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Comparative Study of a Life Cycle Assessment for Bio-Plastic Straws and Paper Straws: Malaysia's Perspective

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Supplementary Data

Table S1. Equipment details of corn starch production (Section 1) based on SuperPro Designer.

Equipment Code/Name	Description	Equipment Setup Information
V-101 Pre-treatment tank	Increase the moisture content in the corn kernel.	• 3 pretreatment tanks in series • 6 h of residence time • Operating temperature of 55 °C • Power consumption 23 kW per unit
V-102 Enzymatic treatment tank	Remove the soluble solids.	• 4 enzymatic treatment tanks in series • 3 h of residence time • 75% volume filled • Operating temperature of 50 °C and pH 4.5 • Power consumption 23 kW per unit
DS-101 Centrifuge 1	Mill Starch (MS) thickener	• 7939 L/min throughput • 25% (*w*/*w*) solids in underflow • Power consumption 189 kW per unit
DS-102 Centrifuge 2	Primary separator	• 3218 L/min throughput • 33% (*w*/*w*) solids in underflow • Power consumption 148 kW per unit
DS-103 Centrifuge 3	Gluten thickener	• 3112 L/min throughput • 17% (*w*/*w*) solids in underflow • Power consumption 50 kW per unit
DS-104 Centrifuge 4	Clarifier	• 3945 L/min throughput • 28% (*w*/*w*) solids in underflow • Power consumption 25 kW per unit
CY-101 Hydrocyclone	Starch washing	• 4558 L/min throughput • 1.3 kg fresh water/kg of dry corn • Power consumption 15 kW per unit

Table S2. Equipment details of lactic acid production (Section 2) based on SuperPro Designer.

Equipment Code/Name	**Description**	**Equipment Setup Information**
V-101 Condenser	Condensation	• Remove water with 90% efficiency • Power consumption 0.5 kW per unit
R-101 Depolymerization tank	Stoichiometric Reaction	• Depolymerization process • Formation of lactide • Power consumption 0.0022 kW per unit
R-102 Polymerization tank	Stoichiometric Reaction	• Ring-opening polymerization • Formation of PLA • Power consumption 0.0025 kW per unit
CR-101 Crystallizer	Crystallization	• Solidify PLA • Power consumption 0.3 kW per unit
GRN-101 Granulator	Granulation	• Formation of PLA resins • Power consumption 5.5 kW per unit

Table S3. Equipment details of bio-plastic production (Section 3) based on SuperPro Designer.

Equipment Code/Name	Description	Equipment Setup Information
R-101 Saccharification tank	Stoichiometric Reaction	• Operating temperature of 90 °C • Saccharification of starch into dextrose molecules: $(C_6H_{10}O_5)_n + nH_2O \rightarrow nC_6H_{12}O_6$ • Power consumption 7.7 kW per unit
FR-101 Fermentation tank	Stoichiometric Fermentation	• Operating temperature of 37 °C and pH 6 • Fermentation of dextrose into lactic acid: $C_6H_{12}O_6 \rightarrow 2C_3H_6O_3$ + biomass • Calcium lactate formation: $2C_3H_6O_3 + Ca(OH)_2 \rightarrow C_3H_5O_3^{-}Ca^{+}O_3^{-}H_5C_3 + 2H_2O$ • Power consumption 690 kW per unit
MF-101 Microfilter	Microfiltration	• Power consumption 606 kW
V-101 Acidification tank	Acidification	• Dissociation of calcium lactate with sulfuric acid: $C_3H_5O_3^{-}Ca^{+}O_3^{-}H_5C_3 + H_2SO_4 \rightarrow CaSO_4 + 2C_3H_6O_3$ • Power consumption 3.7 kW per unit
RVF-101 Rotary vacuum filter	Rotary Vacuum Filtration	• Remove gypsum ($CaSO_4$) • Power consumption 224 kW per unit
EV-101 Evaporator	Evaporation	• Remove water • Power consumption 3.2 kW per unit

Table S4. Equipment details of bio-plastic straws production (Section 4) based on SuperPro Designer.

Equipment Code/Name	**Description**	**Equipment Setup Information**
XD-101 Extruder	Extrusion	• Power consumption 20 kW per unit • Screw Angular Velocity 300 rpm
IM-101 Injection molder	Injection Molding	• Physical properties assume to be same as PP • Power consumption 15 kW per unit • Straws diameter 2–12 mm Raw material capacity 20–60 kg/h
LB-101 Labeler	Labeling	Power consumption 2.2 kW per unit
BX-101 Packet packager	Packaging	• Power consumption 5.4 kW per unit A packet consists of 300 bio-plastic straws
BX-102 Box packager	Packaging	• Power consumption 0.34 kW per unit A box consists of 16 unit packets

Table S5. Equipment details of delivery to consumer and disposal of bio-plastic straws (Section 5) based on SuperPro Designer.

Equipment Code/Name	Description	Equipment Setup Information
CM-101 Consumers	Indicate Consumers	• Simply pass through block • Assume no reaction occurs
FSP-101 Flow splitter	Flow Splitting	• The used PLA are split equally to industrial composting facility, landfill and incineration
LF-101 Landfill	Landfill process	• PLA decompose in anaerobic landfill environment: PLA → methane + carbon dioxide
INC-101 Incinerator	Incineration	• Required fuel and air
CPT-101 Composter	Composting	• PLA in industrial composting facility: PLA + heat + microbe → carbon dioxide + water

Table S6. Equipment details of paper straws production (Section 4) based on SuperPro Designer.

Equipment Code/Name	Description	Equipment Setup Information
PSM-101 Paper straw machine	Gluing, Winding and Cutting	• Power consumption 7 kW per unit

Table S7. Equipment details of delivery to consumer and disposal of paper straws (Section 5) based on SuperPro Designer.

Equipment Code/Name	Description	Equipment Setup Information
CM-101 Consumers	Indicate Consumers	• Simply pass through block • Assume no reaction occurs
FSP-101 Flow splitter	Flow Splitting	• The used paper straws are split equally to industrial composting facility, landfill and incineration
LF-101 Landfill	Landfill process	• Paper decompose in anaerobic landfill environment: Paper → methane + carbon dioxide
INC-101 Incinerator	Incineration	• Required fuel and air
CPT-101 Composter	Composting	• Paper in industrial composting facility: Paper + heat + microbe → carbon dioxide + water

Table S8. Process data inventory of bio-plastic straws production obtained from SuperPro Designer simulator (based on 100 drinking straws unit functional).

Section/Process	Corn Starch Production (Section 1)					Lactic Acid Production (Section 2)					
	Corn Steeping	**Germ Separation**	**Fiber Separation**	**Gluten Separation**	**Starch Separation**	**Saccharification of Starch**	**Fermentation of Dextrose into Lactic Acid**	**Microfiltration**	**Acidification**	**Rotary Vacuum Filtration**	**Evaporation**
Power Consumption (kWh)	1.7	9.8	5.2	4.0	5.3	6.8×10^{-2}	6.1	5.4	3.3×10^{-2}	2.0	2.8×10^{-2}
CO (g)	2.6×10^{-1}	1.5	7.7×10^{-1}	6.0×10^{-1}	8.0×10^{-1}	1.0×10^{-2}	9.2×10^{-1}	8.0×10^{-1}	5.0×10^{-3}	3.0×10^{-1}	4.2×10^{-3}
VOC (g)	3.0×10^{-2}	1.7×10^{-1}	8.9×10^{-2}	6.9×10^{-2}	9.2×10^{-2}	1.2×10^{-3}	1.1×10^{-1}	9.3×10^{-2}	5.7×10^{-3}	3.4×10^{-2}	4.9×10^{-4}
CO_2 (g)	1.1×10^{3}	6.3×10^{3}	3.4×10^{3}	2.6×10^{3}	3.5×10^{3}	4.4×10^{1}	4.0×10^{3}	3.5×10^{3}	2.2×10^{1}	1.3×10^{3}	1.8×10^{1}
NO_x (g)	1.5	8.5	4.5	3.5	4.6	5.9×10^{-2}	5.3	4.7	2.9×10^{-2}	1.7	2.5×10^{-2}
SO_2 (g)	7.9	6.7	3.6	2.8	3.7	4.7×10^{-2}	4.2	3.7	2.3×10^{-2}	1.4	2.0×10^{-2}
NH_3 (g)	0.0	9.8×10^{-3}	0.0	2.4×10^{-2}	1.3×10^{-4}	0.0	0.0	0.0	0.0	0.0	0.0
CH_4 (g)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table S9. Process data inventory of bio-plastic straws production obtained from SuperPro Designer simulator (based on 100 drinking straws unit functional) (continue).

Section/Process	Polylactic Acid Production (Section 3)					PLA Straw Production (Section 4)				To Consumer and End of Life of PLA Straw (Section 5)		
	Condensation	**Depolymerization**	**Ring-opening Polymerization**	**Crystallization**	**Granulation**	**Extrusion**	**Injection Moulding**	**Labelling**	**Packaging**	**Composting**	**Landfill**	**Incineration**
Power Consumption (kWh)	4.4×10^{-3}	1.9×10^{-5}	2.2×10^{-5}	2.7×10^{-3}	4.9×10^{-2}	1.8×10^{-1}	1.3×10^{-1}	2.0×10^{-2}	5.1×10^{-2}	1.3×10^{-2}	4.5×10^{-4}	1.8×10^{-3}
CO (g)	6.6×10^{-4}	2.9×10^{-6}	3.3×10^{-6}	4.0×10^{-4}	7.4×10^{-3}	2.7×10^{-2}	2.0×10^{-2}	2.9×10^{-3}	7.6×10^{-3}	2.0×10^{-3}	6.8×10^{-5}	2.7×10^{-4}
VOC (g)	7.7×10^{-5}	3.3×10^{-7}	3.8×10^{-7}	4.6×10^{-5}	8.5×10^{-4}	3.1×10^{-3}	2.3×10^{-3}	3.4×10^{-4}	8.8×10^{-4}	2.3×10^{-4}	7.8×10^{-6}	3.1×10^{-5}
CO_2 (g)	2.9	1.2×10^{-2}	1.4×10^{-2}	1.7	3.2×10^{1}	1.2×10^{2}	8.7×10^{1}	1.3×10^{1}	3.3×10^{1}	2.4×10^{1}	2.0	1.9×10^{1}
NO_x (g)	3.9×10^{-3}	1.7×10^{-5}	1.9×10^{-5}	2.3×10^{-3}	4.3×10^{-2}	1.5×10^{-1}	1.2×10^{-1}	1.7×10^{-2}	4.4×10^{-2}	1.1×10^{-2}	3.9×10^{-4}	1.5×10^{-3}
SO_2 (g)	3.1×10^{-3}	1.3×10^{-5}	1.5×10^{-5}	1.8×10^{-3}	3.4×10^{-2}	1.2×10^{-1}	9.2×10^{-2}	1.3×10^{-2}	3.5×10^{-2}	9.1×10^{-3}	3.1×10^{-4}	1.2×10^{-3}
NH_3 (g)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CH_4 (g)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	6.0×10^{-4}	0.0

Table S10. Process data inventory of paper straws production obtained from SuperPro Designer simulator (based on 100 drinking straws unit functional).

Section/ Process	Wood Preparation (Section 1)		Kraft Pulping Process (Section 2)						Papermaking Process (Section 3)			Paper Straw Production (Section 4)	To consumer and End of Life of PLA Straw (Section 5)		
	Debarking	**Chipping & Conveying**	**Biomass Combustion**	**Recovery of Boiler**	**Lime Combustion**	**Smelt Tank**	**Bunker Oil Use**	**Aerobic Biological Treatment**	**Paper Refining & Screening**	**Paper Forming, Pressing, Finishing**	**Paper Drying**	**Paper Drinking Straw Machine**	**Composting**	**Landfill**	**Incineration**
Power Consumption (kWh)	7.6×10^{-3}	2.7×10^{-2}	0.0	0.0	0.0	0.0	0.0	0.0	6.4×10^{-2}	1.4×10^{-1}	7.6×10^{-3}	1.2×10^{-1}	2.6×10^{-2}	8.8×10^{-4}	3.5×10^{-3}
CO (g)	1.1×10^{-3}	4.0×10^{-3}	0.0	0.0	0.0	0.0	0.0	0.0	9.6×10^{-3}	2.1×10^{-2}	1.1×10^{-3}	1.8×10^{-2}	3.8×10^{-3}	1.3×10^{-4}	5.2×10^{-4}
VOC (g)	1.3×10^{-4}	4.6×10^{-4}	0.0	0.0	0.0	0.0	0.0	0.0	1.1×10^{-3}	2.4×10^{-3}	1.3×10^{-4}	2.1×10^{-3}	4.4×10^{-4}	1.5×10^{-5}	6.0×10^{-5}
CO_2 (g)	5.0	1.7×10^{1}	8.1×10^{5}	1.6×10^{3}	3.7×10^{5}	0.0	3.0×10^{4}	2.6×10^{3}	4.2×10^{1}	8.9×10^{1}	5.0	7.9×10^{1}	4.7×10^{1}	3.3×10^{1}	3.7×10^{1}
NOx (g)	6.6×10^{-3}	2.3×10^{-2}	7.3×10^{2}	2.7×10^{2}	8.6×10^{1}	2.5	7.8×10^{1}	0.0	5.6×10^{-2}	1.2×10^{-1}	6.6×10^{-3}	1.1×10^{-1}	2.2×10^{-2}	7.7×10^{-4}	3.0×10^{-3}
SO_2 (g)	5.3×10^{-3}	1.8×10^{-2}	0.0	5.2×10^{1}	1.4×10^{2}	7.6	4.6×10^{2}	0.0	4.4×10^{-2}	9.5×10^{-2}	5.3×10^{-3}	8.4×10^{-2}	1.8×10^{-2}	6.1×10^{-4}	2.4×10^{-3}
NH_3 (g)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CH_4 (g)	0.0	0.0	2.2×10^{2}	0.0	0.0	0.0	8.5×10^{-1}	2.8×10^{1}	0.0	0.0	0.0	0.0	0.0	1.2×10^{-2}	0.0
N_2O (g)	0.0	0.0	2.9×10^{1}	0.0	0.0	0.0	2.1×10^{-1}	1.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0

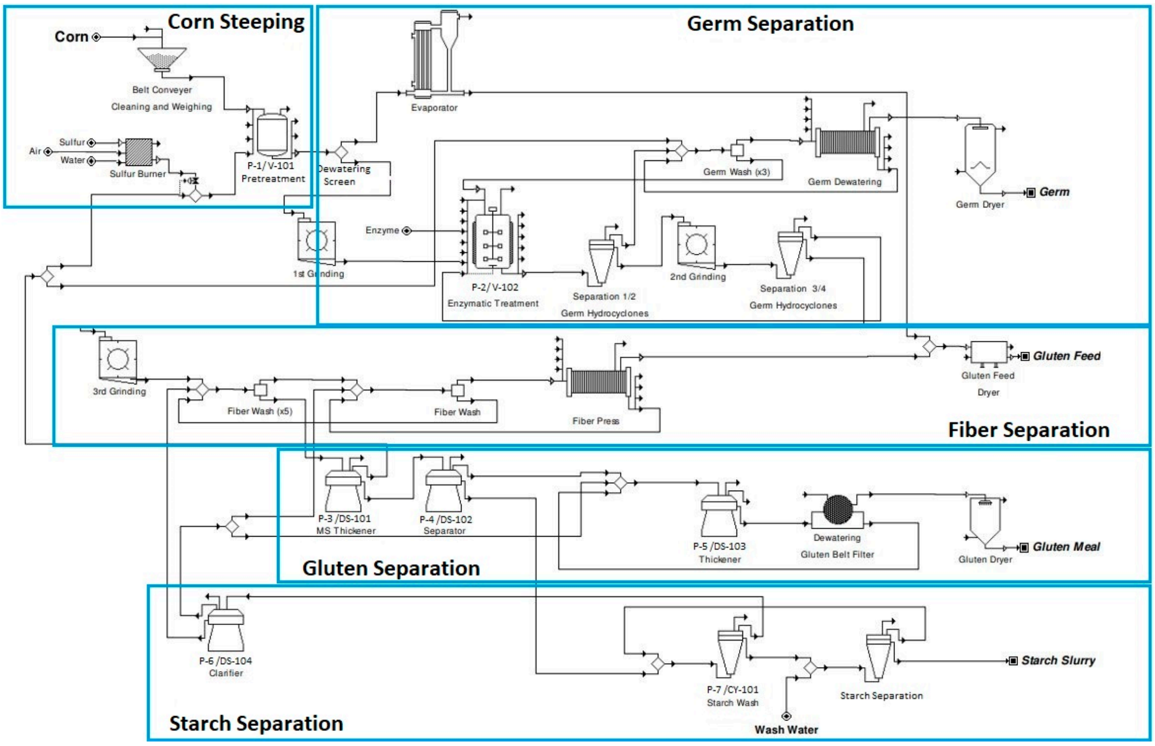

Figure S1. Overall process flow diagram of the corn starch production (Section 1).

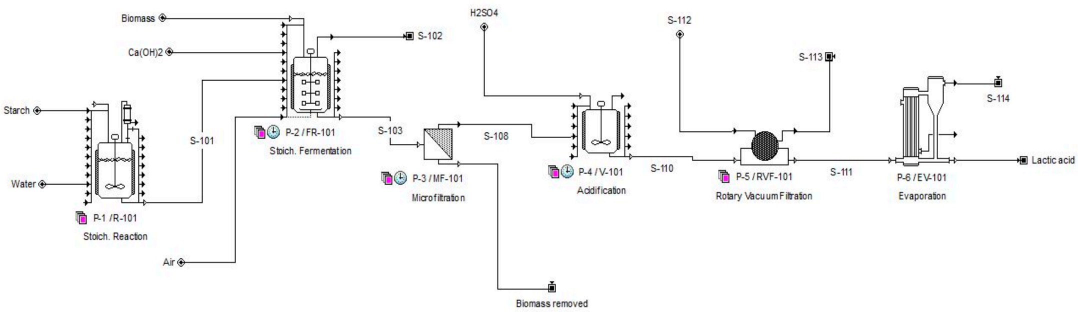

Figure S2. Process flow diagram of the lactic acid production (Section 2).

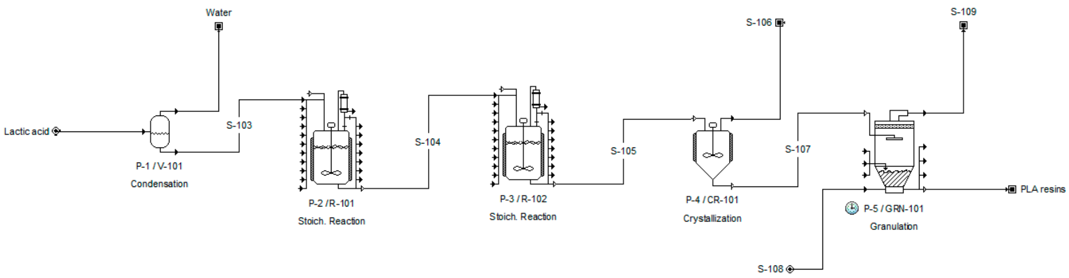

Figure S3. Process flow diagram of the bio-plastic production (Section 3).

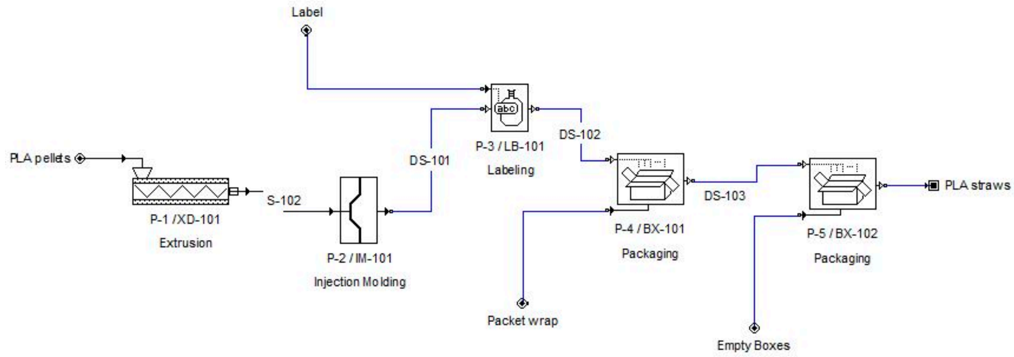

Figure S4. Process flow diagram of the bio-plastic straws production (Section 4).

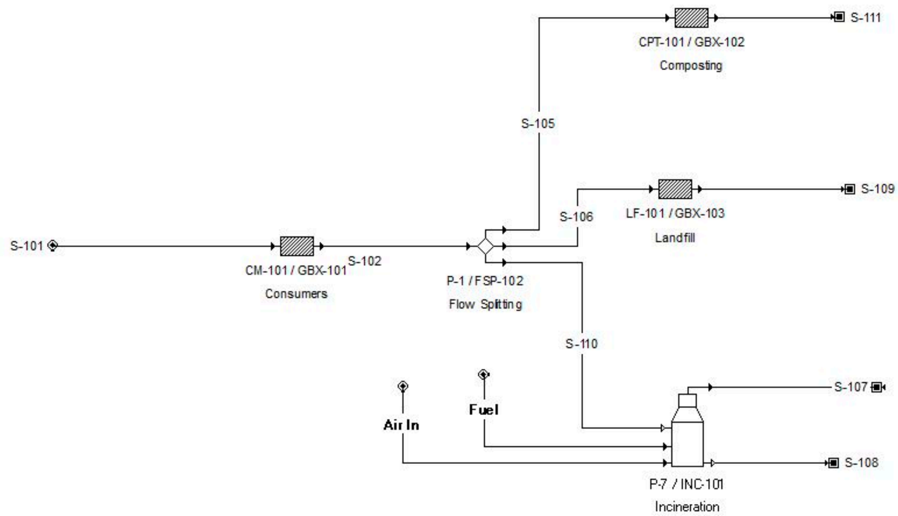

Figure S5. Process flow diagram of the delivery consumer and disposal of bio-plastic straws (Section 5).

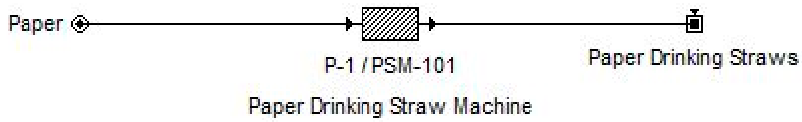

Figure S6. Process flow of the production of paper straws (Section 2).

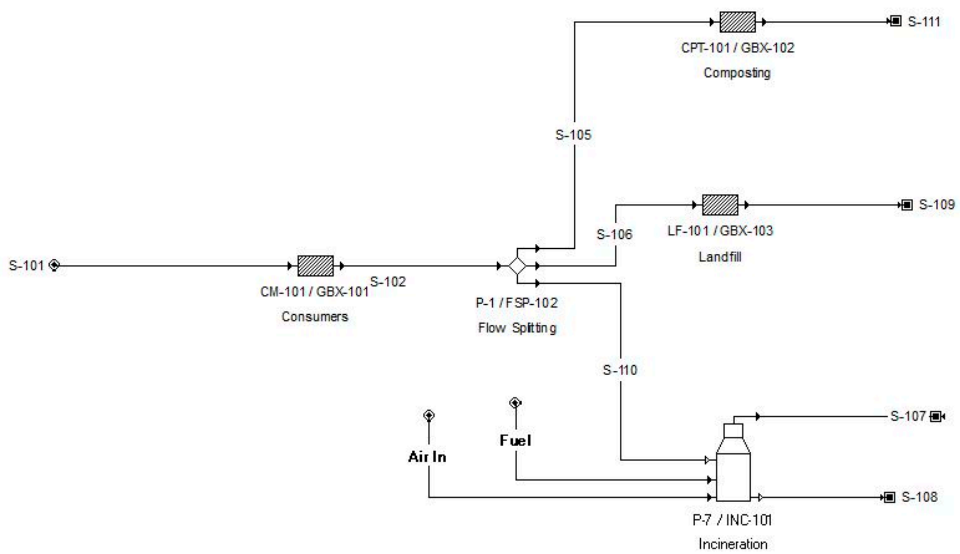

Figure S7. Process flow diagram of the delivery to consumer and disposal of paper straws (Section 5).

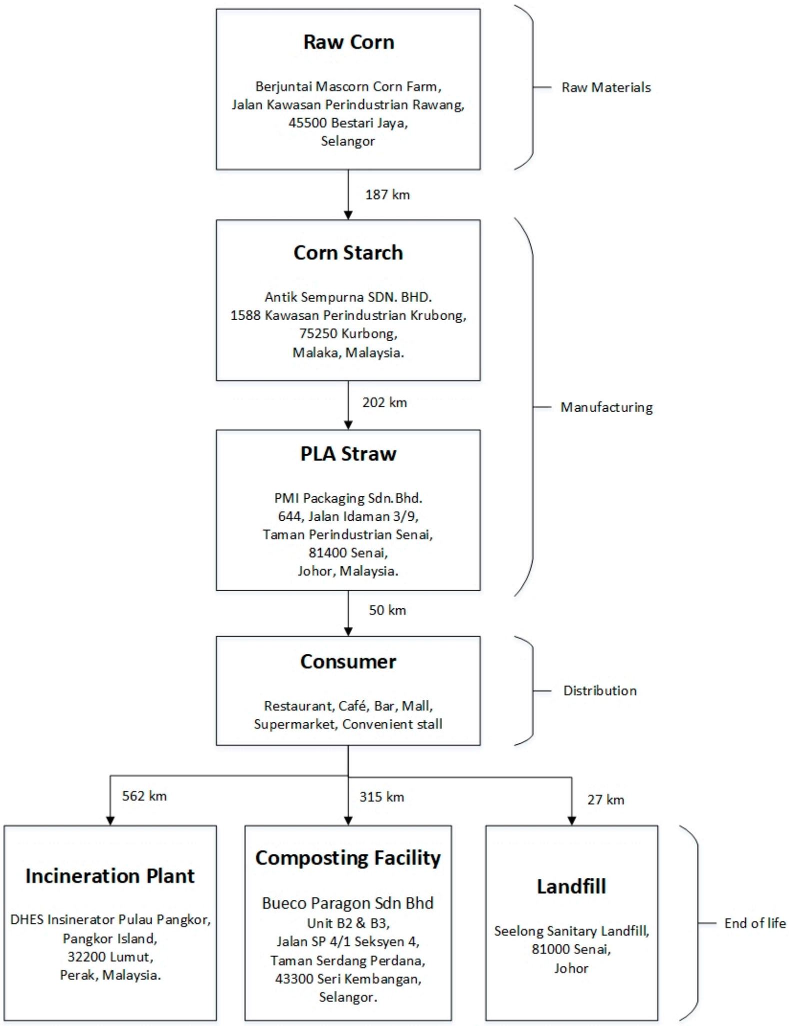

Figure S8. Transportation detail for the overall process for bio-plastic straws from gate to grave.

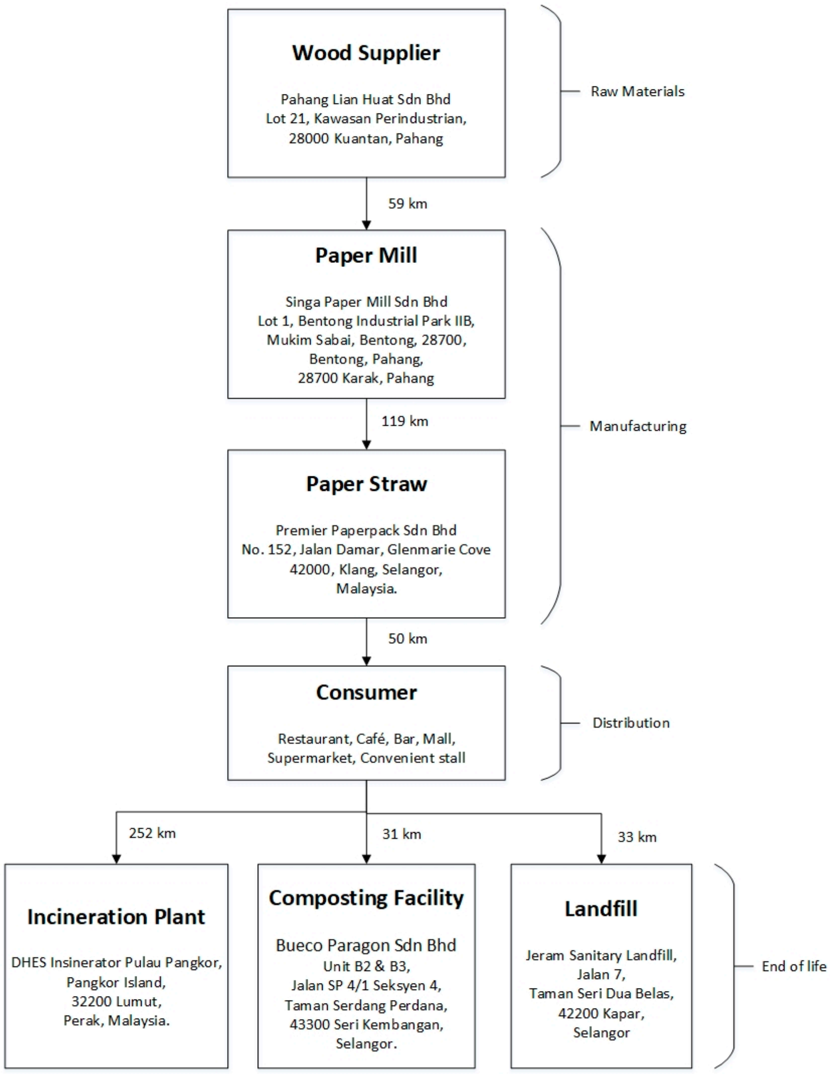

Figure S9. Transportation detail for the overall process for bio-plastic straws from gate to grave.