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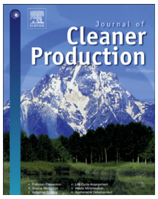

Carbon footprint calculation for thermoformed starch-filled polypropylene biobased materials

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ABSTRACT

Thermoformed trays made from biobased materials were prepared from agricultural waste (seeds or tubers), plasticizer and polypropylene (PP). A talc-filled PP thermoformed tray was used for comparison. The carbon footprint of the thermoformed trays was calculated according to PAS 2050. System boundaries were established according to a business-to-business approach, based on data collected regarding the raw material production, transportation and processing. Biobased trays yield a lower carbon footprint than talc-filled polypropylene trays as a result of renewable resource input, a lower processing temperature and shorter thermoforming cycle. The carbon footprint reduction could be achieved through optimization of the thermoforming process and the use of low-footprint raw materials.

1. Introduction

The increasing concentration of greenhouse gases (GHGs) enhances heat trapping in the atmosphere, leading to an increase in global temperatures, also known as global warming. Carbon dioxide (CO_2) is one of the primary GHGs that are contributing to the climate change. The atmospheric concentration of CO_2 has increased since 1800 from approximately 275 ppm–390 ppm in 2011 (Kutilek, 2011). It is released into the atmosphere as a byproduct of fossil fuel combustion and land-use changes (Moriarty and Honnery, 2008).

Malaysia is a developing country and is not legally bound by the Kyoto Protocol agreement to reduce its GHG emissions (UNFCCC, 2011). However, the Malaysian government has voluntarily committed to a 40% reduction of its 2005 gross domestic product (GDP) emissions intensity levels by 2020 and, under these conditions, receives assistance from developed countries (The Star, 2009). United Nations Statistics show that Malaysia's CO_2 emissions in 2005 stood at 183 million metric tons, or 7.0 metric tons per capita. In comparison, that same year, the neighboring countries of Singapore and Indonesia produced 11.6 and 1.5 metric tons per capita, respectively (United Nations Statistics, 2012). One approach to cut down the carbon emissions in Malaysia is by encouraging the use of biobased products.

According to the American Society for Testing and Materials (ASTM), a biobased material is an organic material containing carbon that has been derived from a renewable resource via a biological process. Renewable resources are available on a recurring basis, such as starch and grass. A biobased product can be fully or partially made from renewable resources. The starch-filled PP prepared here is considered a biobased material. The use of biobased plastics (e.g., PLA and thermoplastic starch) can reduce the dependency on fossil fuels, and these materials' production process may be more energy efficient than petroleum-based plastics processing (Álvarez-Chávez et al., 2012). A previous study by Madival et al. (2009) reported that the CO_2 emission during the production of a PLA clamshell (extrusion and thermoforming) was 7–9% lower than that of polyethylene terephthalate (PET).

Determining a product's carbon footprint involves the quantification of all GHGs released during all or part of it life cycle, expressed as CO_2 equivalents (CO_2eq) (Yuttitham et al., 2011). Publicly Available Specification (PAS) 2050 is the first standard method developed to measure product carbon footprint (PAS, 2050, 2008; Whittaker et al., 2011). This methodology accounts for emissions of six types of GHGs, including CO_2, nitrous oxide (N_2O), methane (CH_4) and the hydrofluorocarbon (HFC) and perfluorocarbon (PFC) families of gases. PAS 2050 has proven to be practical and scientifically robust for business implementation regardless of

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company size or sector. Many researchers have also adopted PAS 2050 in their product carbon footprint studies; for example, Iribarren et al. (2010) used PAS 2050 to investigate the carbon footprint of a canned mussel according to a business-to-customer basis. Dormer et al. (2013) reported that a food tray made from 85% recycled PET showed 58% carbon footprint reduction compared to a 100% virgin PET tray. Dias and Arroja (2012) reported that the use of three different methodologies (ISO 14040/14044, PAS, 2050 and the CEPI framework) to assess the carbon footprint of A4 paper gave different results, but all methodologies were able to identify the major emission hot spots.

The aim of this work is to study the carbon footprint of thermoformed trays, specifically trays made from biobased materials versus talc-filled polypropylene (PP) trays. The biobased materials were prepared using starch-containing agricultural waste (seeds or tubers), premixed with plasticizer and then melt blended with PP. Talc-filled PP was most likely the first commercialized filled polymer for thermoforming application (Throne, 1999). The homopolymer PP is difficult to process by thermoforming due to its narrow thermoforming window, so it is frequently formed just a few degrees below the melting temperature. Additionally, semi-crystalline PP tends to shrink more than the amorphous polymer (O'Connor et al., 2010). The inclusion of an inorganic filler (talc) into PP can improve the dimension stability, as filled resins shrink less than unfilled resins. Moreover, the talc-filled PP tray output is expected to increase because talc-filled PP has a higher thermal conductivity than unfilled PP (Weidenfeller et al., 2004). Both the biobased and talc-filled PP compounds were shaped through sheet extrusion and vacuum thermoforming into a tray product. The calculation of a product's carbon footprint is important, as this can help the manufacturer understand the key carbon-intense areas that have the greatest impact on the overall footprint and prioritize areas for emission reduction.

2. Materials and methodology

2.1. Materials

The starch-containing agricultural wastes used in this study, agricultural waste seed (AWS) and agricultural waste tuber (AWT), were supplied by Texchem Material Sdn Bhd, Malaysia. The AWS and AWT were derived from local agricultural waste sources with starch compositions of 43 wt% and 50 wt%, respectively. They were cleaned, ground into powder and sieved to obtain an average particle size of 6.5 μm and 27.7 μm, respectively. Polypropylene (PP) and glycerin-based plasticizer were also supplied by Texchem Material Sdn Bhd. The melt flow index (MFI) and density of PP were 3.16 g/10 min (190°C/2.16 kg) and 0.90 g/cm^3, respectively. The glycerin-based plasticizer had a density of 1 g/cm^3, an acid value of $<3\%$ and moisture $<0.2\%$. The talc powder (325 mesh) was obtained from Euro Chemo-Pharma, Malaysia.

2.2. Goals of the study

The objectives of the study were as follows:

- To calculate the carbon footprint of thermoformed trays made from starch-filled PP biobased materials and talc-filled PP.
- To identify the key carbon footprint contributors and to determine actions for emission reduction.

2.3. Functional unit

The functional unit used to express the GHG emissions for the raw materials being investigated is defined as kg CO_2eq/kg raw material. All inputs and outputs of analysis are related to the functional unit (kg CO_2eq/kg tray in this study) in order to allow emission estimation for thermoformed tray production.

2.4. System definition and boundary

The thermoformed tray carbon footprint was calculated according to the PAS 2050 methodology using a business-to-business approach, more popularly known as cradle-to-gate (Mungkung et al., 2012). The exclusion of end-of-life emissions was due to the high uncertainty of the use phase and disposal phase of the tray. The tray is designed as primary packaging to hold and protect consumer products during shipping to the global market. The uncertainty arose because details of the delivery to the consumer product manufacturer and the end consumer are unknown, and there is a lack of accurate data on the disposal options (such as reuse, recycle, landfill or incineration). Moreover, each city and country has different recycling infrastructures and preferred waste management options.

Thus, this study assessment focuses on the areas in which we can initiate improvements, particularly for operation in the Texchem Polymer factory, such as compounding, sheet extrusion and thermoforming processes. The system boundary of the tray product involved three major stages, starting from the production of the raw materials (AWS, AWT, plasticizer, PP and talc), transportation of the raw materials into the Texchem Polymer factory and the processing steps to convert them into the tray product. Both the AWS and AWT are discarded agricultural by-products, and they are not grown exclusively for making biobased trays. Thus, the cradle stage of the AWT and AWS does not include plant cultivation-related emissions, but is instead defined from the stage of the conversion factory to the pulverization of the waste. The overall system boundaries for the production of the biobased (AWS/PP and AWT/PP) and talc-filled PP trays can be observed in Figs. 1–3.

2.5. Other exclusions

The GHG emissions arising from the production of capital goods, such as machinery use, factory building and employee transportation to and from the work site, have been excluded from the system boundary. The human inputs to processes are also excluded from the boundary.

2.6. GHGs and global warming potential

The defined system boundary reveals that the GHGs emitted in this study are mainly CO_2, particularly for activities in the Texchem Polymer factory. CO_2 has a global warming potential (GWP) of 1,

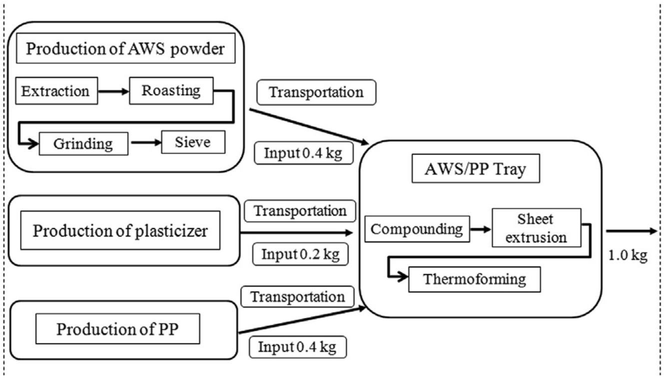

Fig. 1. System boundary for the AWS/PP tray using the business-to-business approach.

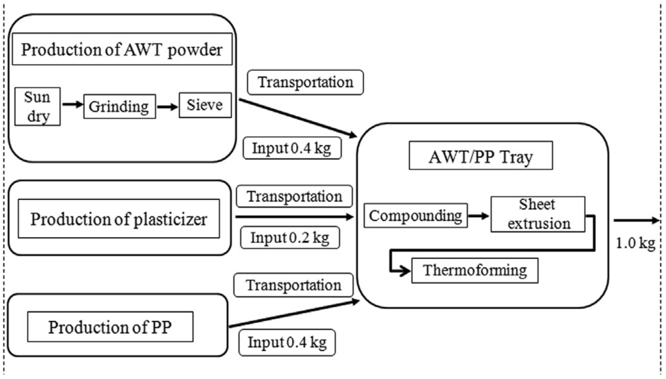

Fig. 2. System boundary for the AWT/PP tray using the business-to-business approach.

and other types of GHGs, such as the N_2O emission associated with the upstream activity of plasticizer production, are converted into CO_2eq using the GWP for a 100-year time horizon, which is available from the Intergovernmental Panel on Climate Change, IPCC (2007).

2.7. Data collection

According to PAS 2050, after establishing the system boundary, the data need to be recorded in relation to product GHG emissions within the system boundary of that product. Two types of data are needed for the carbon footprint calculation: activity data and the emission factor. The activity data refer to all materials and energy used in the product's life cycle (material input, output, transportation, etc). The emission factor provides the information to convert these quantities into resulting GHG emissions, which is the amount of GHG emitted per 'unit' of activity data (e.g., kg GHGs per kg input). Both the activity data and emission factor can come from primary or secondary data sources. Preference is given to the collection of primary activity data (direct data collected from those processes owned, operated or controlled by the organization implementing PAS, 2050). An example of primary activity data is the measurement of the energy used in a process or the amount of fuel used in transportation. Secondary data can be used when primary data are not available or cannot be practically obtained. Secondary data are representative of an average or general measurement of similar processes or materials. An example of secondary data is the reported transportation emissions per km per vehicle type (BSI, 2008; Roy and Tekchandani, 2011).

In this study, primary activity data have been collected for the processes controlled by the Texchem Polymer factory. Whenever possible, primary activity data have also been collected for other processes, such as the production of the starch-containing agricultural waste powder. The stages of data collection are explained below:

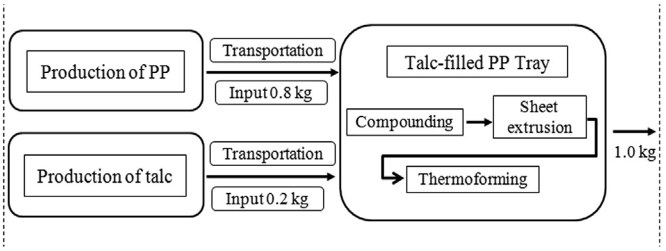

Fig. 3. System boundary for the talc-filled PP tray using the business-to-business approach.

1. *AWS powder production*: After the extraction of the pulp, AWS seeds were roasted, ground and sieved to obtain a fine powder. The activity data included the total energy consumed by the AWS seed to pulverize it.
2. *AWT powder production*: AWT was the residue obtained after industrial processing of the tubers. It was sun-dried, ground and sieved into a fine powder. The total energy consumed during the production process and site-related emissions were considered.

3 *Production of plasticizer, PP and talc:* The plasticizer, PP and talc footprint were obtained from relevant suppliers or secondary data sources (PlasticsEurope, 2008; Rocktron, 2012) by taking into account the resource inputs and emissions associated with the production of 1 kg of plasticizer, 1 kg of PP or 1 kg of talc, based on the cradle-to-gate approach.

4 *Transportation*: The above raw materials were transported to the Texchem Polymer factory via a diesel oil truck with a load of 8 tons. The distance traveled and diesel oil consumed were provided by the logistic supplier.

5 Compounding, sheet extrusion and thermoforming:

A compound of starch-containing agricultural waste powder (AWS or AWT), PP and plasticizer was prepared with a ratio of 4:4:2 using a Berstorff model twin-screw extruder, L/D of 54:1. The compounding temperature was set within a range of 140–170 °C, and the screw speed was set to 200 rpm. Sheet extrusion was carried out in a Berlyn model single-screw extruder with an L/D of 31:1. The sheet extruder processing temperature was set within a range of 150–170 °C, the screw speed was set to 50 rpm and the chill roll was set to a temperature range of 60–80 °C with a speed of 1.0 rpm. The thickness of the extruded sheet was 0.7 ± 0.1 mm. Vacuum thermoforming to shape the tray was carried out in a Hermes model thermoforming machine by heating the sheet at a temperature of 130–150 °C for 15–20 s, with vacuum applied for 3–5 s. The thermoformed tray was cooled by a blower for 8–10 s before it was removed from the mold. Similar processing steps were applied for the talc-filled PP tray production, which involved the compounding of 20% talc with PP resin, sheet extrusion and thermoforming processing. In this study, three types of thermoformed trays were prepared, namely a talc-filled PP tray, an AWS/PP tray and an AWT/PP tray. The data arising from this study included the feedstock energy and processing energy during the manufacturing process.

2.8. Calculation

As shown in equation (1), the product carbon footprint is the sum of all materials and energy across all activities in a define boundary multiply by their emission factors and GWP, the unit is kg CO_2eq/kg product. In this study, the raw materials carbon footprint must be obtained first. It will be used as an input for calculation on the subsequent tray forming processes in the Texchem Polymers factory. The feedstock emission for the biobased tray production can be calculated according to the blend ratio of the raw materials. The emission factor for the electricity grid in Peninsular Malaysia is 0.631 kg CO_2eq/kWh (Roy and Tekchandani, 2011), and the combustion of 1 L diesel oil emits 2.67 kg CO_2eq/kg (Carbon Trust, 2011).

$$\text{Carbon Footprint} = \text{activity data} \times \text{emission factor} \times \text{GWP} \qquad (1)$$

3. Results and discussion

The activity data collected for the raw materials, namely AWS and AWT powder production and their respective transportation energy consumption are shown in Table 1. The travel distance to

Table 1
Raw materials activity data.

Activity	Energy consumption
AWS powder	(kWh/kg)
Extraction	0.01
Roast	0.05
Grinding	0.06
Sieve	0.03
AWT powder	(kWh/kg)
Grinding	0.27
Sieve	0.03
Transportation	(L diesel oil/kg)
AWS	0.0005
AWT	0.0005
PP	0.0440
Plasticizer	0.0005
Talc	0.0014

transport the AWS, AWT and plasticizer is 8 km; the talc is transported 22 km, while the PP resin is shipped a distance of 700 km to the Texchem Polymer factory. The activity data regarding the processes to form the tray are shown in Table 2.

After obtaining the energy consumption data for each activity, the carbon footprint for the raw materials and thermoformed trays can be calculated using equation (1). The carbon footprint for the raw materials is presented in Table 3. It is observed that the footprints of the AWS and AWT (0.09–0.19 kg CO_2eq/kg) are the lowest, followed by mineral talc (0.854 kg CO_2eq/kg), plasticizer (1.96 kg CO_2eq/kg) and PP resin (2.02 kg CO_2eq/kg).

The low carbon footprints of AWS and AWT were expected due to their renewable agricultural waste origin, which can be perceived as carbon neutral, and the low CO_2-producing process steps. Renewable resources such as plants can play a role as a carbon sink in the ecosystem (Jana et al., 2009; Jansson et al., 2010). Food crops take up CO_2 in the atmosphere during photosynthesis, converting the carbon into glucose and releasing oxygen at the same time. The storing of carbon in living plants represents a rather short-term sequestration because when the plants decay, the carbon is returned to the atmosphere. Thus, the CO_2 extracted from the atmosphere during plant growth and the end-of-life carbon emission can be regarded as offsetting each other, resulting in carbon neutrality. However, if the living biomass is well maintained or undisturbed, plants can continue to act as a carbon sink for several centuries (Jansson et al., 2010). The removal of CO_2 via photosynthesis can thus reduce the CO_2 level in the atmosphere and address global warming. The plant biomass after harvesting can be converted into biobased products (in this case, for the production of biobased thermoformed trays). The production of biobased products creates an additional stock of captive carbon, and more carbon is sequestered in that stock as the volume of production increases every year (Sedjo, 2001). AWS and AWT powder production is rather simple with no or little heating steps and no addition of chemical reagent. The grinding process is among the high-energy intensive steps; however, it was carried out on a high-efficiency energy-saving grinding machine to achieve an output of 700 kg powder per hour. In addition, AWS and AWT are readily available in Malaysia, and with the short travel distances between the factories, this results in low transportation emissions. The raw waste material supply is enough to support commercial-scale production, with a capacity of at least 100 tons per month committed by a local supplier. Thus, the utilization of agricultural wastes is highly encouraged, particularly for the making of low footprint biobased materials; moreover, it is a creative way to resolve the environmental problem of waste disposal while generating a side income for the farmer.

Table 2
Thermoformed trays activity data.

Activity	Energy consumption
AWS/PP	(kWh/kg)
Compounding	1.00
Sheet extrusion	0.80
Thermoforming	2.00
AWT/PP	(kWh/kg)
Compounding	1.00
Sheet extrusion	0.80
Thermoforming	2.00
Talc-filled PP	(kWh/kg)
Compounding	1.00
Sheet extrusion	0.88
Thermoforming	2.30

Table 3
Raw materials carbon footprint.

Activity	Carbon footprint (kg CO_2eq/kg)				
	AWS	AWT	PP	Plasticizer	Talc
Production	0.09	0.19	1.90	1.96	0.85
Transportation	0.001	0.001	0.12	0.001	0.004
Total	0.091	0.191	2.02	1.961	0.854

The talc powder production process involved mining and milling. The talc ore obtained from the mines (either underground or open-pit) was partially crushed and sorted to different grades according to their chemical compositions, color and crystalline structure. At the milling factory, the talc ore was further crushed and finely ground into powder (Olson, 1990). The mining activity and ore processing steps are not as energy intensive as the polyolefin production process; thus, these minerals have a lower greenhouse effect than the petroleum-based resins (Crépin-Leblond, 2011). The plasticizer carbon footprint is the second highest after the PP resin. This result could be attributed to the combination of its complex synthesis process with multiple conversion steps and the intensive use of reactants and catalysts. Its production involved the cultivation and extraction of the raw material, followed by a series of chemical reactions and treatments under different temperature and pressure controls to yield a high-purity final product.

As discussed earlier, the PP resin carbon footprint is the highest among the raw materials used for the thermoforming input. The high carbon footprint is attributed to its crude oil origin, high CO_2-producing process and the long travel distance from the resin manufacturing plant. The use of polyolefin as feedstock releases into the atmosphere large quantities of carbon previously held in fossil fuels, causing global climate changes. According to a previous study by Harding et al. (2007), PP synthetic resin showed a high carbon footprint due to the energy-intense propylene monomer unit production and the use of crude oil for energy generation. The GHG emission of PP resin originates from four main sources: the emission caused by the production of crude oil and natural gas (the feedstock), and the production of propylene monomer and the long chain polymer (PP). The first step of polyolefin production, the acquisition of crude oil and natural gas, contributes approximately 17% of the total GHG emission; this amount results from the extraction and refining of the crude oil and natural gas. The hydrocarbons obtained from refined petroleum and natural gas are heated to extremely high temperatures during the cracking process to break down the large molecules into smaller molecules, such as propylene. More than 50% of the carbon footprint is contributed by this stage of propylene unit production. The next step is the polymerization phase to produce the long chain PP from small hydrocarbon molecules, and it contributes approximately 31% of the GHG emissions (Borealis, 2008; PlasticsEurope, 2008).

Previous studies also indicate that the CO_2 emission generated by the production of biobased polymers is significantly lower than the amount generated by the production of petrochemical-based polymers. For example, the production of polyhydroxyalkanoate (PHA) from the bacterial fermentation of soybean oil has a carbon footprint of 0.26 kg CO_2/kg plastic compared to a footprint of 1.9 kg CO_2/kg plastic for low-density polyethylene (LDPE) and a footprint of 1.7 kg CO_2/kg plastic for high-density polyethylene (HDPE), as calculated in a cradle-to-gate basis (Akiyama et al., 2003). The lower CO_2 emission of PHA is mainly due to the renewable origin of the feedstock, where soybean plants absorb CO_2 from the air and offset the downstream process CO_2 emissions. As another example, for every 100 kg of polyethylene (PE) resin produced, biobased PE derived from sugar cane can save 314 kg of CO_2 emission compared to fossil fuel-based PE (Narayan, 2009). If the rate of CO_2 released into the environment at end-of-life equals the rate of CO_2 fixed through photosynthesis by new crops, a net "zero carbon footprint" can be achieved (Narayan, 2009).

The carbon footprint for thermoformed trays is shown in Table 4. The AWT/PP, AWS/PP and talc-filled PP thermoformed trays emitted 3.64, 3.68 and 4.43 kg CO_2eq/kg tray, respectively. In this study, the use of different agricultural wastes (seeds or tubers) gives different material performance, although their carbon footprints are comparable. The performance of the AWS/PP and AWT/PP (as measured by the biodegradation rate, tensile properties and water absorption behavior) depends on their starch composition (amylose to amylopectin ratio), particle size and dispersion in the PP matrix (Pang et al., 2013). The starch granules are embedded in the PP matrix, thus maintaining most of the desirable PP properties and can be processed via conventional equipment. Both AWS/PP and AWT/PP can be used to form biobased trays, from shallow to deep-drawing items, with a life span of 1.5–2 years.

The biobased tray footprints are 20–22% lower than that of the talc-filled PP tray. As expected, the low footprint of the AWS and AWT results in a low footprint production of thermoformed trays. In addition to the low raw material footprint of renewable input, the lower carbon footprint of biobased trays is due to two key factors. First, biobased material typically requires lower processing temperatures; for example, the sheet extrusion of biobased material can be performed at 160 °C, while the talc-filled PP sheet must be extruded at 170 °C. Second, the thermoforming cycle was longer for the talc-filled PP tray even with the inclusion of talc. According to Throne (1999), when talc is compounded into PP at 20 wt% or more, the resulting sheet has good sag resistance and an increased forming window. However, this study showed that the talc-filled PP extruded sheet still required a longer heating time and a longer cooling period for its thermoformed tray than biobased trays. This finding is supported by a study by Álvarez-Chávez et al. (2012): they reported that thermoplastic starch production requires 68% less energy than its petroleum-based plastics. Biobased materials can thus reduce the dependence on fossil fuel and help mitigate the global warming issue through the reduction of the carbon footprint of manufactured goods (BioPreferred, 2011).

Table 4
Carbon footprint for thermoformed trays made from biobased and talc-filled PP materials.

Activity	Carbon footprint (kg CO_2eq/kg tray)		
	AWS/PP	AWT/PP	Talc-filled PP
Feedstock	1.24[a]	1.28[a]	1.79[b]
Compounding	0.63	0.63	0.63
Sheet extrusion	0.51	0.51	0.56
Thermoforming	1.26	1.26	1.45
Total	3.64	3.68	4.43

[a] Biobased tray feedstock values are calculated based on the raw materials input ratio 4:4:2, e.g., AWS/PP/plasticizer: $0.4(0.091) + 0.4(2.02) + 0.2(1.96) = 1.24$.

[b] Talc-filled PP tray feedstock value is calculated according to a ratio of 8:2 for PP/talc: $0.8(2.02) + 0.2(0.854) = 1.79$.

One of the objectives of this study is to identify the carbon-intense areas during the life cycle of the thermoformed trays. The quantification of the GHG emissions of each process aids the effort to reduce the impact of the processes with the highest contributor. The carbon footprint contribution breakdowns for the biobased and talc-filled PP trays are shown in Figs. 4 and 5. AWS/PP and AWT/PP trays have similar carbon footprint breakdowns. Fig. 4 reveals that the thermoforming process contributes the greatest part of emission at 35%. This contribution is followed by the contribution from the raw material processing at 33% and compounding at 17%. In contrast to popular belief, the transportation emissions are responsible for only 1% of the total carbon footprint of biobased trays. Fig. 5 illustrates that the greatest GHG emission contributor for the talc-filled PP tray is the raw material processing at 38%, followed by thermoforming at 33% and compounding at 14%. In this study, both cases showed that the contribution of transportation emissions is very small (1–2%). This finding is in agreement with that of a Ross and Evans (2003) assessment of the plastic packaging life cycle, in which the authors reported that the contribution of the transportation energy is negligible when compared to the overall energy consumption of the system.

It is worth noting that the thermoforming emissions are 2–2.5 times more than the emissions from compounding and sheet extrusion. The high emission is attributed to a long cycle time that involves complex stages of operation: clamping of the sheet, applying heat to soften the sheet, moving up the mold, turning on vacuum to remove the air between the sheet and the mold, cooling and demolding. The long cycle time leads to low output, which means fewer trays can be produced in a defined period. In comparison, compounding and sheet extrusion are fairly simple and fast processes. They involve the extrusion of polymer melts into pellets and sheets. The twin-screw extruder provides powerful compounding and good dispersion; thus, its energy consumption is slightly higher than that of single-screw extruder, which is used for sheet extrusion. The output for the compounding and sheet extrusion can range from 15 to 30 kg/h, which is higher than thermoforming at 8 kg/h. The high speed and high output processes (i.e., compounding and sheet extrusion) can thus reduce energy use and overall emission.

The identification of the largest emission sources can help the thermoformed tray manufacturer to focus and prioritize the areas for improvement. In this study, the potential emission reduction can be achieved by the revealing of thermoforming and raw material processing emissions as the key carbon footprint contributors (in excess of 68%). The carbon reduction strategy for the

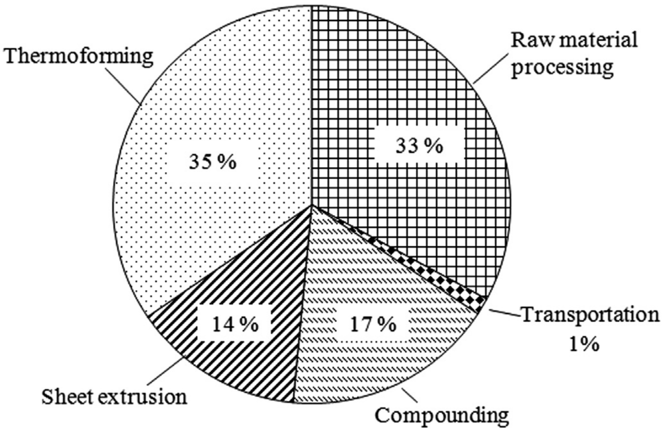

Fig. 4. Carbon footprint contributor for AWS/PP and AWT/PP trays.

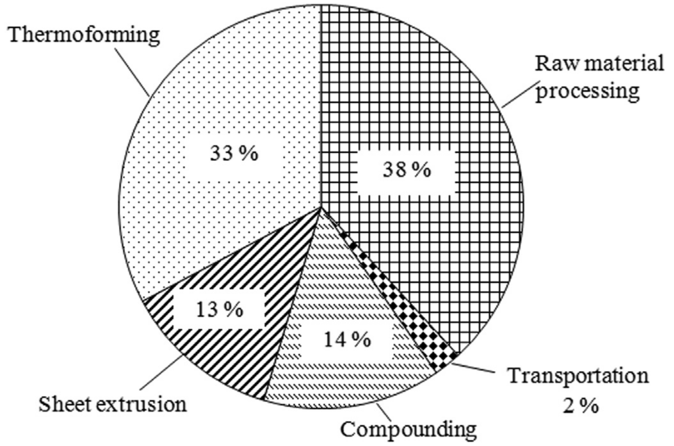

Fig. 5. Carbon footprint contributor for talc-filled PP tray.

thermoforming area includes the optimization of the thermoforming parameters, such as by shortening the thermoforming cycle time via effective heating and cooling of the product. Moreover, it is also important to review the design of the mold cavities and possibly to work on a better multi-cavity mold design that can increase the output with a given quantity of extruded sheet and can subsequently lead to a reduction in the thermoforming waste. The emission reduction for the raw material processing relies on the raw material process owner (the PP resin producer); however, substantial emission reduction can still be achieved by reducing the use of high footprint raw materials. One of the options here is to replace the virgin PP with low footprint recycled PP resins, which account for only 30% of the footprint of virgin PP (attributed to the exclusion of raw material extraction and energy-intense processing steps) (Bourmaud et al., 2011; Ross and Evans, 2003; Gregor-Svetec et al., 2009). The drawback of recycled PP is deterioration in the mechanical properties, particularly the ultimate properties (i.e., elongation at break) and the increment of the melt flow index value attributed to the chain scission mechanism after multiple processes (da Costa et al., 2007). In future publications, we will attempt to quantify the GHG emissions after the optimization of the thermoforming process and the use of low footprint raw material.

4. Conclusions

This study presents a business-to-business analysis (PAS, 2050) of the GHGs emitted in the production of thermoformed trays. Biobased trays, which include starch-containing agricultural wastes as part of the formulation, can be produced with a lower carbon footprint than talc-filled PP trays (approximately 20% emissions reduction). This result is attributed to the renewable resource input, lower processing temperature and shorter thermoforming cycle when using biobased materials. The thermoforming process is the largest contributor (35%) to the emissions associated with biobased trays followed by the raw material processing (33%). Transportation emissions account for only a small share (1–2%) of the carbon footprint. In the future, further reductions may be achieved through optimization of the thermoforming process and the use of raw materials with an even lower carbon footprint.

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