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Life cycle assessment of cleaning-in-place operations in egg yolk powder production

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ABSTRACT

The manufacture of egg yolk powder by spray drying requires regular cleaning in order to remove fouling deposits and prevent microbiological growth on the pasteurisation heat exchanger and the spray dryer. A life cycle assessment (LCA) study on a typical powder manufacturing plant, using literature data, indicated that the egg breaking, storage and pasteurisation steps were the major contributors to the plant's environmental impacts rather than the cleaning-in-place (CIP) operations owing to their high water and electricity consumption (for refrigerated storage). CIP impacts on thermal energy and wastewater emissions were nevertheless significant, and the benefits of using intermittent flows of aqueous NaOH solution in the dryer CIP stage, reported by Yang et al. (2019), were assessed. The latter gave a 21% improvement in terrestrial ecotoxicity impact. Optimising the NaOH/temperature conditions based on experimental data gave more efficient cleaning with lower water, chemicals and energy consumption. Over-cleaning had significant impacts on terrestrial and marine ecotoxicity as well as reducing productivity. Three changes in cleaning technology were considered briefly: electrical heating, solar heating and pumping, and membrane treatment of wastewater. These gave little overall global improvement, partly due to the polluting nature of the available electricity supply (coal-fired) and local benefits to the factory being offset by impacts associated with equipment manufacture.

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1. Introduction

The food industry consumes large quantities of water and energy for processing and cleaning, which is expected to increase as the population, and hence food demand, continue to grow. Clean water is required to maintain process and product hygiene, creating particular challenges in regions where this resource is limited. Efforts to improve the sustainability of food manufacturing need to identify methods of reducing its demands for water and energy, and improving the efficiency of cleaning operations is one route to achieve this goal.

Modern large-scale food manufacturing facilities usually employ automated cleaning-in-place (CIP) systems to circulate aqueous solutions to flush, clean, disinfect and/or condition process plant between products or batches. The capability of CIP is determined by four parameters according to Sinner's Circle: operating temperature; chemical agents; the hydrodynamic forces imposed by the cleaning fluid on the soil or deposit; and cleaning time (Tamime, 2009). For example, increasing the flow rate of cleaning fluid increases the local tangential force (wall shear stress) exerted on the soil and enhances its removal (Joppa et al., 2017; Yang et al., 2019a; Yiantsios and Karabelas, 1995). Alkaline solutions are often used to clean proteinaceous deposits as the high pH promotes swelling and weakening of the deposit, which is then removed by a combination of surface shear and diffusion mechanisms in the erosion stage (Gillham et al., 1999). Higher temperatures give faster reaction and diffusion rates, and promote phase changes such as the melting of fats which facilitate cleaning (Cuckston et al., 2019). Although such aggressive cleaning measures can reduce the time to clean and improve production efficiency, they can also increase environmental burdens associated with higher temperatures and greater flow rates (*e.g.* larger pumps, heat losses). There is therefore a trade-off between cleaning effectiveness and overall environmental performance of CIP which needs to be assessed carefully (Christaki and Tzia, 2002).

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Operating CIP process more efficiently can reduce water, chemical and energy consumption as well as the volume of contaminated water to be treated. The latter can be significant owing to the high biological oxygen demand associated with food wastewater, which is often treated by on-site water treatment facilities. A number of techniques have been developed to improve the efficiency of CIP process, such as addition of caustic and acid blends (Bremer et al., 2006), enzymes (Lequette et al., 2010) and technologies such as ice-pigging (Quarini, 2002). Cleaning solutions are circulated through process equipment items such as mixers and heat exchangers but for large tanks and vessels, static spray ball, rotary spray head and rotary jet devices are used to distribute cleanser on surfaces to be cleaned (Goode et al., 2013; Tamime, 2009) rather than filling the whole unit up in a 'fill and soak' mode. Operating the rotary jet devices with burst or pulsed flows have been reported to reduce water and chemical consumption during cleaning (Briggs et al., 2004; Kjellberg, 2016).

To date many efforts to optimise the efficiency of spray cleaning have focused on cost perspectives without evaluating the impact on overall environmental performance. With the current focus on sustainability, new developments in CIP methods need to be evaluated from a wider perspective.

Measures of cleaning efficiency have included production-based metrics (Köhler et al., 2015) as well as environmental footprint indicators. Life cycle assessment (LCA) is a widely recognized quantitative method for evaluating environmental impacts associated with industrial and agricultural processes and products. The dairy sector has received noticeable attention, with several LCA studies reported (Dvarionienė et al., 2012; Eide et al., 2003; Finnegan et al., 2017; Gésan-Guiziou et al., 2019; Høgaas Eide and Ohlsson, 1998; Milani et al., 2011; Zouaghi et al., 2019): these showed that cleaning operations contributed nearly one-third of the total environmental impacts of milk processing (Gésan-Guiziou et al., 2019). The pasteurisation-CIP operation was identified as an environmental hotspot owing to the large amount of wastewater produced (Zouaghi et al., 2019), containing milk residues and detergents which result in negative environmental impacts such as eutrophication (Eide et al., 2003). CIP processes employing lower temperatures (or energy recovery) and water use, such as enzyme-based and alkaline cleaning, were found to be more environment-friendly, but they are often more financially costly (Eide et al., 2003).

Annual global egg production has more than doubled since 1990 and reached about 80 Mte/y in 2017, and is expected to surpass 100 Mte/y in the near future (Shahbandeh, 2020). The demand for dried egg products, manufactured mostly by spray drying, has been increasing strongly due to both their functional properties and storage benefits, such as microbiological safety, long shelf life, and low transportation cost (Bergquist et al., 1995). Of the dried product forms, egg yolk powder is more widely used than whole egg powder (Transparency Market Research, 2017). The high temperatures and humidity in the dryer can cause acute fouling (Langrish et al., 2007), which, with the pasteurisation heat exchanger, represent hotspots for cleaning. Similar issues arise in milk powder manufacturing (Krokida et al., 2016; Zouaghi et al., 2019). While several LCA studies on milk powder processing have been performed (Finnegan et al., 2017; Krokida et al., 2016; Yan and Holden, 2018), the environmental profile of egg yolk powder processing, especially the impact of CIP operation, has not been analysed. The CIP operations in egg yolk and milk powder processing share similarities in terms of solutions and equipment used since both deal with proteinaceous deposits. However, their deposits exhibit different cleaning mechanisms (Li et al., 2013; Pérez-Mohedano et al., 2016) which can affect their environmental footprints.

This paper uses LCA approaches to quantify the impact of CIP operating strategies on the environmental performance of an idealised egg yolk powder manufacturing line. Different strategies which have been reported in the literature are compared, with a conventional strategy serving as a reference case. Both the environmental impacts and the overall process productivity are considered, in recognition of the importance of both criteria in determining the sustainability of a manufacturing line.

2. Methods

2.1. Goal and scope

The goal of this LCA study is to analyse the environmental performance of an alternative CIP method, based on intermittent application of cleanser (termed 'pulsed flow' by Yang et al., 2019b), for the spray dryer employed in an egg yolk powder processing plant. The analysis is performed for different production levels and compared with a conventional continuous-flow-based CIP process. The study illustrates how an operator presented with a new technology or strategy might engage in a comprehensive assessment of the change. There are also lessons for those developing 'green cleaning' technologies for food processing applications.

The egg yolk powder manufacturing process was analysed from gate to gate of a plant in Indiana, US, with the process flows shown in Fig. 1. The upstream stages including feed production, hen farming, egg harvesting and transportation were not considered. Similarly, impacts associated with packaging, considered in dairy studies such as (Finnegan et al., 2017), were not considered. After inspection, the shell egg is washed and broken, after which the egg yolk is separated and homogenised. The liquid egg yolk is stored refrigerated before pasteurisation using heat exchangers which are cleaned by the first CIP process (CIP1). The pasteurised liquid egg yolk is then spray-dried to generate powder and some adheres to the walls. Whereas deposition (also called make-up) on the wall of spray driers has been studied (*e.g.* Langrish et al., 2007), fouling in egg yolk powder production has not (to the authors' knowledge). A second CIP operation is used to clean the dryer (CIP2). The wastewater streams from the two CIP processes are collected for treatment before discharge. The functional unit (FU) of this study was defined as 1 kg egg yolk powder product. It should be noted that the egg yolk powder process discussed here differs from many dairy powder production processes in that there is no evaporator upstream of the drier.

2.2. Life cycle inventory (LCI)

The inputs and outputs for producing 1 kg egg yolk powder are summarised in Table 1. Unless specified otherwise, all the background inventory data (*e.g.* energy carriers, chemicals, *etc.*) were taken from the ecoinvent database v3.0 published by Wernet et al. (2016). The LCI data on shell egg, the raw material of egg yolk powder, including associated resources and emissions, was obtained from Pelletier et al. (2013). The data on water and energy consumption for the breaking and pasteurisation operations, as well as the use of coolants for liquid egg yolk refrigeration, was also taken from this source. A series of plate heat exchangers with a holding tube of length 7.6 m was used for pasteurisation (Gut et al., 2005).

The base case featured a 5 m diameter spray drier operating on a 10.3 h production cycle, including 33 min downtime for an automated CIP cycle to clean the pasteurisation unit, primarily to prevent microbiological growth. The same CIP operation, CIP1, was used in both scenarios (continuous- and pulsed-flow cleaning of the dryer) and featured three steps: pre-rinsing to flush out

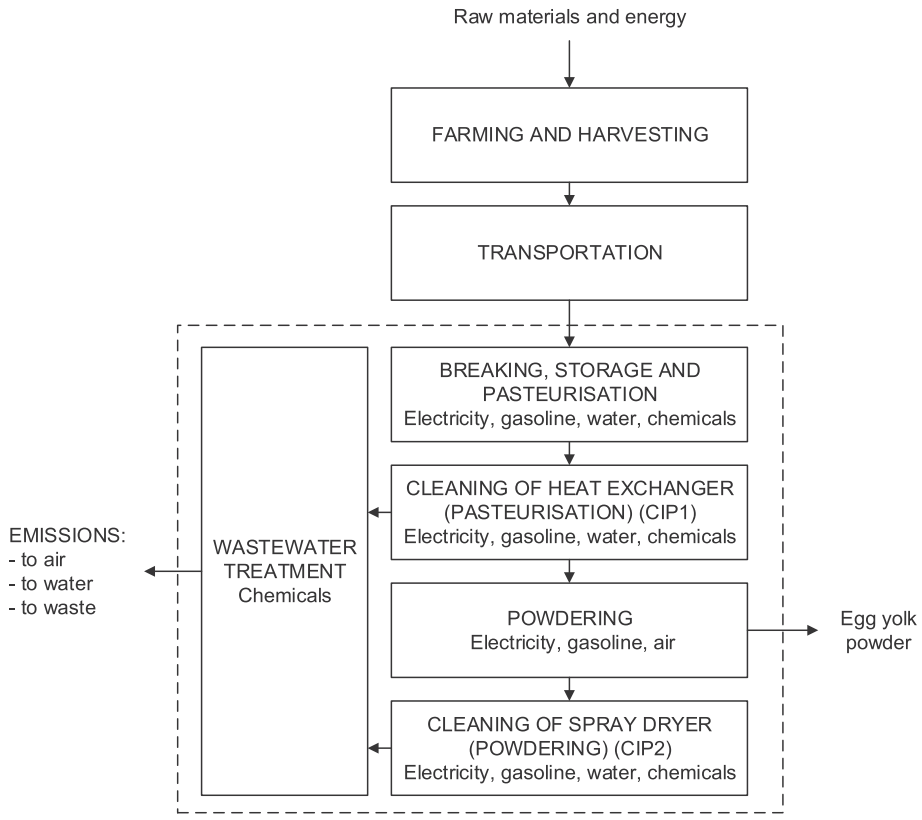


Fig. 1. Process flow diagram of egg yolk powder manufacture. Dashed box refers to the system boundary.

residual egg yolk, once-through application of NaOH (aq) to remove any egg yolk fouling deposits, followed by a second rise to remove residual caustic. Each rinsing step lasted 10 min. The caustic cleaning time was estimated based on the flow channel cleaning experiments of Helbig et al. (2019), where the effects of NaOH concentration and temperature on cleaning rate of egg yolk fouling deposits were investigated.

For the spray drying process, the energy use and conversion ratio from liquid egg yolk to egg yolk powder were calculated based on industrial data. As with the pasteurisation process, the spray dryer cleaning operation, CIP2, was performed after 8 h of powder production. CIP2 consisted of three steps similar to CIP1: (*i*) 1.5-min pre-rinse with water, (*ii*) cleaning with NaOH (aq), and (*iii*) 1.5-min rinse, with all liquids delivered by a rotary spray head. The duration of step (*ii*) was based on the pilot-scale studies of Yang et al. (2019b). Those showed complete cleaning of uncooked egg yolk layers over the time of their experiments, and partial cleaning of cooked egg yolk layers. The latter data were considered to be more representative of the spray drying operation because the dryer walls are hot (the air enters at 180 °C) and promote the formation of fouling deposits. The data were extrapolated to give estimates of the required cleaning times. Two different flow patterns were considered: continuous (C) and pulsed (P), with different concentrations of NaOH, C_{NaOH}, at different temperatures, *T*. The pulsed-flow operation employed holding and application periods, each of 1 min length, as shown in Fig. 2.

The wastewater collected from both CIP processes was treated using a conventional chemical coagulation method (*i.e.* adding ferric chloride and anionic polymer) to remove more than 80% of COD, BOD, total suspended solid, phosphorus, organic nitrogen and oil, and neutralised using nitric acid before discharge (Nasr et al., 2012). The solid waste from coagulation was collected and sent for incineration.

2.3. Impact assessment

The midpoint environmental impacts caused by the egg yolk powder manufacturing were modelled using the ReCiPe 2016 Midpoint (E) v1.02 method. Eight indicators including global warming (GW, kg CO_2 eq), ionization radiation (IR, kBq Co_{60} eq), terrestrial ecotoxicity (TE, kg 1,4-DCB), marine ecotoxicity (ME, kg 1,4-DCB), human carcinogenic toxicity (HCT, kg 1,4-DCB), human non-carcinogenic toxicity (HNCT, kg 1,4-DCB), fossil resource scarcity (FRS, kg oil eq) and water consumption (WC, m^3) are reported in this study because they have been indicated by previous LCA studies as the most important environmental impacts associated with food manufacturing processes (*e.g.* dairy) in which CIP operations were considered (Gésan-Guiziou et al., 2019; Vasilaki et al., 2016; Zouaghi et al., 2019). The calculations were performed using the commercial LCA software, SimaPro v8.0.

2.4. Sensitivity analysis

CIP is generally operated at elevated water temperatures (up to 55 °C in this study) to improve the rate of cleaning, making it an energy-intensive process. The impact of alternative energy sources on the environmental performance of cleaning was therefore investigated, with the pulsed-flow CIP2 operation (described in Section 2.2) using natural gas for heating as the baseline scenario (Scenario 1P, as shown in Table 1). The other scenarios considered were:

(i) replacing natural gas by electricity for heating cleaning solutions (Scenario 2) and
(ii) using solar energy for heating and pumping (Scenario 3).

Table 1
Life cycle inventory (per functional unit) of egg yolk powder production.

Item	Unit	Breaking, storage and pasteurisation (BSP)	CIP1 (pasteurizing heat exchanger)	Drying	CIP2 (Spray dryer)	CIP2 (Spray dryer)
					Continuous flow	Pulse flow
Input						
Transported eggs	kg	8.11				
Water	m^3	2.44×10^{-2}	5.69×10^{-4}		2.39×10^{-3}	1.03×10^{-3}
Electricity	kWh	0.782	1.73×10^{-4}	3.84×10^{-4}	3.32×10^{-4}	1.43×10^{-4}
Natural gas	kWh	0.487	2.05×10^{-2}	2.31	8.58×10^{-2}	3.69×10^{-2}
Diesel	kWh	2.05×10^{-3}				
Gasoline	kWh	4.51×10^{-6}				
Glycol	kg	4.38×10^{-3}				
Anhydrous ammonia	kg	0.105				
R-22	kg	7.90×10^{-2}				
NaOH	kg		5.51×10^{-4}		1.10×10^{-2}	4.70×10^{-3}
HNO_3	kg		8.68×10^{-4}		1.73×10^{-2}	7.46×10^{-3}
$FeCl_3$	kg		5.53×10^{-3}		5.52×10^{-3}	2.38×10^{-3}
Anionic polymer	kg		2.39×10^{-5}		2.39×10^{-5}	1.03×10^{-5}
Incinerated waste	kg		4.12×10^{-3}		4.12×10^{-3}	1.78×10^{-3}
Pasteurised liquid egg yolk	kg			2.18		
Output						
Pasteurised liquid egg white	kg	4.43				
Pasteurised liquid egg yolk	kg	2.18				
Discarded eggs	kg	0.57				
Egg shells	kg	0.90				
Egg yolk powder	kg			1.0		
Emissions to water						
COD	Kg	4.15×10^{-4}			1.73×10^{-3}	1.73×10^{-3}
BOD	Kg	2.11×10^{-4}			8.81×10^{-4}	8.81×10^{-4}
Phosphorus	Kg	2.28×10^{-6}			9.53×10^{-6}	9.53×10^{-6}
Organic nitrogen	Kg	1.42×10^{-5}			5.59×10^{-5}	5.59×10^{-5}
Oil and grease	Kg	1.13×10^{-6}			4.76×10^{-6}	4.76×10^{-6}
Emissions to air						
Waste heat	kWh			0.68		
Evaporated water	Kg			1.19		

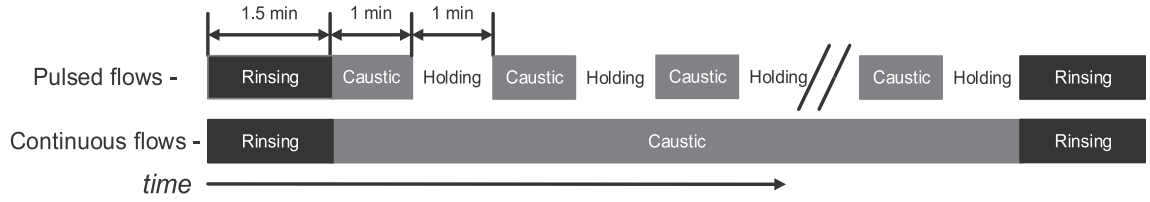


Fig. 2. Schematic of schedules in CIP2 (adapted from Yang et al., 2019b).

Furthermore, since the CIP processes investigated here require significant amounts of water (and generate similar amounts of wastewater), the feasibility of using a hybrid technique, an ultrafiltration forward osmosis membrane reactor (UFO-MBR) (Holloway et al., 2016), was assessed for recycling and reusing the spent cleaning solution from CIP2 (Scenario 4). The UFO-MBR system consisted of a membrane bioreactor, forward and reverse osmosis membranes, and membrane ultrafiltration. The lifetime of the membranes was assumed to be 5 years, and the resource inputs for membrane manufacturing were also included (sourced from (Tarnacki et al., 2012)). The life cycle inventories for Scenarios 2, 3 and 4 are provided in the Supporting Information (Table S1).

3. Results and discussion

3.1. Inventory analysis

Table 1 summarises the gate-to-gate LCI result for production of 1 kg egg yolk powder. The main inputs were egg, water, electricity and natural gas. The conversion ratio (8.11 kg egg for 1 kg powder) was similar to that reported by Berggren (2013), of 9.21. The difference can be attributed to the difference in moisture content of the products. Other inputs were similar, with both consuming approximately 0.011 kg NaOH, while heating here required 2.90 kWh generated by natural gas *cf*. Berggren's value of 2.51 kWh from 0.219 kg fuel oil. The total water (0.0274 m^3) and electricity (0.783 kWh) consumption were higher than Berggren's values, at 0.0156 m^3 and 0.61 kWh, respectively. This was attributed to the water used to wash and clean the fresh eggs and the egg breaking and separating machinery, as well as the energy used for refrigerated storage of the liquid egg yolk. The breaking, storage and pasteurisation (BSP) stage accounted for the bulk of the water consumed (0.0244 m^3, 89.2%).

The hotspots for energy use were the spray dryer (with 2.31 kWh of electricity and natural gas, 62.7% of the total consumption) followed by pasteurisation (1.27 kWh, 34.4%). This reflects the difference in heating duties, with drying requiring hot air at 180 °C to heat the droplets and evaporate water while

pasteurisation simply raised the temperature of the liquid egg yolk to 67 °C.

While the total amount of water consumed for the CIP processes (*i.e.* CIP 1 and CIP 2) of egg yolk powder manufacture (2.96×10^{-3} m^3) was comparable to that used for producing 1 kg yogurt (2.45×10^{-3} m^3, Vasilaki et al., 2016), the cleaning of egg yolk deposits required significantly greater NaOH use (0.012 kg) than yogurt deposits (4.2×10^{-3} kg). This is related to the higher egg yolk protein and fat contents, as well as the high temperature encountered in the dryer. The water and NaOH consumptions for egg yolk powder production were also noticeably higher than those reported for hot filling of juices into aseptic packaging (1.76×10^{-4} m^3 water and 9.37×10^{-6} kg NaOH per kg juice) by Manfredi and Vignali (2015).

3.2. Impact assessment

3.2.1. Environmental profile, continuous-flow CIP2

The individual contributions for the two dryer cleaning strategies are given in Table 1. Fig. 3 shows the relative contribution of each stage to each set of environmental impacts. Egg BSP dominated all impacts with the exception of TE and FRS. The high GW, ME, HCT and HNCT for this stage arose from the electricity consumption for refrigeration, at 0.782 kWh (Table 1). In the US, electricity is mainly generated by fossil fuel combustion (coal, natural gas, petroleum) (USEIA, 2012), which causes emissions of a variety of pollutants associated with human and ecological toxicity, including NO_x, SO_2, Hg, *etc* (Kim and Dale, 2005). Drying dominated FRS (at 60%), as noted above, and was responsible for about a third of GW.

CIP 2 was responsible for the majority of the environmental impacts associated with cleaning. BSP (73.8%) and drying (20.4%) consumed more water than cleaning, which is due to the inefficiency of fresh egg washing, and electricity generation and fossil fuel extraction having high water demands (approximately 0.263 m^3 and 0.0523 m^3 per 1 kWh of natural gas and electricity, respectively) (Wernet et al., 2016).

The impact of cleaning was largest for TE, which is associated with metal ions. Natural gas contains several heavy metals that are emitted to air and water during burning for energy generation. The high TE for cleaning, especially CIP2 (42.2% cf, BSP, 41.7%, and drying, 6.82%) is due to (*i*) natural gas burning for water heating, (*ii*) coagulation of $FeCl_3$ used for wastewater treatment, and (*iii*) the use of nitric acid for adjusting the pH of the cleaning water.

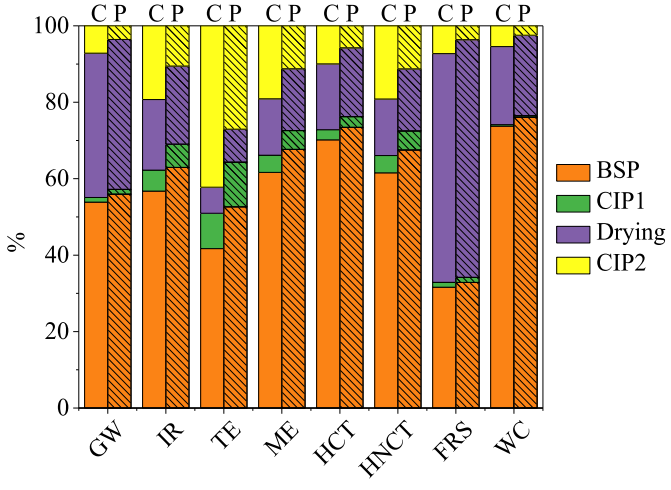


Fig. 3. Environmental impact profiles of egg yolk powder manufacture with different methods for spray dryer cleaning; solid – continuous flow; hatched – pulsed flow. Impacts: GW – global warming; IR – ionizing radiation; TE – terrestrial ecotoxicity; ME – marine ecotoxicity; HCT – human carcinogenic toxicity; HNCT – human carcinogenic non-toxicity; FRS – fossil resource scarcity; WC – water consumption.

The absolute values of the different impacts are given in Table 2. While the total GW and FRS of the operation with continuous-flow CIP2 were approximately 30% higher than Berggren (2013), the other impacts were one (HCT, WC) to four (ME) orders of magnitude larger. The differences in TE, ME, HCT and WC were mainly because egg washing and refrigeration storage included within the system boundary of this study, and these stages were the hotspots for electricity and water.

These results can be compared with the LCA study of Krokida et al. (2016) on skimmed milk powder production, which is one of the most energy-intensive processes in the dairy sector. The total GW obtained here (for continuous-flow CIP2, 1.71 kg CO_2 eq) was similar to their value for operation without concentration via reverse osmosis (1.42 kg CO_2 eq). The WC for egg yolk powder was, however, 50% lower, at 0.627 m^3 *cf.* 1.19 m^3. This can be attributed to the greater complexity of skimmed milk powder, including steps for separation, standardisation, pasteurisation, evaporation, spray drying, fluidised bed drying and air clean-up by cyclones, resulting in more cleaning being required.

Although it is known that the results of LCA on food products could intrinsically be subject to large uncertainties in both the inventory and impact assessment (characterization factor) levels, these uncertainties are mainly associated with the farming stage (*e.g.* crop cultivation, animal raising) and arise from regional variability of species, climate and soil conditions, and farming practices (Chapa et al., 2019; Pfister and Scherer, 2015). In contrast, all the unit processes (pasteurisation, drying, cleaning, *etc.*) included in the system boundary of this gate-to-gate study are relatively standardised and can be well-controlled. The environmental impacts reported here are expected to feature lower levels of uncertainty.

Several factors in the calculation could also result in uncertainty. Taking the cleaning time for removing cooked egg yolk layers as an example, Yang et al. (2019b) only reported one data point for each condition, and some points were estimated by extrapolation. Moreover, the geometry of spray dryer was considered as a normal tank for calculation, which could also cause some uncertainty. However, compared to other sources, these uncertainties were not considered significant.

3.2.2. Pulsed-flow CIP

Fig. 3 indicates that efforts to reduce the environmental impact of cleaning should focus on the dryer (CIP2). Yang et al. (2019b) demonstrated that applying the cleanser intermittently improved the efficiency of jet cleaning of walls soiled by egg yolk in terms of water usage. Cleaning by intermittent application improved the overall rate of cleaning compared to continuous application when the egg yolk had been cooked. This scenario is more representative of the deposit generated in a spray drier. The delay between each application of cleanser provides extra time for NaOH to diffuse into the soil and promote its dissolution, so that more fouling deposit can be removed per unit volume of cleanser per unit of NaOH contact time (Kjellberg, 2016). How this affects the overall environmental performance of egg yolk powder manufacturing is assessed by comparing pulsed-flow cleaning of the dryer (CIP2) with Scenario 1C (*i.e.* continuous-flow CIP2). Table 2 (and Fig. 3) shows that pulsed flow of cleanser reduced the environmental impacts of this stage in all categories by about 50%, with the greatest effect on the total impact for TE. The reduction stems mainly from the pulsed-flow CIP process having a shorter caustic contact time (15 min compared to 34.8 min for continuous-flow) and subsequently consuming less energy, electricity, water and alkaline solution.

Table 2
Environmental impacts of different stages in egg yolk powder manufacturing.

Stage	GW	IR	TE	ME	HCT	HNCT	FRS	WC
	(kg CO_2 eq)	(kBq Co_{60} eq)	(kg 1,4-DCB)	(kg 1,4-DCB)	(kg 1,4-DCB)	(kg 1,4-DCB)	(kg oil eq)	(m^3)
BSP	0.92	3.78×10^{-2}	0.38	82.4	1.04	67.8	0.13	0.437
CIP1	2.04×10^{-2}	3.66×10^{-3}	8.61×10^{-2}	6.0	3.97×10^{-2}	5.0	5.19×10^{-3}	2.25×10^{-3}
Drying	0.644	1.23×10^{-2}	6.34×10^{-2}	19.7	0.256	16.3	0.246	0.121
CIP2 continuous/pulsed	0.122/0.058	12.8×10^{-3}/6.3×10^{-3}	0.39/0.20	25.5/13.7	0.148/0.082	21.1/11.3	2.98×10^{-2}/ 1.43×10^{-2}	3.2×10^{-2}/ 1.4×10^{-2}
Total continuous CIP2/pulse CIP2	1.71/1.64	6.66×10^{-2}/ 6.00×10^{-2}	0.92/0.73	134/122	1.48/1.42	110/100	0.411/0.395	0.592/0.574
% change in total for pulsing	−3.7%	−9.8%	−21%	−8.8%	−4.4%	−8.9%	−3.8%	−3.0%

3.2.2.1. Optimising pulsed-CIP2. Cleaning solution temperature and alkali concentration are key parameters determining the cleaning efficiency of a CIP process (Tamime, 2009). The effects of temperature ($25\ °C \leq T \leq 55\ °C$) and NaOH concentration ($0 \leq C_{NaOH} \leq 1.5\ kg/m^3$) were investigated experimentally by Yang et al. [35]. The impact on GW, TE, ME and WC for pulsed-flow CIP2 were investigated to determine how these parameters could be manipulated to reduce the environmental burden. The results are presented in Fig. 4, normalised to Scenario 1P ($C_{NaOH} = 5\ kg/m^3$, $T = 55\ °C$) as the reference case.

All four impacts exhibited similar patterns, with the values being more sensitive to NaOH concentration than temperature over the range of {T, C_{NaOH}} considered. Decreasing C_{NaOH} and increasing T reduced all four impacts, from 7% for GW (Fig. 4*a*) to 50% for TE (Fig. 4*b*): the increase in cleaning efficiency (Xin et al., 2002) obtained at higher temperatures more than offset the impact of increased energy consumption for heating the solutions. The effect of higher alkali concentration is not simple. Although alkaline conditions favour cleaning of proteinaceous deposits, high pH can alter the structure of the deposits and retard deposit removal (Bird and Fryer, 1992). Hence, operating CIP2 at a low alkali concentration (~2 kg/m^3 NaOH) and elevated temperature was more efficient (Helbig et al., 2019), resulting in lower energy, water and chemical consumption, and thus lower associated environmental impacts. The effect of NaOH concentration differs between protein types and requires experimental investigation to generate a reliable cleaning model (Mercadé-Prieto and Chen, 2005; Morison and Thorpe, 2002; Xin et al., 2002). It is important to note that the WC measure includes the water used for NaOH production in addition to rinsing steps, which explains how WC for cleaning with water alone in Fig. 4*d* has a lower total WC than using alkaline solution.

3.3. Effect of production and cleaning times

Periodic cleaning of food processing equipment is essential for meeting hygiene standards. However, very frequent cleaning can be costly due to the loss of production. Cleaning is often applied in practice for a longer period than required to ensure product quality and safety, which leads to excess consumption of materials and energy, as well as increasing wastewater discharge. The environmental consequences of this practice were assessed by varying the productivity of the processing line in terms of production and

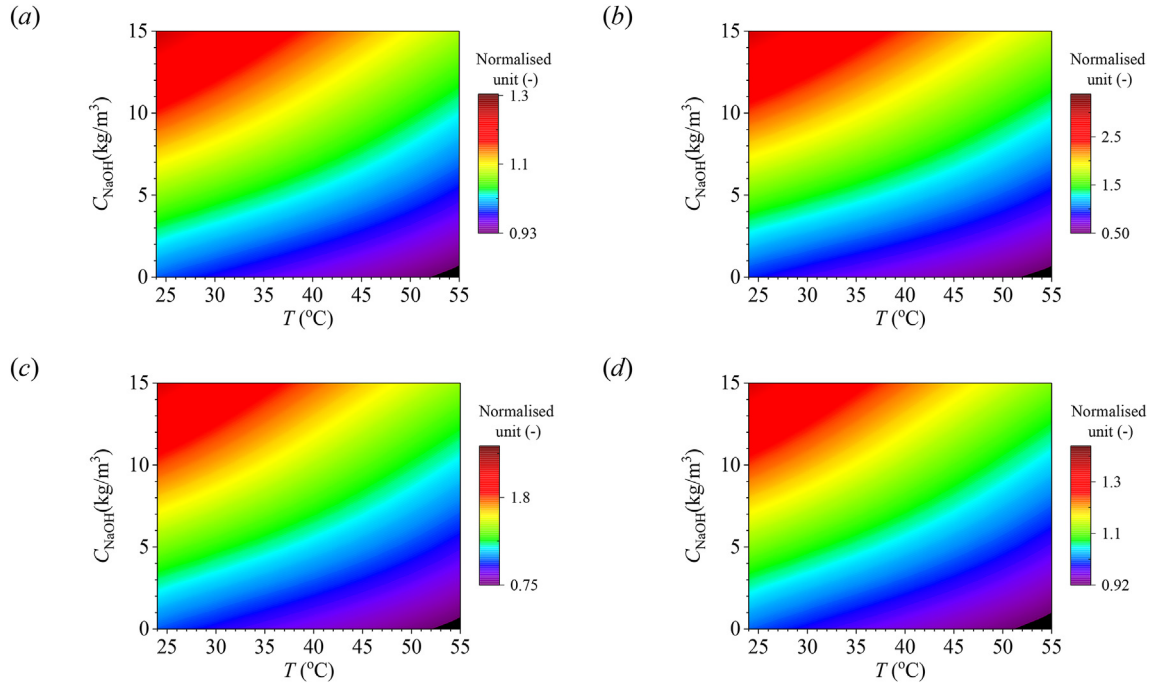


Fig. 4. Effects of NaOH concentration and temperature on normalised (*a*) GW, (*b*) TE, (*c*) ME and (*d*) WC for pulsed-flow CIP2. Values normalised by Scenario 1P ($C_{NaOH} = 5\ kg/m^3$, 55 °C).

cleaning times. The functional unit remains 1 kg egg yolk powder produced. Fig. 5 compares the environmental impacts of applying different ratios of cleaning to production time, τ. The standard operating period with pulsed-flow CIP2 (*i.e.* Scenario 1P) was 8 h, which included 33 min for cleaning (giving $\tau_{std} = 0.074$). The relative productivity, RP, is defined as

$$RP = \frac{(\text{rate of production})}{(\text{rate of production})_{std}} = \frac{t_{production}}{\left(t_{production}\right)_{std}} \times \frac{\left(t_{production} + t_{clean}\right)_{std}}{\left(t_{production} + t_{clean}\right)}$$

$$= \frac{\left(1 + t_{clean}/t_{production}\right)_{std}}{1 + t_{clean}/t_{production}} = \frac{1.074}{1+\tau}$$

which varied from 1.03 to 0.86 over the range tested ($0.039 \leq \tau \leq 0.24$).

All four environmental impacts increased almost linearly with τ. The rates differed, as expected from the sensitivity of each impact to CIP2 discussed above (Table 2). TE was the most sensitive due to the use of natural gas and nitric acid for cleaning, indicating that it could be more effectively mitigated by reducing the cleaning time. In contrast, ME showed a modest increase and GW and WC had small changes over the range studied.

Although the results indicate that decreasing τ (*i.e.* shorter cleaning times or longer production runs) can reduce the environmental footprints and increase productivity for egg yolk powder production, smaller ratios were not considered as these introduce a risk that the heat exchanger and spray dryer might not be cleaned completely. If the cleaning time is too short, residual material may remain which can promote bacterial growth (Simões et al., 2010). Longer production times are likely to result in ageing of fouling deposits, which makes the deposit more difficult to remove (Pogiatzis et al., 2012). These phenomena introduce hard constraints on any optimisation of cleaning schedules considering productivity, sustainability and hygiene, and are considered as part of the validation of CIP operating cycles.

3.4. Design considerations

3.4.1. Production scale

The spray dryer and its peripherals are major capital items in a powder production plant and the size (diameter, D) of the dryer determines the production rate. The effect of throughput on the environmental impact per FU was investigated by considering a range of dryer sizes from one manufacturer. A 5.0-m diameter dryer was used as the reference case, with a production rate of 5360 kg of egg yolk powder per batch. Other diameters considered were 5.5 m (6430 kg/batch), 4.5 m (4300 kg/batch), and 2.5 m (1300 kg/batch). Pulsed-flow CIP2 was used for cleaning. The flow rate of the cleanser, $\dot{m}$, for the 5.0 m spray dryer was 20300 kg/h. The flow rates for the smaller units were calculated based on the wetting rate, $\dot{m}/\pi D$ (0.36 kg/m-sec) (Yang et al., 2019b).

Fig. 6 summarises the environmental impacts of spray dryers with different diameters. The values for the 4.5-m and 5-m systems were similar, while that of the smaller system was noticeably higher in IR, TE, HCT and HNCT. The largest diameter gave the most favourable impacts because its higher productivity more than compensated for the extra energy and cleaning water consumed in the operating and cleaning cycles. It should be noted that the FRS value increased with D up to 5 m, but was significantly lower for $D = 5.5$ m. The change in trend is the result of non-linear trends in the industrial data: the amounts of powder produced and natural gas input did not increase linearly with D. The size of the dryer is normally determined on financial grounds: these results indicate that larger dryers are not environmentally unfriendly in terms of the metrics considered here.

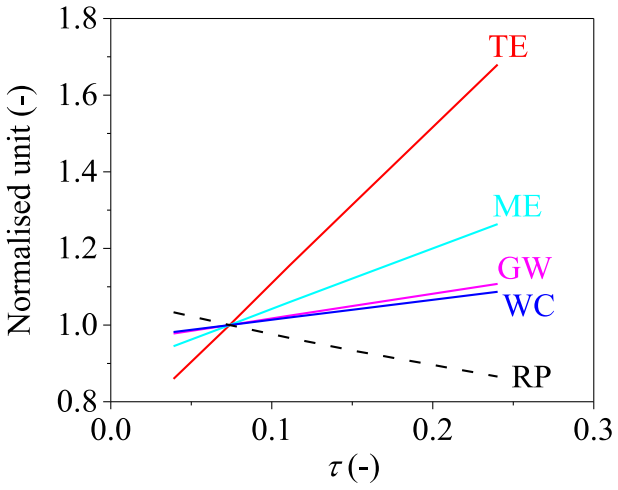


Fig. 5. Effect of cleaning time on normalised environmental impacts and productivity.

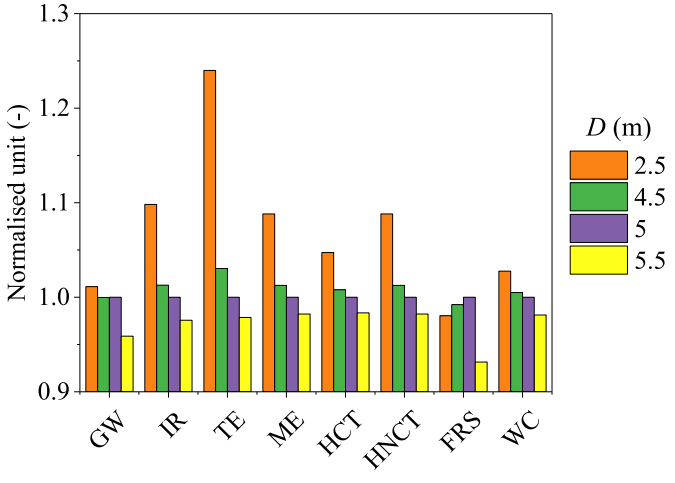


Fig. 6. Effect of production scale on total environmental impacts of the process. Data normalised against results for 5-m diameter spray dryer.

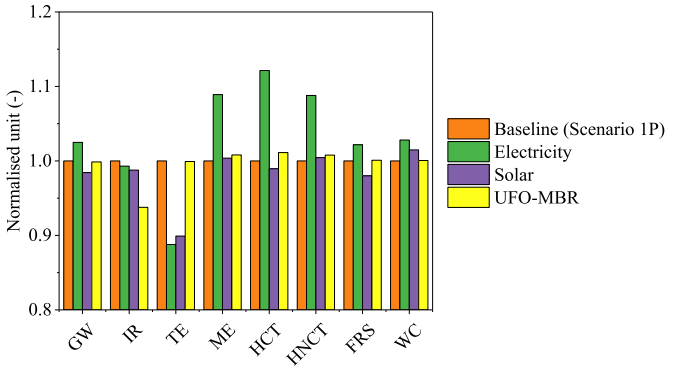


Fig. 7. Effects of alternative processing scenarios on the environmental impacts of egg yolk powder manufacturing.

3.4.2. Process improvements

Three alternative operating scenarios offering potential benefits in sustainability were considered:

Scenario 2: using electricity for heating cleaning solutions,
Scenario 3: using solar energy for heating and pumping,
Scenario 4: using a UFO-MBR process for wastewater treatment

These were evaluated and compared to Scenario 1P as the baseline. The results are summarised in Fig. 7.

Table 2 shows that the CIP steps contribute most strongly to the TE impact of the process. This is reflected in the results in Fig. 7. There were only small changes in GW, IT, FRS and WC for Scenarios 2–4. Replacing natural gas for solution heating by simple electrical heating (Scenario 2) reduced TE by around 11%, but the use of electricity increased ME, HCT and HNCT as a result of increased coal burning. This result would vary if electricity was derived from alternative sources and if heat pump technologies were used, although the air inlet temperature of 180 °C is currently beyond the capability of these devices (Arpagaus et al., 2018). For example, implementation of solar energy (Scenario 3) lowered TE by approximately 10% and gave a small decrease in HCT. The latter decrease was modest (and WC increased) owing to the consumption of materials such as Si and CdTe (Peng et al., 2013) for solar panel manufacture.

Recycling and reusing wastewater using the UFO-MBR (Scenario 4) decreased the IR impact by approximately 6% but WC remained the same. This was due to the additional water consumption for producing the chemicals and membranes used in the UFO-MBR system. However, about two thirds of the total water used in the plant could be saved. This is an example of where the environmental impact of the egg yolk powder production facility is reduced locally, with significant benefit for the local ecosystem if it is located in an area of high water stress, but not globally.

The results indicate that there was no single alternative technology amongst those considered which offered significant improvement in overall environmental performance. The results are, notwithstanding, dependent on local factors such as electricity source. The LCA approach provides valuable insight into the trade-offs between local improvements in efficiency, such as pulsed cleaning, and the overall environmental importance. Inspection of Table 2 suggests that opportunities should be sought in the BSP steps.

4. Conclusions

A gate-to-gate LCA was used to quantify the environmental footprint of cleaning and other operations in an egg yolk powder production plant. The inventory analysis identified the spray drying step as a hotspot for total energy consumption, followed by pasteurisation. The midpoint impact assessment highlighted that the preparation processes, of egg BSP, made the largest contribution to all impact categories apart from FRS. Coal combustion for electricity generation resulted in large emissions of pollutants, increasing the human and ecological toxicity impacts. The egg breaking stage was the dominant water consumer, more than both CIP processes.

The benefit of using intermittent flow of cleaning liquid in the dryer CIP cycle was compared with the standard, continuous, steady flow. This intermittent wetting reduced the environmental impacts in all categories by approximately half. Impacts GW, TE, ME and WC were sensitive to the temperature and NaOH concentration of the cleaning liquid and the optimal parameters for pulsed flow cleaning were investigated. Higher temperature and low alkali concentration gave the most environment-friendly combination due to the higher cleaning rates. The sensitivity analysis indicated that over-cleaning has negative environmental as well as productivity impacts.

Three potential improvements for the egg yolk powder production process were compared. Using electrical heating to warm cleaning solutions reduced TE significantly, but the other impacts increased. Using photovoltaics and solar thermal energy decreased TE and had little effect on GW, HCT and FRS. However, membrane wastewater treatment (UFO-MBR) gave no significant improvement for most impacts.

Although the CIP stages were not the main contributors to the plant's environmental impacts, the study illustrated how LCA techniques can be used to include such factors in considering plant modifications.

CRediT authorship contribution statement

Jheng-Han Tsai: Methodology, Software, Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing, Funding acquisition. **Jen-Yi Huang:** Conceptualization, Methodology, Resources, Data curation, Writing - review & editing, Visualization, Supervision, Project administration, Funding acquisition. **D. Ian Wilson:** Conceptualization, Methodology, Writing - review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2020.123936.

Nomenclature

Roman

C_{NaOH}	Concentration of sodium hydroxide (kg/m^3)
D	Diameter of spray dryer (m)
FRS	Fossil resource scarcity (kg oil eq)
GW	Global warming (kg CO_2 eq)
HCT	Human carcinogenic toxicity (kg 1,4-DCB)
HNCT	Human non-carcinogenic toxicity (kg 1,4-DCB)
IR	Ionization radiatio (kBq Co_{60} eq)
ME	Marine ecotoxicity (kg 1,4-DCB)
RP	Relative productivity (−)
t_{clean}	Cleaning time (s)
$t_{production}$	Production time (s)
T	Temperature (°C)
TE	Terrestrial ecotoxicity (kg 1,4-DCB)
WC	Water consumption (m^3)

Greek

τ	Cleaning time ratio, $\tau = t_{clean}/t_{production}$ (−)

Acronyms

BOD	Biochemical oxygen demand
BSP	Breaking, storage and pasteurisation
C	Continuous
CIP	Cleaning-in-place
CIP1	CIP process for cleaning pasteurizing heat exchangers
CIP2	CIP process for cleaning spray dryer
COD	Chemical oxygen demand
FU	Functional unit
LCA	Life cycle assessment
LCI	Life cycle inventory
P	Pulsed (intermittent)
UFO-MBR	Ultrafiltration forward osmosis membrane reactor

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