Sustainability by Reduced Energy Consumption: Ingredients Selection and Manufacturing Processes for Oil-in-Water Emulsions

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Introduction

Endeavours to reduce carbon footprint often involve swapping synthetic ingredients for natural alternatives, yet comparative studies are lacking. Energy consumption is often researched in isolation to raw materials and information within this domain remains scattered. Energy input in emulsion manufacture comprises of 95% thermal and 5% mechanical energy. Reductions in energy consumption are usually made by substituting hot processes for cold. Gaps in the literature relate to sustainability from an operational perspective, i.e. how to make the change to sustainable manufacturing.

This project compares the use of thermal energy in forming oil-in-water (O/W) emulsions through three different manufacturing processes: hot, hot-cold and cold. The aim was to quantify the energy consumption and carbon footprint of two types of O/W emulsions at a manufacturing scale of 500kg. One was made with standard synthetic ingredients and another with very similar physiochemical characteristics made with COSMOS-approved natural alternatives; both were produced using three manufacturing processes.

Materials and Methods

- Six O/W emulsions were tested (**Figure 1**).
- Hot-cold process involved heating oil phase only.
- '**Scale-down' calculations** were performed beforehand, to coordinate laboratory and manufacturing conditions for a typical 500 kg vessel
- 500 g batches were prepared at 6600 rpm for 2 minutes and 20 seconds using L5M homogeniser (Silverson, UK)

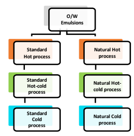

Figure 1. Emulsion samples

Table 1. Standard & natural hot, hot-cold and cold process formulations

Phase	INCI	Standard hot and hot-cold % (w/w)	Standard cold % (w/w)	Natural hot and hot-cold % (w/w)	Natural cold % (w/w)
A	Aqua	q.s. 100 %	q.s. 100 %	q.s. 100 %	q.s. 100 %
B	Acrylates/C10-30 Alkyl Acrylates Crosspolymer	0.20	0.50	-	-
	Potassium Sorbate	-	-	0.20	0.20
C	Glycerine	3.00	3.00	3.00	3.00
	Xanthan Gum	-	-	0.20	0.20
D	PEG-7 Glyceryl Cocoate	2.00	4.00	-	-
	Glyceryl Oleate Citrate	-	-	2.00	4.00
	Diethylhexyl Carbonate	20.00	20.00	-	-
	Helianthus Annuus (Sunflower) Seed Oil	-	-	20.00	20.00
	Glyceryl Stearate	4.50	-	4.50	-
	Cetearyl Alcohol	2.00	-	3.00	-
	Bentonite (and) Xanthan Gum (and) Citric Acid (and) Sodium Stearyl Glutamate	-	-	-	7.00
E	Phenoxyethanol, Ethylhexylglycerin	0.70	0.70	-	-
	Levulinic Acid (and) Sodium Levulinate (and) Glycerin (and) Aqua	-	-	0.70	0.70
F	Sodium Hydroxide	q.s. pH 4.60-6.60	q.s. pH 4.60-6.60	-	-

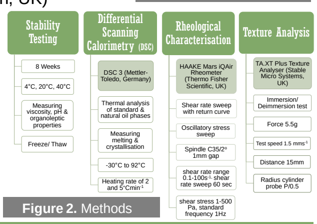

Figure 2. Methods

$$v = R \cdot d \cdot \pi$$

Where: v = Velocity (m/s); R = Revolutions Per Minute (rpm); d = Diameter (m); π = 3.14

$$\dot{\gamma} = \frac{v}{\delta}$$

Where: $\dot{\gamma}$ = Shear Rate (1/s); v = Velocity (m/s); δ = Gap between rotor and stator (m)

$$R = \frac{v}{d \cdot \pi} \cdot 60$$

Where: R = Revolutions Per Minute (rpm); v = Velocity (m/s); d = Diameter (m); π = 3.14

$$E_m = \frac{P}{M}$$

Where: E_m = Specific Energy Input (W/kg); P = Power (W); M = Mass (kg)

$$\text{Factor in Time} = \frac{E_m\,(\text{Laboratory})}{E_m\,(\text{Manufacturing})}$$

Where: Factor in Time = Time factor between Manufacturing and Laboratory; E_m(Laboratory) = Specific Power Input at a Laboratory Scale (W/kg); E_m(Manufacturing) = Specific Power Input at Manufacturing Scale (W/kg)

$$T_L = \frac{T_M}{\text{Factor in Time}}$$

Where: T_L = Laboratory Homogenisation Time (Minutes); T_M = Manufacturing Homogenisation Time (Minutes); Factor in Time = Time factor between Manufacturing and Laboratory

Equation 1. 'Scale-down' calculations

Scale-down calculations calculated the shear rate of the manufacturing homogeniser to find the rpm that the laboratory homogeniser needs to be used at, to achieve this same shear rate. The comparison between specific energy input of both laboratory and manufacturing homogenisers is used to determine the laboratory homogenisation time.

$$Q = m \cdot Cp \cdot \Delta T$$

Where: Q = Energy Content (J); m = Mass (kg); Cp = Specific Heat Capacity (J/kg/K); ΔT = Temperature difference (°C)

Equation 2. Thermal energy calculations

Thermal energy consumption can be reduced through varying manufacturing processes, and to quantify this between the hot and hot-cold processed emulsions, **Equation 2** was used for 30% oil phase and 70% water phase for a 500kg emulsion.

A Life Cycle Assessment (LCA) was implemented to determine overall Carbon dioxide equivalent (CO_2e) values, assessing environmental impacts of O/W emulsions from cradle-to-gate. CO_2e figures from Ecoinvent 3.8 used the Global Warming Potential of 100 years.

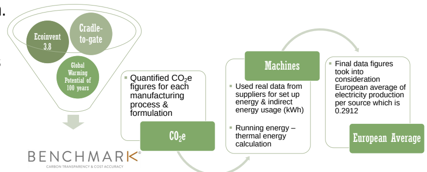

Figure 3. Life Cycle Assessment Method

Results and Discussion

The purpose of scaling down is to ensure repeatable and successful large-scale production of emulsions with the same characteristics as laboratory produced. The concept of scale-down calculations can be applied to any vessel following an understanding of the capabilities of the manufacturing vessel. Calculations relative to manufacturing vessel EKATO UNIMIX S JET 500 and laboratory homogeniser SILVERSON L5M obtained a laboratory homogenisation speed and time:

6,600 rpm	2 minutes 20 seconds

Stable formulations were achieved, Freeze/thaw test displayed no observable changes.

DSC results found melting ranges were lower for standard oil phase compared to natural oil phase. Understanding this prevents overheating and using more thermal energy than necessary when melting the oil phases. Crystallisation temperature indicates the suitability of an oil phase for hot-cold processing. Standard oil phase crystallises at lower temperatures, therefore would readily disperse when manufacturing an emulsion with hot-cold process. In natural oil phase, the higher crystallisation temperature increases the risk of oil solidification during hot-cold processing at a laboratory scale.

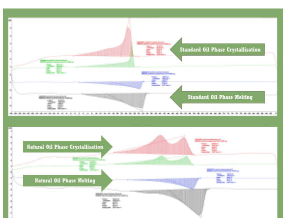

Figure 4. DSC Graphs

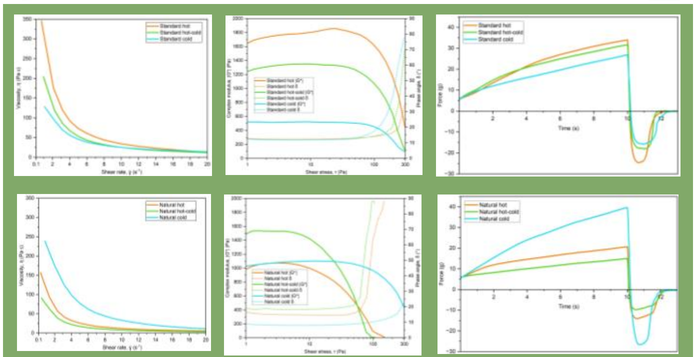

Figure 6. Shear rate sweep curves, oscillatory stress sweep curves and texture analysis curves for standard and natural hot, hot-cold and cold process emulsions

Sufficiently similar emulsions were achieved as illustrated by rheological characterisation and texture analysis results. The main difference is natural cold formulation due the bentonite within this emulsion.

An 82% thermal energy reduction is possible when swapping from hot to hot-cold process in emulsion manufacturing. For cold process, 100% reduction is achieved, but it needs considerable reformulation.

Cooling requirements are reduced by the same amount, which brings a further benefit of significant reduction in processing time.

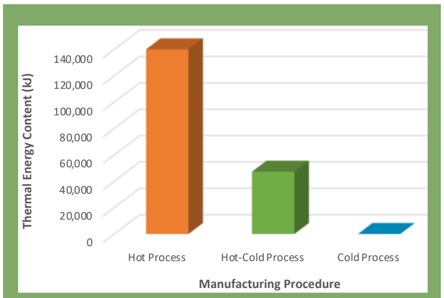

Figure 4. Thermal energy consumption results

Table 2. Life cycle assessment results

Formulation (per 500kg)	CO_2e for Ingredients	CO_2e figure with Manufacturing	CO_2e for Packaging	Total CO_2e Figure
Standard Hot	0.30	204.38	29.58	**234.26**
Standard Hot-Cold	0.30	141.15	29.58	**171.03**
Standard Cold	0.31	136.86	29.58	**166.75**
Natural Hot	0.80	161.22	29.58	**191.60**
Natural Hot-Cold	0.80	141.15	29.58	**171.53**
Natural Cold	0.98	136.86	29.58	**167.42**

The overall impact of the manufacturing process present a **26% CO2e reduction from hot to hot-cold, and a 28% CO2e reduction from hot to cold**. However, the cold process presents considerable formulation and stability challenges. LCA has shown **very small differences in the overall carbon footprint between synthetic and natural ingredients**.

Conclusion

Following similarities between emulsions, a comparative study on their respective cradle-to-gate carbon footprint was performed. Quantitative figures show very little impact of synthetic and natural ingredients on the overall emulsion carbon footprint. Manufacturing procedures continue to have the largest impact on the carbon footprint. A 26% CO2e reduction from hot to hot-cold process, and a 28% CO2e reduction from hot to cold process was achieved. **Hot-cold emulsion manufacturing seems to be an acceptable compromise, reducing thermal energy consumption by 82% and reducing carbon footprint by 26%, whilst maintaining emulsion characteristics.** This project has shown that emulsion manufacturing with reduced energy consumption is achievable. The next steps would be practically implementing these techniques at the manufacturing scale.

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