A Review of Waste Tyre Gasification

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Abstract

There has not been any comprehensive review on waste tyre gasification. This review evaluates the status of global research on gasification of waste tyres and the gaps in knowledge. Some recommendations for future research work are made.

Most of the studies on the gasification of tyres are in the production of syngas. Others are the production of hydrogen gas with high purity, activated carbon and carbon nanotubes. There are few studies on the numerical modelling of the tyre gasification process. It is recommended that the conditions for the optimal production of hydrogen and carbon nanotubes and other value-added products be carried out. The investigation of loss of activity of catalyst in the gasification and co-gasification of waste tyres requires further research. The co-gasification of waste tyres and biomass is advantageous in increasing the rate of tyre gasification and the reduction in the cost of production of methanol. However, there are few studies on the co-gasification tyres and biomass. A database of reaction kinetics parameters such as activation energy of tyre- char/biomass-char blends for different biomass feedstock is required. Lastly, a detailed techno-economic analysis of tyre gasification and co-gasification with biomass is required.

Key Words: Waste Tyre, Gasification, Energy recovery, Syngas, Carbon Products.

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1. Introduction

There is a worldwide drive to dispose of tyres effectively. This is due to the huge number of waste tyres produced annually. About 2.7 billion units of tyres were produced in 2017 and 1 billion units were disposed [1]. The disposal of waste tyres is currently a challenge because the dumping of tyres in landfills is no longer permitted in some countries, including South Africa [2-4]. The reasons are biological and chemical resistance to degradation in the landfills and thereby resulting in a negative impact on the environment [5-6]. Presently, the preferred ways for the disposal of waste tyres are basically:

- The reconstruction of the tyre –This involves the re-treading of the tyre for reuse. This is only done for tyres where the structural features are still intact. This is the best form of recovery [7].
- Recovery of material -This involves the shredding of the tyres to produce rubber chips for applications such as use for noise barriers, roofing materials, sport flooring, asphalt etc.
- Recovery of energy-Energy can also be recovered by thermal valorisation. The three technologies for waste tyre thermal valorisation are pyrolysis, combustion and gasification [8-10].

The focus of this study is on gasification. Gasification of tyres is a process in which air, oxygen and or steam reacts with tyres in an endothermic reaction to produce mainly syngas (CO and H_2) and other by-products are CO_2, light hydrocarbons and char [11]. The syngas can be used in gas turbines or fuel cells [12-14].

Most of the studies on the gasification of tyres are in the production of syngas [9-17]. The others are the production of hydrogen gas with high purity [21-25], activated carbon [19-20] and carbon nanotubes [21-22]. Most of these studies have been carried out either at laboratory scale or at pilot scale [9-24]. There are few studies on the numerical modelling of a tyre gasification process [25-27].

There has not been any comprehensive review on waste tyre gasification. This study aims to fill this gap. This review would evaluate the status of global research on gasification of waste tyres; identify the active players in gasification of waste tyres and the gaps in the knowledge. Finally, make some recommendations on future research work.

2. Mechanism of tyre gasification

Raman et al [10] stated that there are two key processes in the gasification of tyres. They are the primary decomposition reaction and secondary reactions. The primary decomposition reaction involves the decomposition of tyres into heavy and light hydrocarbons and solid char. The secondary reactions involves the cracking of the heavy hydrocarbons, the reforming of light and heavy hydrocarbons and lastly the gasification of the solid char material to increase the gas yield. These reactions are illustrated in Equations 1-5. The hydrocarbons include C_3H_8, C_2H_6 and C_2H_4

Primary Reaction

$$Tyres \rightarrow heavy\ hydrocarbons + light\ \ hydrocarbons + char\ \ \ldots\ldots\ldots\ldots\ldots\ldots Equation\ \ 1$$

Secondary Reactions

$$heavy\ hydrocarbons \xrightarrow{cracking} light\ \ hydrocarbons + H_2\ \ \ldots\ldots\ldots\ldots\ldots\ldots Equation\ \ 2$$

$$heavy\ hydrocarbons \xrightarrow{steam\,reforming} CO + H_2 + hydrocarbons\ \ldots\ldots\ldots\ldots\ldots\ldots Equation\ \ 3$$

$$light\ \ hydrocarbons \xrightarrow{steam\,reforming} CO + H_2 + hydrocarbons\ \ldots\ldots\ldots\ldots\ldots\ldots Equation\ \ 4$$

$$chars \xrightarrow{gasification} CO + H_2\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots Equation\ \ 5$$

2.1 Types of waste tyre gasification processes

Tyre gasification has been carried out in three modes; conventional gasification, plasma gasification or solar-assisted gasification [9-28]. Most of the research reports have been on conventional gasification of waste tyres [9-23]. This is followed by work on plasma gasification [24-26] and lastly on solar-assisted gasification [27-28]. In conventional gasification, the heat used for the decomposing of the organic fraction of tyres is generated from partial oxidation of the tyres using air or oxygen [9].

In plasma gasification of tyres, a thermal plasma is used to decompose tyres into syngas and vitrified slag. The thermal plasma is generated by the transfer of a high electric current between two electrodes and it is done in the presence of a working gas flowing between the two electrodes [25].

Plasma gasification of tyres has been carried out at higher temperatures than conventional gasification of tyres. Most conventional studies on gasification of tyres have been carried out below 1273 K regardless of the reactor configuration [25-26]. Plasma gasification of tyres has been reported above 1273 K. Lerner et al [25] carried out plasma gasification of tyres at a maximum temperature of 2073 K. The study involved a two-step process to produce hydrogen. The first step involves the creation of steam using a plastrom for gasification and the use of calcium oxide as a catalyst to increase the yield of hydrogen gas. The hydrogen content of the product gas increased from 58% to 99%. This is the highest yield of hydrogen content reported for tyre gasification. Janarejeh [26] modelled plasma and conventional gasification (air) of tyres and reported 42% cold gas efficiency for plasma gasification and 72% for conventional gasification.

In solar assisted gasification of tyres, part of the heat used for the decomposing of the organic fraction of tyres is generated from solar energy. Piatkowski and Steinfeld [27] investigated solar gasification of tyres, industrial sludge and sewage sludge. The results showed that industrial sludge had the highest cold gas efficiency from solar to fuel. It was 28% for the industrial sludge, 18 % for the sewage sludge and 17 % for the waste tyre.

A comphrensive study that compares the yield of syngas, hydrogen, and carbon products from the three different types of tyre gasification is absent and this would be useful in the development of a detailed techno-economic analysis of waste tyre gasification.

3 Global research on waste tyres gasification

3. 1 History of waste tyre gasification

The first report of waste tyre gasification was by Raman et al [10] in 1981. They carried tyre gasification in a pilot-scale fluidised bed reactor and the feed rate was in the range of 6-15 kg/hr, temperature range was 900-1100 K and steam was used as the gasifying agent. The gas yield and heating value of the gas were optimised to increase the energy recovery ratio. The energy recovery ratio is the ratio of the product of the gas yield and its heating value divided by the heating value of the tyre measured on a dry ash free basis. Raman et al [10] obtained a maximum energy recovery ratio of 0.4 at 1100 K and the lowest energy recovery ratio of 0.2 was at 900 K. The maximum gas yield and the gas heating value were 0.76 Nm^3 /kg and 39.6 MJ/Nm^3 respectively and were obtained at 1100 K.

Subsequent work have been carried out under laboratory conditions to study different parameters that can increase the product gas yield and the heating value of the product gas [11-16]. The studies involve the effect of air equivalence ratio [11-13], pressure[16], temperature[17], steam/CO_2 [12-13,18-19], and catalyst on gas yield and product gas [21-24]. By-products such as activated carbon and carbon nanotubes have also been produced from tyre gasification [18-19; 21]. Lately, there has been an increased interest in the production of high purity hydrogen from waste tyres [21-25]. A summary of the activities on waste tyre gasification from 1981 till date can be found in Table 1.

Table 1 :Summary of research activities on waste tire gasification

Year	**Authors**	**Type of reactor/Scale**	**Catalyst**	**Gasifying agent**	**Summary of work carried out**	**Ref**
1981	Raman et al-	Bubbling Fluidised bed reactor- Pilot-scale	None	Steam and Air	In this study, gasification of tyres was carried out in a pilot-scale bubbling fluidised bed reactor. Operating temperature 900-1100 K and the tyre feed rate 6-13 kg/hr, steam feed rate 2-3 kg/hr; air 0.38-0.45 m/sec. The maximum gas yield and the gas heating value was 0.76 Nm^3/kg and 39.6 MJ/Nm^3 respectively and was obtained at 1100 K	10
1987	Saito et al.	Kiln Pilot-scale	None	Air	Onoda Cement Co. Ltd in Japan, gasified waste tyres in a Kiln for energy recovery. The energy conversion ratio from waste tyres to gas including carbon particles is about 95%.	29
1995	Volk	Texaco gasifier Pilot-scale	N/A	N/A	The report is on the Texcao program of gasification of tyres and solid fuels such as plastics and sludge. The main aim is for solids disposal and not energy recovery	30
1995	Kom & Kim	N/A	None	Air	The report is on the characterisation of organic and inorganic by-products from the gasification of waste tyres. The organic product distribution consists of various aromatic compounds such as naphthalene,1-limonene, methylbenzene Inorganic compounds such as Zinc iron, and Si, Al, Ca, Cu, Ni, S, and Cd were found in the ash generated observed. Also, polynuclear aromatic hydrocarbons (PAHs) toxic organic compounds were observed in the bottom and fly ash.	31
1996	Lee & Kim	Thermo-balance reactor Laboratory scale	None	Air	In this study, tyre gasification rate was found to be independent of particle size. The particle size of the tyre studied was in the range of from 0.25 mm to 1mm.	32
1996	Curan et al	Texaco gasifier-Pilot-scale	N/A	N/A	This involves further studies on the Texcao program of gasification of tyres and the focus was now on energy recovery.	33
1999	Matsuna	Laboratory scale			In this study, solar thermochemical gasification of waste tyres	34

	mi et al				and plastics (PET) was carried out using concentrated solar energy and the key products were synthesis gas ($CO + H_2$)	
2001	Li et al	TGA Laboratory scale	None	CO_2	The study reports on the gasification tyre-char in a TGA. Prior to gasification the waste tyres were pyrolysed in a rotary kiln and the chars were then gasified in a TGA. The chars were gasified using a CO_2 as the gasifying agent and the reactivity of the chars was estimated. The activity energy ranged between 248 KJ/mol and 383 KJ/mol	35
2002	Mastral et al.	Laboratory scale			In this study, pyrolysis oil obtained from waste tyre was gasified to produce hydrogen.	36
2003	Leung & Wang	Bubbling Fluidised bed reactor Laboratory scale			The work report on the laboratory scale–fluidised bed reactor. The effect of different variables such as equivalence ratio, particle size and feed rate on gas yield and, gas yield, gas heating value, product were investigated. The maximum gas yield and the gas heating value were 11.1 Nm^3/hr and 6 MJ/Nm^3 respectively	11
2004	Caballero	Fixed bed reactor Laboratory scale		Air	This study involves laboratory scale pyrolysis and gasification of waste tyres at three temperatures (723, 973, 1273 K) using air. The best conditions for the gasification of tire rubber were at 1273 K. At these conditions, the char fraction was 26.5%, the oil fraction 1.3%, the tar fraction 10.6% and the gas fraction 61.7% .	37
2004	Coneso et al.	Fixed bed reactor Pilot-scale		Air	This study is similar to that carried out by Caballero at laboratory conditions. The only difference was that it was carried out in a pilot-scale reactor. Similar results were obtained and the best condition was at 1273 K	38
2005	Song	Thermal balance reactor- Laboratory scale	none	Steam	The work compared the gasification rate of waste tyre sewage sludge and coal. The gasification rates followed the order: tyre > coal > sludge.	39
2005	Scot et al	Bubbling Fluidised bed reactor	None	Air	This work also compared the gasification rate of waste tyre char, sewage sludge char, coal char and activated carbon but this carried out in fluidised bed reactor. The gasification rates	40

		Laboratory scale			followed the order: sludge > coal > tyre> activated carbon	
2006	Mitta et al.	Simulation no experiment was carried out.			The study reports on the modelling and simulation of tyre gasification plant for synthesis gas production.	41
2006	Wiess & Castaldi	TGA Laboratory scale	none	CO_2	Gasification was carried out in a TGA and the results were used in the development of a model. A preliminary techno economic analysis showed that 4 million tires per year can produce 18 MW_{eq} of CO and H_2 at an economic rate of return of 19%.	42
2006	Song & Kim	Circulating fluidised bed reactor Laboratory scale		Air	Sewage sludge and waste tyre were co-gasified in a circulating fluidised bed reactor in a temperature range of 923-1123 K. The caloric value of the product gas from gasification of waste tire scrap is 15 MJ/m^3 . The caloric value of the product gas decreases below 5 MJ/m^3 when wet sludge is co-gasified	43
2006	Gonzalez et al	TGA Laboratory scale	none	Steam & CO_2	In this study, activated carbons were prepared from waste tyres gasification using steam and carbon dioxide. Activated carbon produced from steam gasification had higher porosity and surface than those produced using carbon dioxide as the gasifiying agent.	19
2006	Miao et al	Bubbling Fluidised bed reactor Laboratory scale	None	Air	In this study, gasification of waste tyres was carried at different equivalence ratio and. The optimum operation conditions were achieved when the gasification temperature was 973 K and the equivalence ratio (ER) was 0.4. The heating value(LHV) of the product gas was about $4804kJ/m^3$ and composition was CH_4, CO, H_2, C_2H_6, and longer-chain hydrocarbon.	44
2008	Xia et al	Bubbling Fluidised bed reactor Laboratory scale	None	Air	In this study, gasification of waste tyres was carried at different equivalence ratio (ER) of 0.2-0.6. at a temperature range of 400-800°C. Syngas and carbon black were the major products. LHV and yield of syngas are about 4000-9000 KJ/Nm^3 and 1.8-3.7 Nm^3/kg, respectively. The surface area of	14

					the carbon black was about 20-30 m^2/g and a product yield of 550-650 g/kg.	
2009	Straka and Bucko	Commercial scale Lurgi gasifier	None	Air	In this study, waste tyre and lignite were co-gasified in a commercial scale Lurgi gasifier. The ratio of the mixture was 20% tyre and 80 % lignite. The heating value of the product gas increased by 3% when tyre and lignite are co-gasified. A 10% mixture of tyre and 90% of lignite was suggested as the optimal feed ratio.	45
2009	Piatkowski & Steinfeld	Solar-packed gasifier -Laboratory scale	None	Steam	In this study, steam gasification of industrial sludge, sewage sludge and waste tyre was carried out in a solar gasifier. The results showed that industrial sludge had the highest efficiency from solar to fuel. It was 28% for the industrial sludge, 18 % for the sewage sludge and 17 % for the waste tyre.	27
2009	Galvangno et al	Rotary- Kiln-Laboratory scale	None	Steam	In this study, steam gasification of refuse-derived fuel, poplar wood and waste tyre was carried out in a rotary-kiln reactor. The gas composition were different for the feed stock. The product gas from tyre gasification had the highest heating value and would be more suitbale for fuel applications.	46
2010	Elbaba et al	Fixed bed Laboratory scale	Yes-Commercial catalyst (Ni-Mg-Al)	Steam	In this study, the catalytic gasification of waste tyres and tyres elastomers was carried out in a fixed bed reactor. The gasifying agent used was air and the catalysts used are Ni-Mg-Al catalyst. The main aim is to produce high purity hydrogen. The catalyst got deactivated and the total amount of coke deposition on the reacted catalyst for waste tyre was 18.4 wt % for the waste tyre.	47
2010	Dontelli et al	Rotary-Kiln reactor- Pilot-scale	None	Steam	In this study, steam gasification of waste tyres was carried out in a pilot-scale rotary kiln reactor. Numerical analysis was also carried out too. A numerical model was developed and experimental results were used to validate the model. There were some difference in the product gas composition obtained experimentally and the those predicted by the numerical	17

					model. Hence the conclusion was that the model cannot replace the gasification experiment.	
2011	Portofino et al	Rotary-kiln reactor- Laboratory scale	Yes-two Commercial catalyst-(Nickel), Two natural catalyst (Dolomite, Olivine	Steam	In this study, the catalytic gasification of waste tyres was carried out in rotary kiln reactor .The gasifying agent used was steam. The catalysts used were two commercial catalysts-(Nickel) and two natural catalysts (Dolomite, Olivine). The main aim of the project is to produce high purity hydrogen gas. The commercial nickel catalysts produced the highest hydrogen content of 78%, followed by dolomite producing a hydrogen of 64% and lastly olivine produced hydrogen of 60%.	21
2011	Elbaba et al	Fixed bed Laboratory scale	Yes-Commercial catalyst $Ni/CeO_2/Al_2O_3$	Steam	This study was similar to their earlier study on catalytic gasification on waste tyre; the difference was in the type of catalyst. Previously Ni-Mg-Al catalyst was used and in this study $Ni/CeO_2/Al_2O_3$ was used. The difference was in the degree of catalyst deactivation. A lower degree of coke deposition on the catalyst was obtained for the $Ni/CeO_2/Al_2O_3$ catalyst.	48
2012	Lerner et al.	Plasma gasifier Laboratory scale	Yes -Cao	Steam	In this study, steam gasification of waste tyre using plasma as the source of high-temperature process heat. The hydrogen content of the product gas increased from 58% to 99%. This is the highest yield of hydrogen content reported for tyre gasification.	23
2012	Karatas et al.	Bubbling Fluidised bed reactor Laboratory scale	No	Air & CO_2& Steam	In this study, a tyre gasification was carried out in a laboratory scale bubbling fluidized bed gasifier. The gasification agents were air &CO_2, air & steam and steam only. The heating value of the gas from the three different gasifying agent 9.59, 7.34 and 15.21 MJ/Nm^3 respectively air&CO_2, air &steam and steam only.	12
2012	Elbaba and	Fixed bed Laboratory scale	Yes-Commerci	Steam	This study was similar to their earlier study on catalytic gasification on waste tyre using a Ni-Mg-Al, however steam	49

	Williams		al catalyst (Ni-Mg-Al)		was used as the gasification agent as against air that was used in the previous one. The hydrogen content was higher than the previous and so was the amount of coke deposition on the catalyst.	
2012	Lopez et al.	TGA Laboratory scale	No	Oxygen & Steam	The study reports on the gasification of char derived from the distallion of waste tyre. The gasification process was carried out at different pressure conditions. The yield, H_2 and CO contents and HHV of the syngas produced from char gasification increased with pressure.	23
2013	Sanchez et al	TGA Laboratory scale & Aspen Stimulation	No	Air & Steam	In this study, the gasification of tyres was carried in a TGA and production of ammonia from the syngas was evaluated using an ASPEN simulation model.	50
2013	Yusup et al	Bubbling Fluidised bed reactor- Pilot-scale	Yes	Steam	In this study, the production of high purity hydrogen gas was carried out in a pilot-scale bubbling fluidised bed reactor by gasifying a mixture of waste tyres and palm kernel shell (PKS). The highest H_2 and total syngas content was 66.15 vol% and 83.8 vol% respectively with a CVof a of 14.76 MJ/Nm^3. The optimal blend ratio was 30 wt% of waste tyre blended with PKS.	51
2013	Molino et al	Rotary-Kiln reactor- Pilot-scale	None	Steam	In this study, the steam gasification of tyres was carried out in a pilot-scale rotary kiln reactor to produce activated carbon. Subsequently the activated carbon was used as an absorbent for the removal of cadmium from wastewater. The adsorbents obtained from tire gasification were used to adsorb cadmium ions from aqueous solutions and outperformed some commercial sorbents reported in the literature.	20
2013	Wieckert et al	Packed-Bed Solar Reactor	No	Air	In this study, solar gasification of waste tyres and five other fuels (industrial sludge, fluff, dried sewage sludge, low-rank coal, and sugar cane bagasse) was carried out in a pilot-scale	28

		Pilot-scale			packed bed reactor. The production of high quality syngas was observed, with the best energy efficiency observed in the coal sample ($\eta = 35\%$) and waste tyre ($\eta = 27\%$).	
2013	Adeyemi & Janajreh	Simulation	No	Air	In this study, a numerical model was developed for the gasification of waste tyres in a drop tube reactor (DTR). The model was able to predict optimal conversion conditions.	52
2013	Lahijani et al	TGA Laboratory scale	No	CO_2	In this study, the co-gasification of waste tyre char and palm empty fruit bunch (EFB) and almond shell (AS) was carried out in a TGA using CO_2 as the gasfying agent. The aim of the study was increase the reactivity of tyre char by co- gasifying with solid biomass fuels with a higher reactivity. The co gasification of tyre-char/AS-char and tyre-char/EFB increased the rate of conversion by a factor of 5 and 10 respectively when compared pure tyre-char.	5
2013	Portofino et al	Rotary-kiln reactor-Laboratory scale	None	Steam	In this study, the steam gasification of waste tyres was carried out in rotary kiln bed reactor. The main aim of the study was to determine influence on temperature on gas yield and gas composition. The results showed that higher temperature results in a higher syngas production (86 wt %) and a lower char yield, due to an enhancement of the solid–gas phase reactions with the temperature. Higher operating temperatures also resulted in higher hydrogen concentrations: the hydrogen content rapidly increases. In this case the hydrogen was higher than 65%.	18
2013	Karatas et al.	Bubbling Fluidised bed reactor Laboratory scale	No	Air	In this study, gasification of waste tyre was carried out in a laboratory scale fluidised bed reactor. Based on the results obtained two different correlations for the prediction of heating value of the product gas were developed. The first is valid for ER conditions of $0.15 \leq ER \leq 0.29$ and the second is valid for $0.29 \leq ER\ 0.45$	13

2013	Elbaba and Williams	Fixed bed Laboratory scale	Yes- Ni and Dolomite	Steam	In this study, catalytic gasification of waste tyre using Ni and Dolomite as catalyst was carried out in a laboratory fixed bed reactor. The results indicated that the gas yield was significantly increased from 30.3 to 49.1 wt.% and the potential H_2 production was doubled with the introduction of 5% Ni into the calcined dolomite catalyst. The results show also a further increase in the gas yield and the potential H_2 production with increasing Ni loading from 5 to 20 wt%.	22
2014	Brachi et al	Bubbling fluidised bed-pilot scale	Yes- pure γ-Al_2O_3 (AL) and a Ni/γ-Al_2O_3 catalyst	Air	In this study, the co-gasification of tyres plastics and biomass residue in the production of bioethanol was carried out in a pilot scale fluidised bed reactor. Nickel and Alumina catalysts were used. The biomass used was olive husk and the plastics were Polyethylene Terephthalate (PET) from drinking bottles	53
2014	Elbaba and Williams	Fixed bed Laboratory scale	Yes- Ni/Al_2O_3 and Ni/dolomite	Steam	In this study, catalytic gasification of waste tyre using Ni/Al_2O_3 and Ni/dolomite catalysts was carried out in a laboratory fixed bed reactor. The Ni/dolomite catalyst produced a higher hydrogen yield and the highest theoretical hydrogen potential to produce hydrogen gas compared to the Ni/Al_2O_3 catalyst. In addition, the used Ni/dolomite catalyst had the lower carbon deposition,	54
2015	Zhang et al	Fixed bed Laboratory scale	Yes- Co/Al_2O_3, Cu/Al_2O_3, Fe/Al_2O_3, and Ni/Al_2O_3.		In this study, catalytic gasification of waste tyre using Co/Al_2O_3, Cu/Al_2O_3, Fe/Al_2O_3, and Ni/Al_2O_3 was carried out in a laboratory fixed bed reactor. The main aim was to produce high purity hydrogen gas and carbon nanotubes. The results showed that the Ni/Al_2O_3 catalyst produced high-quality multi-walled carbon nanotubes along with the highest H_2 yield of 18.14 mmol g^{-1} tire compared to the other catalysts.	23
2015	Kandasa	TGA	No	Air	The main products detected during gasification were CO_2,	9

	my &Gokalp	Laboratory scale			CO, and H_2, indicating that oxidation, water gas, and water gas shift reactions were predominant.	
2015	Janajreh & Raza	Simulation	No	Air	In this study, a numerical simulation of a tyre gasification process in a fixed bed down draft gasifier was carried out. A CFD model was used to investigate the behaviour of tyre conversion and the effect on syngas production at different resident time inside the gasifier. The change in the velocity of the inlet air directly affects the residence time of the reactants and products in the gasifier	55

3.2 Status on waste gasification research

Most of the research works have been carried out under laboratory conditions [11-15,19, 21-23,28, 31-38, 41-52] with a few carried out under pilot scale [10,17-18,20,29-30,39,51].There are only two reports on the gasification and co-gasification of tyres at a commercial scale [1, 45].

3.2.1 Laboratory scale gasification of tyres

Most of the laboratory studies on the gasification of waste tyres have been carried out on a bench-scale fluidised bed reactor [11-13; 42, 45, 47]. The others have been carried out in a rotary kiln reactor [17,19,46], in a fixed bed reactor [22-23, 35, 49-50] and in a thermogravimetric analyser (TGA) [5, 9, 18, 54]. Sometimes the TGA is coupled with a mass spectrometer for gas analysis [9]. A comparative analysis of gas yield and the purity of solid products such as activated carbon and carbon nanotubes from the different reactor configurations have not been carried out. The outcome of such a study would be useful in developing a techno-economic analysis for tyre gasification.

3.2.2 Pilot scale gasification of waste tyres

There are fewer reports on pilot-scale gasification of waste tyres compared to the laboratory studies. Donatelli [17] and Molina et al [20] carried out the gasification and activation of waste tyre in a rotary kiln pilot-scale plant with a capacity of 10kg/h. The internal diameter of the rotary kiln reactor is 0.4m and it has a length of 1m. The particle size fraction of the waste tyre was 1.5 to 2 mm. In the study of Donatelli et al [17], the main products reported are H_2, CO, CO_2, CH_4. The highest CV of the gas was 36.55 MJ/kg was obtained at steam/tyre ratio of 0.33. In the study of Molina [20], activated carbon was the main product reported and it was used as an absorbent for the removal of cadmium from simulated waste water.

Saito et al [29] also reported on the pilot-scale gasification of tyres in a rotary-kiln reactor carried out in Onoda cement in Japan. The energy conversion ratio from waste tyres togas including carbon particles is about 95%. The heating value of the gas was not reported.

Raman et al [10] carried out tyre gasification in a pilot-scale fluidised bed reactor. The internal diameter of the reactor was 0.23 m, with an expanded freeboard of 0.4 m and a bed height of 0.6m. The tyre particles were 3mm in diameter and 5mm in length.

The tyre feed rate was in the range of 6-12 kg/hr and the steam feed rate was in the range of 2.40- 3.40 kg/hr for the different tests. The maximum heating value of the product gas was 36 MJ/Nm^3.

Brachi et al [53] reported on the co-gasification of tyres, plastics and biomass residue in the production of bioethanol. Their research was carried out in a pilot scale fluidised bed reactor. Nickel and Alumina were used as catalysts. The co-gasification of waste tyres, plastics and biomass led to a reduction in the production cost of methanol. The biomass used was olive husk and the plastics were Polyethylene Terephthalate (PET) from drinking bottles.

Volk et al [30] reported on the gasification of waste tyre in a Texaco gasifier. The main aim of the study was solid disposal and not energy recovery. That is the treatment of waste material in a gasifier before disposal in order for the waste to meet certain environmental legislation for solid disposal. The solid wastes gasified are waste tyres, plastics and sludge.

Yusup et al [51] reported on the production of high purity hydrogen gas in a pilot-scale bubbling fluidised bed reactor by gasifying a mixture of waste tyres and palm kernel shell (PKS). Experiments were carried out at 600-800°C with steam/feedstock ratio (S/F) of 2-4 (kg/kg) and waste tyre/PKS ratio of 0-0.3 (kg/kg).

The highest H_2 and total syngas content of 66.15 vol% and 83.8 vol% was achieved respectively under condition of 800°C and 30 wt% of waste tyre blended with PKS and S/F ratio of 4 (kg/kg). The fuel gas had a calorific value of 14.76 MJ/Nm^3

Coneso et al [38] investigated tyre gasification in pilot-scale fixed bed reactor at three temperatures (723, 973, 1273 K) using air with the best condition reported as being 1273 K

In summary, pilot-scale gasification of tyres has been carried out using different reactor types such as rotary kiln, fluidised bed reactor and fixed bed reactor. Rotary kiln and fluidised bed reactor are the most investigated at pilot-scale conditions. A comparison of the gas product yield from different reactor configurations at pilot-scale conditions for tyre gasification has not been reported.

3.2.3 Commercial scale waste tyre gasification

There are only two reports on the gasification of tyres and lignite at commercial scale. [45] The first report on commercial scale gasification of tyres is a study on the co-gasification of waste tyre and lignite in a commercial scale moving bed Lurgi commercial scale gasifier.

The ratio of the mixture was 20% tyre and 80 % lignite. The heating value of the product gas was increased by 3% in comparison with the gasification of lignite only. The heating value of product gas from lignite-tyre gasification was 12.77 MJ/m^3.

The other report is on a tyre gasification plant in Spain. The plant is based in La Coruña (Garanesa) and has a capacity of 12000 tonnes per year and its operated by a company called Guascor S.L.[1]. There is no information on the heating value of the product gas and the gas yield from this plant.

3.3 Energy recovery in tyre gasification

In waste tyre gasification energy recovery is the fraction of energy content of the waste tyre that is converted to gas [10,11] .This is illustrated in Equation 6. It is the ratio of the heating value of the product gas and its yield divided by the heating value of the waste tyre [10,11].

$$\text{Energy recovery ratio} = \frac{\mathit{Gas\ heating\ value\ x\ Gas\ yield}}{\mathit{Heating\ value\ of\ waste\ tyre}} \quad \text{……………………..Equation 6}$$

Equation 6 indicates that a higher ratio would mean an higher energy recovery. Raman et al [10] and Leung and Wang [11] have reported an energy recovery ratio of 0.1 to 0.4. This indicates that 40% is the highest energy content of the waste tyre that can be converted to gas.

3.3 .1 Effects of operational parameter on energy recovery from tyre gasification

The key parameters that can affect energy recovery from tyre gasification are the air equivalence ratio [11-13], pressure [16], temperature [17], tyre feed ratio [10-11,18] steam/tyre ratio [17], and types of catalyst [21-24].

Raman et al.[10] varied temperature from 900 K to 1060 K. The lowest energy recovery ratio of 0.1 was observed at 900 K and the highest energy recovery ratio of 0.4 was observed at 1060 K. The increase in energy recovery was linear when the temperature was increased. Leung and Wang [11] investigated the effect of tyre feed rate and air equivalence ratio on energy recovery. The air equivalence ratio (ER) is the tyre /air ratio to the stoichiometric tyre/air ratio.

In gasification conditions air equivalence ratio is always below the stoichiometric ratio and the equivalence ratio studied for tyre gasification has been in the range of 0.1- 0.4 . Leung and Wang [11] estimated energy recovery at different equivalence ratios from 0.07 to 0.4 and observed the highest was in the equivalence ratio of 0.4 and the lowest at an equivalence ratio of 0.1. They also observed close to a linear increase in energy recovery when the equivalence ratio was increased.

They also varied the feed rate of waste tyres at 2,3 and 4 kg/h at different ER ratios. At an ER ratio of 0.07, the energy recovery was similar for the feed rate of 2 and 3 kg/h. At an ER ratio of 0.15 the energy recovery at 3kg/h was now higher. The energy recovery was higher at 4 kg/hr at any ER ratio studied. The highest energy recovery reported was at feed ER ratio of 0.3 and feed rate of 4 4 kg/h.

Donatelli [17] reported that the an increase in the steam /tyre ratio lead to decrease in the total calorific capacity of the product gas and this leads to a decrease in the energy recovery ratio

The use of catalyst have been reported to decrease the energy recovery from tyre gasification. Portofino et al [21] reported that recovery for tyre gasification only was 29.1 MJ/kg and reduced to 21.1 MJ/kg when dolomite was used as catalyst in the gasification of tyres. This was due to reduction in the heating value of the product gas from 25 MJ/Nm^3 to 16.1 MJ/Nm^3.

3.3.2 Product distribution and yield from waste tyre gasification

Gases, char and liquid are three classes of products from waste tyre gasification. The yield of each of these products is a function of the operating temperature, equivalence ratio, tyre feed rate and catalyst [10, 11, 17]. Raman et al [10] reported that the yield of liquid products from tyre gasification reduced from 55 wt % to 15 wt % when the temperature was increased from 900 K to 1060 K. The gas yield increased from 20 wt% to 55 wt% and the char remained relatively constant at 25-28 wt % when the temperature was increased from 900 K to 1060 K**.**

Leung and Wang [11] evauluated the effect of equivalence ratio of 0.1 to 0.4 (air/fuel ratio) on the product yield at three different tyre feed rate (2 kg/h, 3 kg/h and 4 kg/h). The results obtained showed that at an equivalence ratio greater than 0.2 the gas product had the highest yield (70-80 wt %) followed by char (20-30 wt %) and the liquid product (0-5 wt %) for the three tyre feed rates (2 kg/h, 3 kg/h and 4 kg/h). However at an equivalence ratio of around 0.1 the results were different. At 2 kg/h both char and liquid products had the highest yield (40 wt %) and gas had the lowest yield (30 wt %). At 3 kg/h the char product had the highest yield (44 wt%) and the gas and liquid products had similar yield (28 wt%). At 4 kg/h, the gas product had the highest yield (50 wt%), followed the char product (30 wt %) and the liquid product had the lowest yield (20%). This indicates that tyre feed rate had an higher impact on the product yield at a lower equivalence ratio.

Zheng et al [23] investigated the effect of different catalysts on product yield. The catalysts used were Co/Al_2O_3, $Cu/\ Al_2O_3$, Fe/Al_2O_3 and $/NiAl_2O_3$. The results were compared with sand. The char yield was highest (36-39 wt %) followed by gas yield (22-34 wt %) and liquid had the lowest yield (11-20 wt %) in all the catalyst and sand. Carbon products such as nanotubes was 8-14 wt % of the char. There was no formation of carbon nanotubes when sand was used.

3.3. 3 Product gas composition and concentration

The gas composition of the product gas from waste tyre gasification includes CH_4, C_2H_4, C_3H_6, C_2H_6, CO, CO_2 and H_2 [10,15]. The concentration of the gases depends on the operating temperature. Raman et al [10] reported that at 900 K CH_4 had the highest concentration followed by H_2, C_2H_4, C_3H_6, CO_2, C_2H_6 and CO. However at 1060 K the H_2 had the highest concentration followed by CH_4, CO_2, C_2H_4, CO, C_3H_6 and C_2H_6. The study was carried out in fluidised bed reactor without a catalyst. Similar results were reported by Portofino et al [21] for tyre gasification in a rotary kiln reactor using four catalysts. Two of the catalysts were commercial nickel catalysts and the other two are natural mineral such as dolomite and olivine. At a lower temperature of 823K CH_4 had the highest concentration (42 %) followed by H_2 (30%), $C_2H_6 + C_2H_n$ (14%) ,CO (11%),.and CO_2 (5%) and At a higher temperature of 1023K, H_2 (57 %) now had the highest concentration followed by CH_4 (21 %), CO (9), CO_2(7 %) and $C_2H_6 + C_2H_n$ (7%)

One of the challenges of using catalyst in the production of high purity H_2, is the problem of catalyst deactivation [20-21]. The catalyst deactivation can occur through coke formation on the surface of the catalyst, sintering of the catalyst or poisoning of the catalyst. Zheng et al [21] have proposed that the graphitic carbon formed from coke deposition can be optimised to produce carbon nanotubes along side with the production of hydrogen gas.

3.3. 4 Product Gas Quality and Yield

A key issue in waste tyre gasification is the quality of the product gas generated. A higher quality product gas is required for gas turbine and fuel cell applications for heat and electricity generation [56]. Steam gasification of waste tyres has been reported to produce a higher quality product gas [18].

Steam gasification product gas with higher hydrogen content of 55-57 % and a lower heating value (LHV) of 30-37 MJ/kg compared with a low hydrogen content of 15-20% and a LHV value of 4-7 MJ/kg for air gasification [12-13].

The hydrogen gas content in air gasification can be increased by the use of catalyst. Zhang et al [23] reported that the use of Ni/Al_2O_3 catalyst increased the hydrogen content to 57 % compared to the value of 24 % obtained when sand was used as a catalyst in a fixed bed reactor. The CO content also increased from 3% to 16%; however the methane content decreased from 63 to 20%. This might affect the heating value of the product gases. The heating values were not reported in their study.

Meanwhile, in addition to the product gases, carbon nanotubes were also generated. This was due to the deactivation of catalyst by the presence of carbon deposits on the surface of the catalyst. The experiments were carried out in a two-stage fixed bed reactor system. The results indicate that there is a need to optimise the conditions for the production of the carbon nanotubes and hydrogen.

In another study by Xiao et al. [15] the conditions for the production of syngas and carbon black from the air –gasification of waste tyres were optimised. The experiments were carried out in a fluidised bed reactor and the optimal conditions for the production of syngas and carbon black were at 923–973 K and an air/waste tyre ratio of 0.2–0.4. This study was carried out without the use of catalyst. A lower hydrogen content of 15-20% and a CV of 4-7 MJ/kg were obtained.

The use of catalysts for steam gasification of waste tyres has also been reported. Portofino et al. [21] reported that the use of dolomite increased the hydrogen content from 52% to 67% and the gas production rate increased from 1.1 Nm^3/kg to 1.3 Nm^3/kg. However the heating value decreased from 25.3 MJ/Nm3 to 16.1 MJ/Nm^3.

A table showing the composition of hydrogen produced from waste tyre gasification and co-gasification of tyres using catalysts and without catalysts is presented in Table 2. The highest of hydrogen content is 99%. This was obtained from plasma steam gasification of tyres using of calcium oxide as a catalyst [23]. The lowest hydrogen content reported for tyre gasification is 15-20% and is air –gasification of tyres in a fluidised bed reactor[15].

Table 2 Hydrogen production from tyre gasification

Name	Mode of Tyre gasification	Tyre gasification/ Co-gasification	Catalyst	Gasifying agent	Highest Hydrogen content
Leung and Wang [11]	Conventional	Tyre Only	No	Air	8%
Xiao et al [15]	Conventional	Tyre Only	No	Air	20%
Karatas et al [13]	Conventional	Tyre Only	No	Air	20%
Karatas et al [12]	Conventional	Tyre Only	No	Air&CO_2, Air&Steam ; Steam	30% 22% 48%
Raman et al [10]	Conventional	Tyre Only	No	Steam	44%
Donatelli et al [17]	Conventional	Tyre Only	No	Steam	53%
Elbaba and Williams [22]	Conventional	Tyre Only	Yes	Steam	55%
Zhang et al. [23]	Conventional	Tyre Only	Yes	Steam	57%
Elbaba et al [54]	Conventional	Tyre Only	Yes	Steam	57%
Elbaba and Williams [49]	Conventional	Tyre Only	Yes	Steam	61%
Elbaba and Williams [47]	Conventional	Tyre Only	Yes	Steam	62%
Portofino et al [17]	Conventional	Tyre Only	No	Steam	62%
Yusup et al [51]	Conventional	Tyre and Palm kernel shell	No		66%
Elbaba et al[50]	Conventional	Tyre Only	Yes	Steam	67%
Portofino et al [21]	Conventional	Tyre Only	Yes	Steam	78%
Lerner et al [24]	Plasma	Tyre only	Yes	Steam	99%

3.4 Co-gasification of waste tyres with other fuels

There are few reports on the co-gasification of waste tyres, all of which have been carried out under conventional gasification conditions. Waste tyres have been co-gasified with biomass, plastics, sludge and coal [5 43, 45, 51, 53]. Most of the co-gasification of tyres has been done with biomass. The biomass samples that have been co-gasified with tyres are Almond shell, Palm fruit [5] and sewage sludge [43].

Tyre-char reactivity is reported to be lower than that of biomass. [15]. Lahijani et al [5] reported that the aim of co-gasification of tyres with biomass was to increase the reactivity of the tyre-char The biomass used in the study were Almond shell and Palm fruit. The tyre and biomass were blended at a ratio of 1:1 and the conversion rate was increased by a factor of 5 for the Almond shell and a factor of 10 for the Palm fruit. The experiments were carried out in a laboratory scale TGA.

Song and Kim [43] co-gasified sewage sludge and waste tyre in a circulating fluidised bed reactor. The calorific value of the product gas from gasification of waste tyre scrap is 15 MJ/m^3 . The caloric value of the product gas decreases below 5 MJ/m^3 when wet sludge is co-gasified.

Brachi et al. [53] reported that the co-gasification of polymeric waste and biomass led to a cost reduction in the production of methanol. The polymeric waste materials used in the study were waste tyre and Polyethylene Terephthalate (PET) from waste drinking bottles. The biomass used was olive husk. The ratio of the mixture was 80% biomass and 20% polymeric material (PET or tyre granules). Nickel and Alumina catalysts were used in cracking the tars and this resulted in a better gas quality. The experiments were carried out in a pilot-scale fluidised bed reactor.

Straka and Bucko [45] co-gasified waste tyre and lignite in a commercial scale Lurgi gasifier. The ratio of the mixture was 20% tyre and 80 % lignite. The heating value of the product gas (12.05 MJ/kg) was increased by 3% in comparison with the gasification of only lignite (12 .45 MJ/kg). A 10% mixture of tyre and 90% of lignite was suggested as the optimal feed ratio. A reduction in H_2S and CH_3SH in the co-gasification of lignite and tyres was seen as compared to gasification of lignite only.

4. Active players in waste tyre gasification research

Figure 1 shows the top ten countries that are active in gasification and co-gasification of waste tyres based on the analysis of the 58 document retrieved from Elsevier's Scopus database. In decreasing order, the countries are USA, UK , Italy ,Spain, United Arab Emirates, Lithuania, Switzerland, China, Czech Republic and South Korea,. The names of the researchers and their affiliations are presented in Figures 2 and 3.

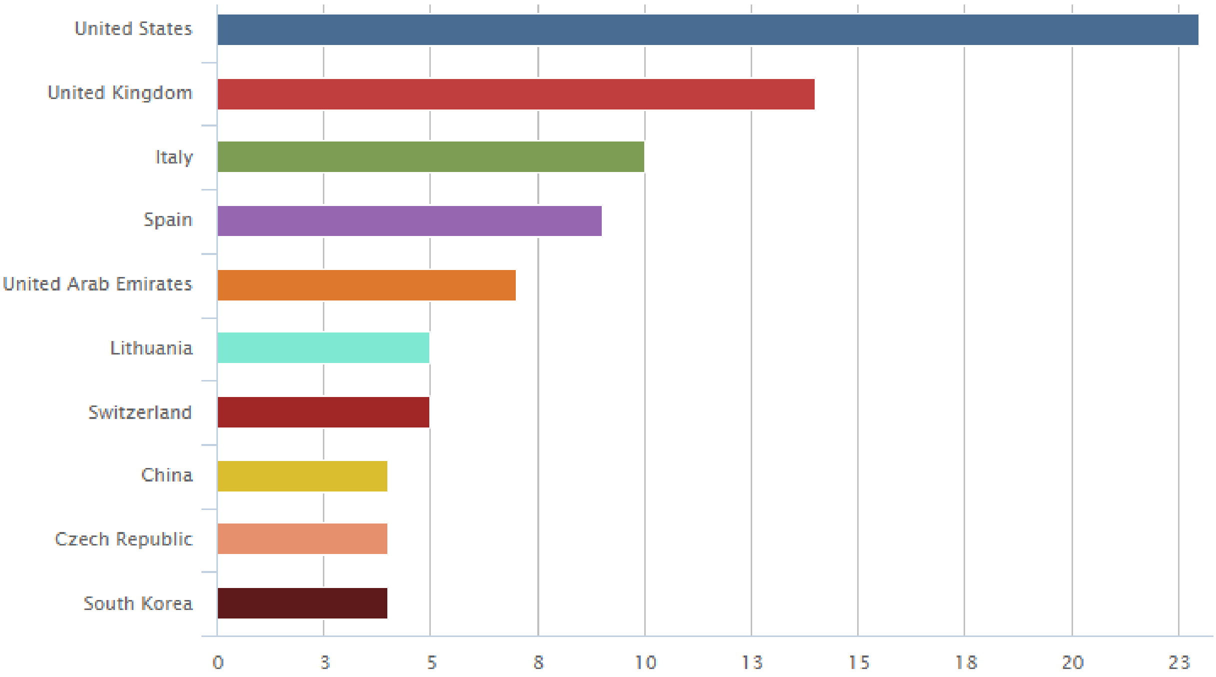

Figure 1:Ranking of 10 most prolific countries on gasification and co-gasification of waste tyres

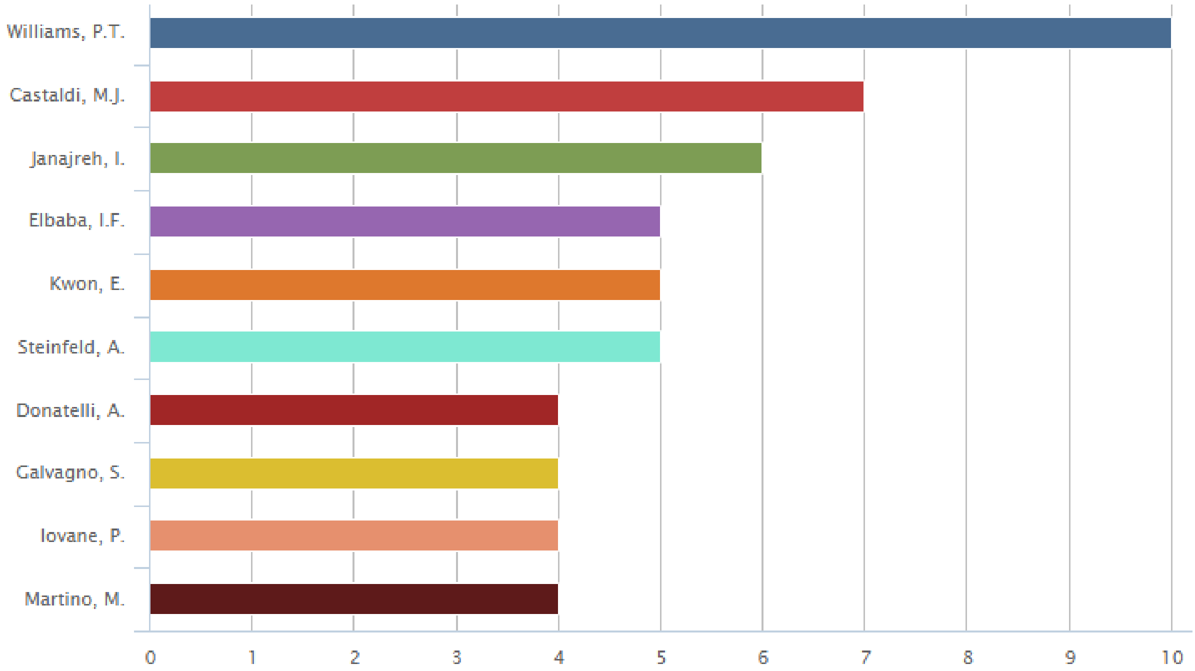

Figure 2:Ranking of 10 most prolific authors on gasification and co-gasification of waste tyres

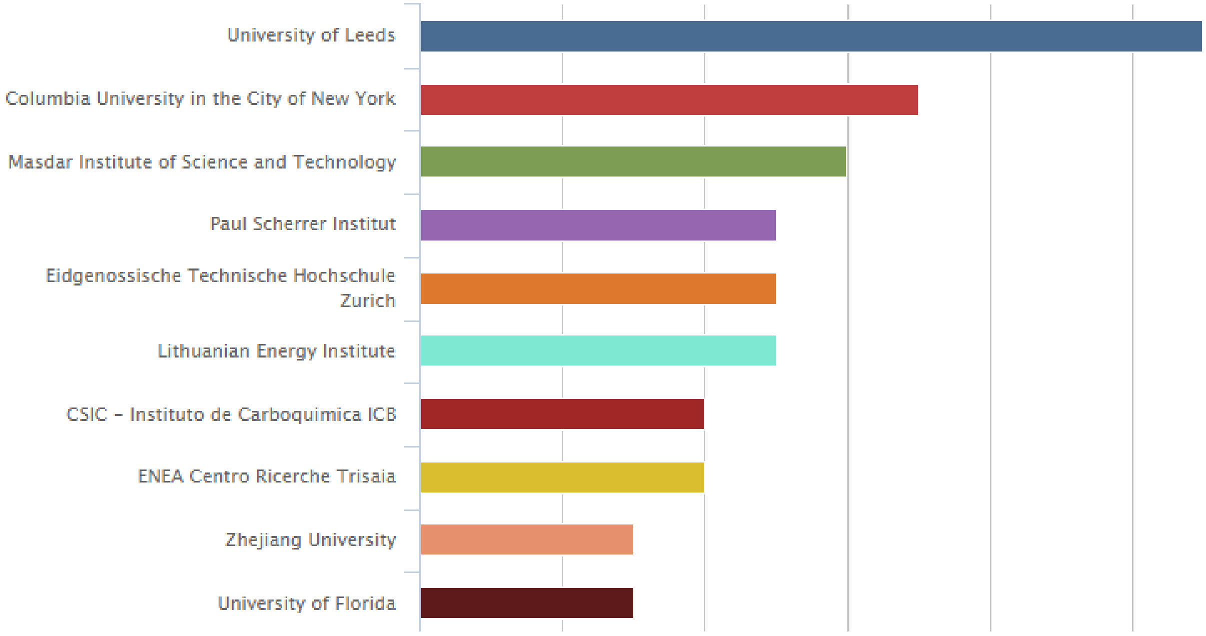

Figure 3:Ranking of 10 most prolific international institutions on gasification and co-gasification of waste tyres

5. Gaps in knowledge in waste tyre gasification and co-gasification

Some of the noticeable gaps in the gasification and co-gasification of waste tyres are listed below:

- Production of hydrogen and syngas from gasification of waste tyre- The production of high quality (concentration) of hydrogen and syngas is still a challenge. The reforming of syngas using catalysts to increase hydrogen concentration and overall gas yield is promising however there are problems of loss of catalyst activity.
- Loss of activity of catalyst in the gasification and co-gasification of waste tyres- The loss of activity is due to the deactivation of catalyst by the formation of carbon deposits on the surface of the catalyst. The carbon deposits are a potential source of the production of by-products such as carbon nanotubes. There is a need to optimise the conditions for the production of hydrogen and the carbon nanotubes and other value-added products.
- Few studies on co-gasification of tyres and biomass- One of the aims for the co-gasification of tyres and biomass is to increase the reactivity of tyre char during gasification. Few biomass samples have been studied. There is a need to determine a database of tyre-char and biomass char intereaction for different biomass.
- Production of methanol from co-gasification of waste tyres- The reduction in the cost of production of methanol from co-gasification of tyres and olive husk. The evaluation of cost of production of methanol from the co-gasification of tyre and other types of biomass need to be carried out too. This would further help in the development of comphresensive techno-economic study for tyre gasification.
- Techno-economic analysis of waste tyre gasification- There have not been any techno-economic analyses of gasification and co-gasification of waste tyres .
- Plasma gasification of tyres- There has not been any report of the co-gasification of tyres and other solid fuels in plasma gasification. There is a need to evaluate co-gasification of tyres with biomass in plasma gasification. The use of calcium oxide as a catalyst to increase the yield of hydrogen gas in plasma gasification has been reported. However the use of dolomite, nickel and iron as catalyst for the plasma gasification of tyres has not been reported. These catalysts have been commonly used in the conventional gasification of tyres [20-22]. A study on the stability and effectiveness of dolomite, nickel, Fe on either syngas or hydrogen formation under

plasma gasification of tyre would be useful and also assist in carrying out comparative study on plasma gasification and conventional gasification .

- Solar-assisted gasification of tyres-The are only two reports on the solar thermochemical gasification of waste tyres for the production of synthesis gas. The optimal conditions for solar-assisted gasification of tyres have not been reported.

6 Conclusions and recommendations

A comprehensive review on waste tyre gasification has been provided. There has been increased research work on tyre gasification and co-gasification with biomass especially from the year 2000. Most of the studies on the gasification of tyres are in the production of syngas. The others are the production of hydrogen gas with high purity, activated carbon and carbon nanotubes.

Tyre gasification has been carried out in three modes; conventional gasification, plasma gasification and solar-assisted gasification. Most of the research reports have been on conventional gasification of waste tyres. This is followed by work on plasma gasification and lastly on solar-assisted gasification. A detailed study that compares the yield of syngas, hydrogen, and carbon products from the three different types of tyre gasification is absent and this would be useful in the development of a detailed techno-economic analysis of waste tyre gasification. Aslo the evaluation of the syngas composition and syngas quality produced from tyre gasification and its applications in various energy applications such as fuel cells, gas turbine and gas engine should be carried out.

There are only two reports of commercial scale gasification of tyres and co-gasification of tyres. Most of these studies have been carried out under experimental conditions which have either been at laboratory scale or at pilot scale. The development of a detailed techno-economic model would help in deployment of commercial scale gasification of tyres .

The co-gasification of waste tyres and biomass is advantageous in increasing the rate of tyre gasification and the reduction in the cost of production of methanol. However, there are few studies on the co-gasification tyres and biomass. There have only be report of tyre gasification with are Almond shell, Palm fruit and sewage sludge. Other types of biomass such as sawdust, wood chips could be investigated

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