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The role of thermo-catalytic reforming for energy recovery from food and drink supply chain wastes

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Abstract

Disposal of food and drink wastes, including packaging wastes, has a significant cost and environmental impact. All carbon containing wastes have an energy potential and the food industry should focus on recovering that energy to offset their reliance on fossil-fuel derived energy sources. This paper focuses on the novel use of intermediate pyrolysis for decarbonizing the food chain, through the treatment of food and packaging waste, to recover energy. The TCR is a versatile technology which overcomes many of the traditional problems associated with fast pyrolysis and can thermo-chemically convert a range of different feedstocks, including inaccessible lignin and some inorganic, recalcitrant materials. The feedstocks are converted into new fuel sources; char, bio-oil (thermally stable) and permanent gases, for further electrical and heat generation. Ultimately with the use of the TCR technology, the food production industry could look to using decentralized power generation located on-site of large food processing facilities to optimize their energy efficiencies.

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Keywords: Food chain waste; Intermediate pyrolysis; Thermo-catalytic reforming; Decarbonisation

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Nomenclature

CHP	Combined heat and power
GHG	Greenhouse gas
HHV	Higher heating value
LHV	Lower heating value
OFMSW	Organic fraction of municipal solid waste
TCR	Thermo-Catalytic Reforming

1. Introduction

The food and drink supply chain produces a vast quantity of wastes as both food and packaging wastes. If the waste can be recovered and used for energy generation, using the most appropriate technology, this will be of considerable benefit to the industry. Unfortunately there isn't a single technology which can effectively recover energy from both wet food and packaging wastes. For example, food waste contaminated with plastic packaging is not an ideal feedstock for anaerobic digestion due to its high content of biogenic and non-organic (rubble) components which cannot be degraded by microorganisms and can fill and clog the digester. However the high moisture content of this type of waste does not make it ideal for pyrolysis or incineration; therefore it is typically landfilled. This paper introduces the concept of intermediate pyrolysis of a similar feedstock to food and plastic wastes generated by the food supply chain and the role intermediate pyrolysis could play in decarbonizing the food supply chain.

2. Food supply chain

The food and drink industry is a significant global industry, with a turnover of \$8 trillion US in 2016 [1]. Within the EU, the food and drink sector represents 8% of employment and almost 6% of EU gross domestic product, equating to €715 billion per year [2]. The average household expenditure on food and drink equates to 13% for EU residents and over 20% for UK residents [3].

Food supply chain wastes includes both waste food and drink and packaging wastes, and is very similar in composition to the residual organic fraction of municipal solid waste (OFMSW). These waste streams represent inefficiency within the industry and a valuable loss of resources (for example energy, nutrients and production costs) [4]. The European Sustainable Development Strategy plans to reduce wastes through reuse and recycling of materials. Wastage of food through the supply chain is a global problem and is estimated to account for one third (approximately 1.6 billion tonnes per annum) of all food produced [5]. The quantity of food waste per person per year varies depending on geographical region from 95-115kg in Europe and North America to 6-11kg in Sub-Saharan Africa, South and South-Eastern Asia [6]. In developed countries, waste food typically enters landfill, where it decomposes and releases greenhouse gases (GHG). If food waste is source-separated from other materials prior to collection, it can be used in animal feed, composting or anaerobic digestion (depending on the food type and technology availability). The majority of packaging wastes are generated from the initial production stage on-farm through to the retail stage, with limited addition waste generated from households and the consumer [6]. Of all packaging wastes produced (to include food waste packaging), the EU produces a total of 82.5 million tonnes per year, with the UK producing 11.4 million tonnes [4]. In 2013, the UK recycled approximately 64% of all packaging wastes and incinerated a further 8% of waste. However of the waste incinerated, the UK did not participate in incineration with energy recovery, missing this opportunity to decarbonize the food supply chain by recovering heat and electricity from incineration. The remaining packaging waste, 3.19 million tonnes, were sent for landfill [4].

Finding alternative methods to reduce, reuse and recycle waste are essential to reduce the quantity of waste and GHG emissions generated from the food and drink supply chain. Wastes generated from the food and drink supply chain account for 20% of the UK GHG emissions, although these GHG emissions would increase to 30% if the required land use change for food production was also considered [7]. The GHG emissions from the food supply chain can be reduced if food waste is source-separated and sent to anaerobic digestion and packaging wastes are

incinerated or pyrolysed with energy recovery facilities, as opposed to landfilling both types of wastes. By reducing these two factors, the food supply chain will be decarbonized and EU targets will be met. To achieve GHG emission reductions, a combination of technological and behavioral changes would need to be introduced [7]. This paper sets out a case for the food chain supply industries to adopt a novel energy generation technology for food waste contaminated with packaging waste, thereby negating the need for source segregation and removing the need for landfill.

3. Thermo-Catalytic Reforming

Pyrolysis is the thermo-chemical conversion of biomass in an inert environment (without oxygen) for the production of char, bio-oil, permanent gases and an aqueous phase (process water). There are three main types of pyrolysis; slow, intermediate and fast pyrolysis, differentiated by temperature, heating rates and vapor residence times [8]. Historically, research has focused upon fast pyrolysis ($>500^{\circ}\text{C}$), however the oil quality is poor as it is highly oxygenated, corrosive, viscous and requires catalytic upgrading for further use [9]. Compared to fast pyrolysis, intermediate pyrolysis utilizes a lower temperature range of $350\text{--}450^{\circ}\text{C}$, has a slower heating rate (of minutes) and a slower vapor residence time of multiple seconds [8]. Fraunhofer UMSICHT has improved intermediate pyrolysis, developing the Thermo-Catalytic Reforming (TCR) (Figure 1), for the processing of a variety of biomass feedstocks. The TCR is a multi-zone horizontal auger screw reactor which heats biomass feedstocks to their specific temperature profiles between $350\text{--}450^{\circ}\text{C}$, in an inert environment [10]. During this phase, vapors and gases volatilizes from the biomass, converting the biomass into char. After the auger reactor, the char, vapors and gases enter the reforming phase at 700°C . The gases and vapors pass through the char bed, catalytically reforming the volatilized molecules. Following reforming, the vapors and gases are condensed to form bio-oil, permanent gases and an aqueous fraction [10].

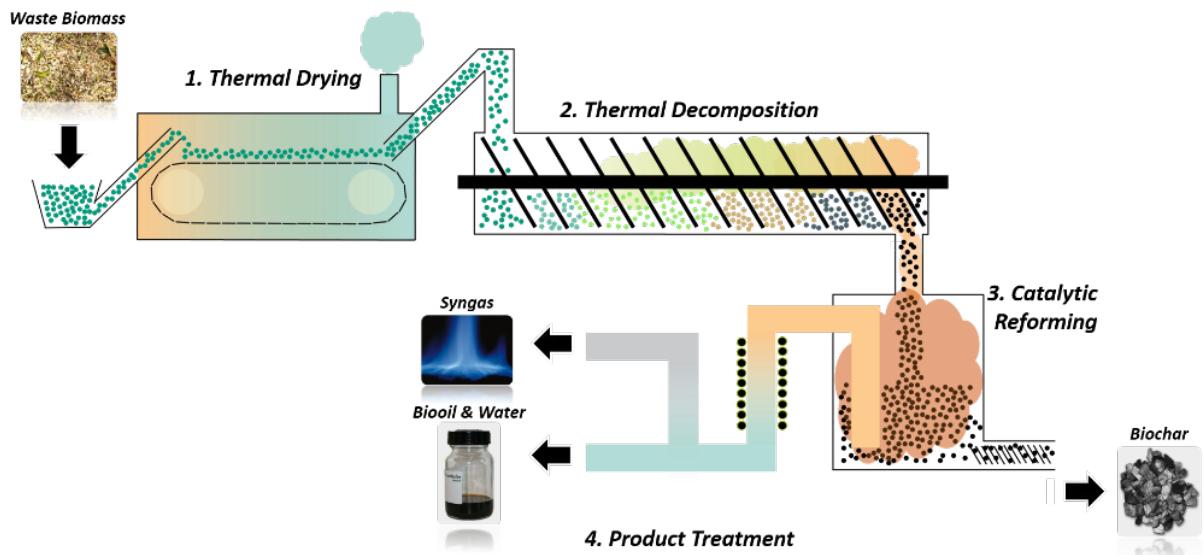


Fig. 1. Schematic of the Thermo-Catalytic Reforming process (Source: [11])

The quantity and composition of the different pyrolysis products vary depending on the original feedstock. As an example, the use of digestate from an anaerobic digestion plant as a feedstock produces 31% char, 8% bio-oil, 41% permanent gases and 20% aqueous phase [12]. Permanent gases typically consist of $>55\%$ hydrogen, $>35\%$ carbon dioxide, $>25\%$ carbon monoxide and trace amounts of methane and volatile hydrocarbons [12]. Bio-oil typically has a low oxygen content (7–11%), a low water content (<2%), a high heating value ($>36.7\text{MJ kg}^{-1}$) and a low total acid number (<5g kg^{-1}). Permanent gases and bio-oil can be burnt in a CHP engine [12], whilst bio-oil can be mixed with

biodiesel and used in a diesel engine [10]. Char can be used for co-incineration and as a potential fertiliser, soil conditioner [10] and building (insulation) material [13]. The TCR is more versatile than other pyrolysis methods as it can process a wide range of feedstocks, including biomasses with high ash and moisture contents and low ash melting points. The TCR can also process electronic scrap materials and plastic wastes. Ideally, feedstocks should have a heating value of $>8 \text{ MJ kg}^{-1}$ and a moisture content of $<20\%$. Feedstocks can have a moisture content $\geq 70\%$, however the economics of heating a feedstock this wet becomes thermally inefficient [12].

4. Thermo-Catalytic Reforming of the organic fraction of municipal solid waste

The food and drink supply chain produces predominantly three different types of wastes; food, packaging and packaging materials contaminated with food. In 2008, the UK sent 76% of clean and contaminated packaging materials to landfill, with thermal processing (pyrolysis and gasification) being used to recover energy from just 0.2% of this waste stream [14]. Although this situation is improving, more could be achieved from using pyrolysis to recover energy in the form of transport oils, electricity and heat.

UK Research Council funded research (EP/K036793/1) has examined the pyrolysis of the OFMSW. Household municipal waste (Fig. 2) was collected and the clean recyclable fractions were removed in a materials recoverable facility. The remaining waste was then processed through a 10mm screen to remove the larger items to produce the OFMSW used for pyrolysis (Fig. 3).



Fig. 2. Untreated municipal solid waste as received at the recycling facility



Fig. 3. The organic fraction of municipal solid waste following removal of recyclables and processing through a 10mm screen

Currently the OFMSW is sent to anaerobic digestion, combustion or landfill. However the OFMSW is not ideal for anaerobic digestion due to the high content of non-degradable components and is overly wet for incineration. If the waste is sent to landfill, the organic fraction of the waste will decompose releasing GHG. The OFMSW is very similar to the mixed wastes generated from the food industry once the recyclable components have been removed. Following screening of the feedstock, the OFMSW was dried to a moisture content of <25% and transported to Fraunhofer UMSICHT in Germany. The OFMSW (Figure 4) had a particle size of 1-10mm, a higher heating value (HHV) 13.7 MJ/kg and a lower heating value (LHV) 12.8 MJ/kg. Through pre-trial testing, Fraunhofer UMISCHT determined that the feedstock did not require pelletizing prior to pyrolysis in a 2kg/hour TCR reactor.



Fig. 4. The organic fraction of municipal solid waste prior to pyrolysis (Source: Fraunhofer UMISCHT, pers. Comm.)

To determine the suitability of the OFMSW for the production of fuel for power and heat generation, four different operation conditions of the reforming stage were examined. The feedstock was pyrolysed at 450°C under the same conditions for all treatments, but the reforming temperature varied from 450°C, 600°C, 700°C and 700°C with steam reforming. Steam reforming is an additional technique which injects water following pyrolysis and before the reforming step, to aid in the catalytic reforming of volatile molecules in the gas streams.

Increasing the reforming temperature was found to alter the mass distribution of char, bio-oil, aqueous and gaseous products. Char, oil and aqueous products were reduced and the mass of permanent gases increased (Table 1). However, if steam reforming was incorporated into the process and compared to treatment 700°C without steam reforming, the mass distribution of the aqueous fraction decreased and increases were seen in all other pyrolysis products.

Table 1. The effect of reforming temperature on the production of different pyrolysis products generated from the organic fraction of municipal solid waste, using the Thermo-Catalytic Reforming process.

Reforming temperature (°C)	Char (%)	Permanent gases (%)	Bio-oil (%)	Aqueous phase (%)
450	45.9	13.6	5.9	34.6
600	42.2	27.0	3.1	27.7
700	34.6	34.6	2.2	28.5
700 with steam reforming	39.6	36.2	2.7	21.5

To be able to decarbonise the food supply chain with the use of pyrolysis, the recovery of high quality fuels for

further application is vital. The char produced from pyrolysis can be used for co-incineration in coal-fired plants. The char from the OFMSW had a HHV which ranged from 5.6-7.5 MJ/kg (Table 2). The HHV is lower than other co-incineration feedstocks, for example refuse-derived fuel which has a HHV of 17.2 MJ/kg [15], and has a higher ash content. However there is still considerable energy that can be recovered from the char and further research should be undertaken to determine the role OFMSW char has in off-setting GHG and the carbon footprint of coal-fired energy plants.

The permanent gases from the OFMSW had a variable LHV dependent on reforming temperature (Table 2). Reforming temperature of 450°C produced the smallest quantity of gas with the lowest LHV of 9.9 MJ/kg. The highest LHV occurred for reforming temperatures 600°C and 700°C with steam reforming, of 16.9 and 17.0 MJ/kg respectively. However reforming temperature 700°C with steam reforming produced considerably more permanent gases, meaning the electric and heat output would be greater if the OFMSW was pyrolysed at this temperature. The energy content of the permanent gases was less than that of methane, 39. MJ/Nm³ [16], but does have sufficient energy content to be used in a CHP engine.

The pyrolysis product generated with the greatest energy content were the bio-oils. The HHV varied little between the different reforming temperatures (Table 2), however reforming temperature did have an effect on the quantity of bio-oil produced. The reforming temperature of 450°C produced 5.9% of bio-oil, whilst a smaller quantity of bio-oil was produced from treatment 700°C. If the technology was going to focus on maximising bio-oil production, a reforming temperature of 450°C should be used. Overall, bio-oil production from OFMSW had low ash and moisture contents, which is good when comparing them to other fuel types.

Table 2 The effect of reforming temperature on the composition of pyrolysis products from the Thermo-Catalytic Reforming of the organic fraction of municipal solid waste.

Reforming temperature (°C)	Analyses of pyrolysis products					
	Char	Permanent gases	Bio-oil			
	HHV (MJ/kg)	Ash (wt %)	LHV (MJ/kg)	HHV (MJ/kg)	Ash (wt %)	Oxygen (wt %)
450	6.4	81.2	9.9	38.6	<0.05	5.6
600	5.6	84.8	16.9	38.8	<0.05	2.1
700	6.8	77.6	13.6	39.0	<0.05	2.3
700 with steam reforming	7.5	78.0	17.0	40.2	<0.05	8.9

HHV – higher heating value; wt – weight; LHV – lower heating value.

The pyrolysis of the OFMSW, has to be energetically favourable and competitive against current and evolving technologies for energy recovery. The pyrolysis process is endothermic, with additional heat required by the process to heat the feedstock to the required temperature. Due to the energy content of the pyrolysis products the overall process has an energy recovery into usable energy products of 89-98%, depending on reforming temperature (Table 4). More commercial-scale TCR units will heat the incoming feedstock from parasitic heat recover from the char. A full energy balance of the process for comparison to alternative technologies for processing this waste stream should be investigated further to determine the net energy required for pyrolysis and what impact this could have in processing the waste generated by the food supply chain.

Table 4 Energy balances from Thermo-Catalytic Reforming process for the organic fraction of municipal solid waste at different reforming temperatures

Reforming temperature (°C)	Energy balance			
	Char (%)	Permanent gases (%)	Bio-oil (%)	Lost (%)
450	36	19	34	11
600	32	47	14	7
700	23	70	4	2
700 with steam reforming	32	57	7	5

Ultimately with the use of the TCR, the food production industry could look to using decentralized power generation located on the site of large food processing facilities to optimize their energy efficiencies and assist in decarbonizing the industry. Not only would food chain waste be minimalized to landfill, but more efficient energy production would be achieved as energy would not be lost during transportation of electricity to point-of-use. By reducing energy loss and maximizing energy recovery from wastes, will help to reduce the GHG emissions of the food chain, whilst simultaneously decarbonizing the industry.

5. Conclusions

The OFMSW is similar in composition to that of the contaminated packaging waste generated from the food supply chain and would be a suitable feedstock for the TCR. The energy recovered from the pyrolysis products represents a high proportion of the energy content of the OFMSW, which is promising that this would be a suitable technology to convert a waste product into useable fuel sources. To develop this research further, an energy balance of the technology alongside a comparison study of energy balances from alternative technologies would be required and an estimation this technology could make in decarbonizing the food supply chain.

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