash-rich fractions could be more suitable for catalytic co-processing or material recovery. Despite this potential, these roles have not yet been systematically investigated.

Cement-kiln co-processing achieves near-complete destruction of hazardous organic substances while incorporating inorganic residues into the clinker matrix [35,65]. But, heavy metals and mineral matter persist in the solid residues (kiln dust or char ash) and must be appropriately managed. The use of catalysts or additives is been investigated to enhance product yields and quality. Chemical activation of APS-derived char using KOH to generate high-surface-area materials [14] and the use of red-mud-based oxygen carriers to improve syngas production during gasification [28]. However, these approaches are mostly at the research stage. In conclusion, APS contains considerable latent energy potential but is simultaneously burdened by high moisture, high ash content and hazardous constituents. Biological methods can recover some biogas recovery but are limited by the presence of toxic and non-biodegradable components, while thermochemical pathways show more potential for energy and resource recovery but need further development and scale-up. At present, cement-kiln co-processing is the most mature and widely adopted option, whereas pyrolysis and gasification remain pre-commercial (Ruffino et al., 2023; Gautam et al., 2010]. Ultimately, any viable technology must meet both environmental and economic requirements. There is further work to be done on improving energy yield, pollutant control and cost-effectiveness in treating paint sludge.

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