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Electro-osmosis dewatering as an energy efficient technique for drying food materials

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Abstract

In recent times, there has been a rise in interest on the applications of electro-technology based food processing methods. With drying in food industries being an energy intensive process with huge environmental impacts, the objective of this study was to design and develop a purpose-built laboratory system, for experimentally characterising an energy efficient electro-osmosis dewatering system. Electro-osmosis is a unique dewatering technique in which, moisture in food materials are removed by the application of low electric field (5-30 V). Different food materials namely, yogurt, orange pulp and egg whites were tested using electro-osmosis at 15 V and 30 V over 15 min and 30 min, respectively. The energy consumption (kWh), carbon footprint ($kgCO_2e$) and cost indices (£/kg dried food) were also evaluated and compared with thermal drying.

Keywords: Electro-osmosis; dewatering; energy efficiency;

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1. Introduction

Electro-osmosis is the phenomenon by which liquid moves through a porous material/slurry as the effect of a constant voltage (DC) applied across the solid/liquid medium. The liquid flows towards the cathode and negatively charged particles move towards the anode [1]. The electrical double layer that is present in interface of the food slurry particles causes electro-osmosis. The solid particles in food materials have a slight electric charge compared to the water medium (zeta potential). When food materials are exposed to an electric field, the electric double layer cause motion of particles (electro-phoresis) and the liquid (electro-osmosis) [2]. Usually in electro-osmosis mechanism, water content in food slurry/sludge moves from the top electrode to bottom electrode, gradually the food slurry bed, near the top electrode decreases and the dewatering rate reduces. To tackle this problem, mechanical compression of the food slurry enables a uniform and consistent dewatering throughout the dewatering material [3] This method has proven to be an economically feasible method to remove water from any slurry/ sludge [4]. This method is ideal for dewatering of food slurries with particle size in the ultrafine range, for food materials that are heat sensitive, and that are usually not dried using thermal technologies.

A few studies have considered the removal of water from food materials using electro technologies for dewatering. Orsat et al. (1996) first proposed the use of electro-osmosis technology for dewatering food materials [2]; this study was able to establish electro-osmosis as an energy efficient alternative to thermal drying (low energy consumption values for electro-osmosis 48.0 to 716 kJ/kg on comparison with thermal drying energy consumption values of 3.5 to 5 MJ/kg) . Subsequent studies using electro-osmotic based dewatering systems were also successful in establishing this technology as an energy efficient system. Energy savings of ca. 75% was established on a study drying tomato paste on comparison with vaporisation of water (using thermal drying) [6]. A study by Ng et al. (2011) [5] found that the energy consumptions were found to be up to 60 % more economical for various food waste samples (BSG, cauliflower trimmings, orange peels and mango peels, respectively) using electro-kinetic technology (combination of electro-osmosis and mechanical pressure dewatering).

The European Union is committed to reduce 20 % greenhouse gases (GHG) by 2020, based on 2010 baseline as a commitment towards the Kyoto Protocol (European Parliament, 2012). This is primarily due to the economic challenges brought forward by climatic changes around the world. United Kingdom is the first country to employ norms and rules to curtail the excess greenhouse emission output through Carbon budgets (Department of Environmental Food & Rural Areas, 2015). In order for the UK food and beverage industry to reduce its carbon emissions, it has to prioritise sustainable developments and innovations using Food Industry Sustainable Strategy (Department for Environment Food and Rural affairs, 2006). One way to reduce carbon dioxide emissions and water wastage is to explore into the use of innovative drying technologies with high energy efficiencies, as opposed to hot-air based conventional drying methods [6]. With this vision kept in mind, the main objective of this work was to design and develop a new electro-osmotic dewatering system, experimentally verify the energy consumptions and environmental impacts. The second objective was to compare the experimental results obtained from dewatering various food materials with thermal drying technology.

2. Materials and Methods

2.1. Food materials

The food products that were used for experimentation in this study were yogurt, orange pulp and egg whites respectively. Natural bio-yogurt produced by Lancashire farm, UK were sourced from a local market. The orange pulp/juice used in the study were the pulp squeezed from oranges (*Citrus sinensis*), sourced from a local fruit market. Egg whites used for experimentation were from free-range chicken eggs sourced from a local market.

2.2. Design of Electro-osmosis dewatering system

The electro-osmosis dewatering system was developed following Orsat et al. (1996) and Ng et al. (2011) with slight modifications [2], [5]. It mainly consists of two parts: the food dewatering cell and ancillary equipment's that are required for operation. The dewatering cell, as shown in Fig. 1, consists of an acrylic cylinder (500 mm in length, 150 mm in radius), the cylinders are held together by purpose built top and bottom base plates (30 mm in thickness and 200 mm in radius).

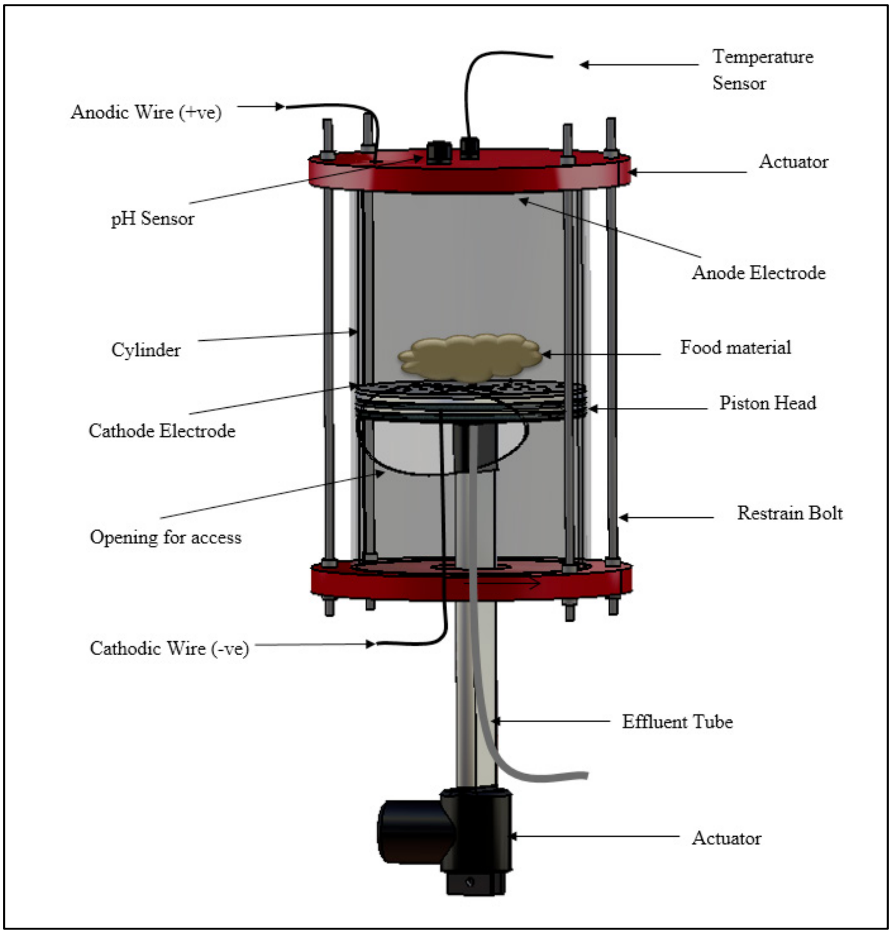


Fig. 1. Schematic representation of electro-osmosis dewatering cell

The plates have apertures of 10 mm deep (rubber gasket lined) to tightly hold the cylinder cell together. The top plate has embedded metallic plate (anode) and openings for temperature and pH probes. The bottom plate with an embedded metallic plate (cathode) was attached to a piston head-like hydraulic hoist, this could be vertically moved up and down based on the experimental requirements. The bottom top plates have openings in the centre to accommodate the mechanical hoist, electrical terminals and water outlet. The water collected from dewatering process were supplied through an effluent tube into a calibrated water collection tank. The metallic bottom plate (cathode) were perforated (openings of 10mm in diameter) to facilitate the movement of water from dewatered materials to outside the cell. There is an opening at the lower half of the cylinder to facilitate access of food materials inside and outside of the dewatering system. The ancillary equipment's consists of; an adjustable DC power source, a multi-meter, a data logger for recording multi-meter reading, pH and temperature probe recording that are all connected to a computer. A schematic representation of the whole electro-osmosis dewatering system is shown in Fig. 2.

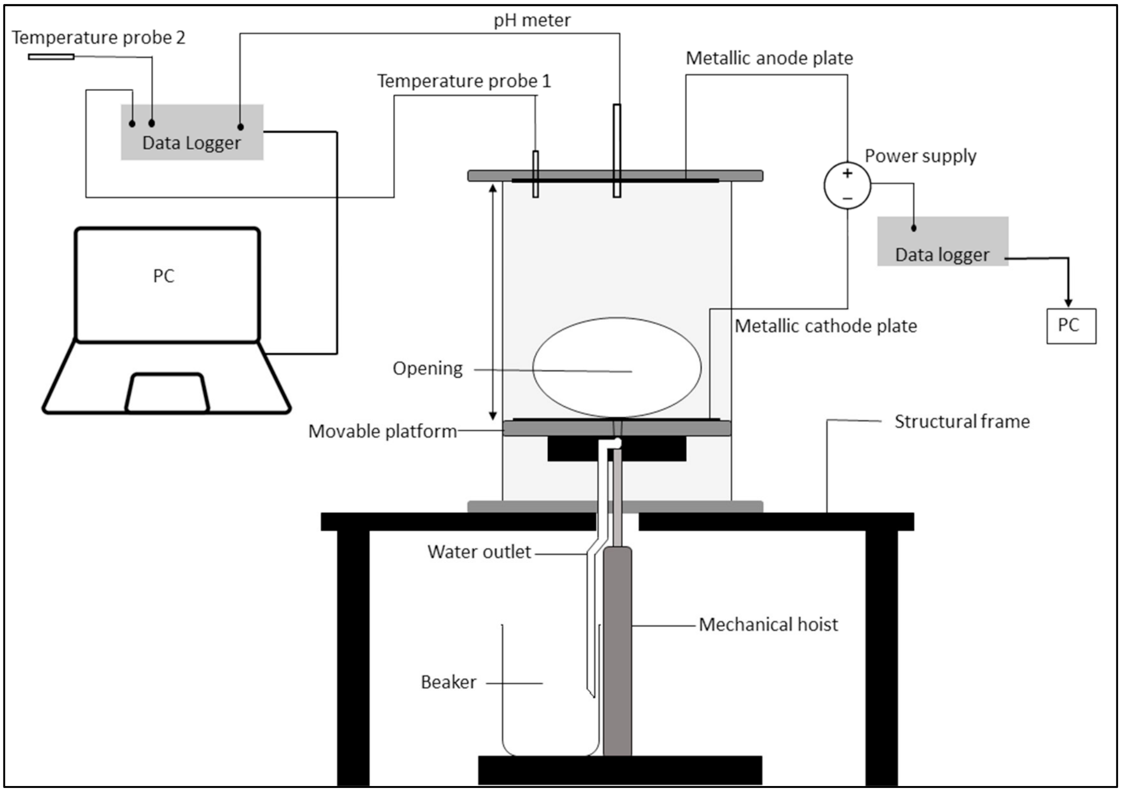


Fig. 2. Schematic representation of electro-osmosis dewatering system

2.3. Experimental Methodology

2.3.1. Electro-Osmosis

About 100 g of each food sample were used for all experiments. The samples were prepared and placed on the movable platform with a filter paper (Whatman 1PS filter paper circles 185 mm). The voltage required for electro-osmosis was set in the adjustable DC power supply at 15 V and 30 V, respectively for exposure times of 15 min and 30 min for all food samples to be dried. An RS232 port was used to link the multi-meter through a data logger to a computer to record current (I) measurements. The RMS multimeter readings were recorded in computer using DMM data logging software (version 1.1, China) at a 1 min interval rate. The movable bottom is placed in such a manner that the upper surface of the food material touches (substrates are slightly compressed) the fixed upper electrode to facilitate electro-osmosis within the food matrices.

2.3.1.1. Evaluation of pH, temperature and moisture content during electro-osmosis dewatering

The pH of the food materials was recorded using a pH electrode HI-1612D Hanna® instruments, UK. The meter was connected to a DrDAq USB data logger, Pico Technology, United Kingdom and recorded for each experimental trial. The electrode was dipped in Hanna® cleaning solution, United Kingdom after each experimental trial for the purpose of calibration and removing food particulate matter. The electrode was placed in such a manner that the electrode tip had fully immersed in the food matrix. Two thermocouple (Pico, USA) were used to measure; the external atmospheric temperature; and temperature inside the food material. Ohaus MB 25 moisture analyser (USA), were used to analyse the moisture contents of the food materials, sequentially. The samples were analysed at 160°C in auto setting until the bone-dry weights were achieved. Picolog Beta 8, (UK) software were used in the computer to measure the changes in pH and the temperatures (external and inside food matrix) from the probes as attached in Fig.1.

2.3.2. Thermal drying

The thermal drying used for experimentation was a MINO 100 convective oven, Genlab (UK). The dimensions of the dryer is 87 x 63 x 80 cm (l x b x h). The food materials were thinly spread on a Whatman 1PS filter paper circles of 150 mm in a meshed sample tray with square openings 0.2 x 0.2 cm. The drying operation was performed at 80°C to simulate industrial drying conditions. The dryer was allowed to pre-heat for 1 h prior to operation and the fan assisted (air circulation) heating option was switched off for all drying operations.

2.4. Energy consumption calculations

In the electro-osmosis system, voltage was maintained at a constant level (15 V and 30 V) and changes current measurements were measured. The electrical energy, E (kWh) was calculated using Equation (1) [5].

$$E = \int \frac{V*I}{1000} dt \tag{1}$$

Where, V is the voltage (V), I the current (A) measured and t (min) is the exposure time of food samples.
The electric energy of thermal drying was also calculated using Equation (1), with assumptions made on the maximum power consumption being 500 W (Current = 2 A, Voltage = 250 V) (Genlab, UK).

In order to calculate the electrical cost incurred in a year, we use the Equation 2.

$$Total\ cost\ incurred\ (per\ annum) = E * Unit\ rate * X \tag{2}$$

Where unit rate for electrical consumption E (kWh) is taken to be 11.676 p (£ 0.11676) considering the price is fixed (npower, 2016). X is the working hours (h) in a year (253 working days with an assumption of 8 h usage per day)

2.5. Carbon footprint evaluation

The carbon footprint is defined as a total measurement of total greenhouse gases which are methane (CH_4), carbon dioxide (CO_2), nitrous oxide (N_2O), perfluorocarbon (PFC's), sulphur hexafluoride (CF_6) and hydroflurocarbons (HFC's) (Carbon Trust, n.d). In order to calculate the organisation's carbon footprint, the conversion factor is multiplied by the energy consumed (kWh). The energy conversion factors adopted from the Department of Environment, Food and Rural Affairs (2018) [7] are shown in Table 1,

Table 1: Energy consumption factors (Department of Environment, Food and Rural Affairs, 2018)

Emission incurred per unit energy consumed (kWh)	kg CO_2 e	kg CO_2	kg CH_4	Kg N_2O
	0.28307	0.28088	0.00066	0.00153

2.6. Percentage difference in greenhouse emissions

The percentage differences in greenhouse emissions for electro osmosis and thermal drying is shown in Equation 3,

$$Percentage\ difference\ = \frac{a-b}{b} * 100 \quad (3)$$

Where ‘a’ is the greenhouse emissions calculated from electro-osmosis dewatering and ‘b’ is the greenhouse emissions of thermal drying.

3. Results and Discussion

3.1. Evaluation of electrical energy consumed

The electrical energy consumed were calculated using Equation (1), the values are represented along with results from published literatures in Table 2. The energy consumptions for electro-osmosis for all food samples were found to be in the range of 0.006 to 0.098 kWh for a period of 30 min dewatering. For electro-osmosis dewatering at 30V/15V the results were; 0.045/0.02 kWh for orange pulp, 0.098/0.026 kWh for yogurt and 0.013/0.006 kWh for egg whites, respectively. It is also interesting to note that the energy consumed by yogurt at 30 V is higher than that of orange pulp and egg whites; this is majorly because of the low electrical resistance characteristic of yogurt matrix. These values are significantly higher ($p<0.05$) from thermal drying energy consumption values (0.5 kWh). There is also a decreasing trend in values of electrical consumptions values between both 30 V and 15 V electro-osmosis dewatering for each food sample. This is because the energy consumption values are a function of voltage and current (Equation 1) and similar results were recorded by Ng et al. (2011) [5]; for example the results obtained for BSG dewatering was 0.004 kWh for 30 V and 0.001 kWh for 15 V.

Table 2: Summary of electrical energy consumptions values for present work and published literatures

Type of Dewatering	Sample	Energy consumed (kWh)	Voltage (V)	References
EO for 30 min	Orange pulp	0.045*	30	Present work
		0.02*	15	
	Yogurt	0.098*	30	
		0.026*	15	
	Egg whites	0.013*	30	
		0.006*	15	
Thermal for 30 min	Orange pulp	0.5	..	
	Yogurt		..	
	Egg whites		..	
EO for 15 min	BSG	0.004	30	[5]
		0.001	15	
	Melon	0.019	30	
		0.007	15	
	Mango	0.02	30	
		0.005	15	
	Orange	0.012	30	
		0.004	15	
	Cauliflower	0.027	30	
		0.006	15	
Thermal for 15 min	BSG	0.08	..	
	Melon	0.22	..	
	Mango	0.08	..	
	Orange	0.09	..	
	Cauliflower	0.2	..	
EO for 60 min	BSG	716-1424 (kJ/kg H20)	~30	[2]
	Vegetable waste	48.8-187.5 (kJ/kg H20)	~5-16.5	
	Apple waste	239.0-1306.9 (kJ/kg H20)	~10-30	

*Significant difference according to one-way ANOVA evaluation

Similar work by Orsat et al. (1996) [2], showed a trend of the energy consumption values ranging between 48.8-1424 kJ/kg H_2O, as the voltage inputs varied from ~5-30 V. The results obtained from the present study are within the ranges obtained by Ng et al. (2011) [5] (0.001-0.027 kWh), however the slight decrease shown in results are attributed to the exposure time of 15 min as opposed to 30 min in the present study. Energy consumptions values of tomato paste using electro-osmosis as reported by Al-Asheh et al. (2004) [6], were found to be 75% more efficient than a thermal drying method which involves vaporisation of water. In this context, the results obtained from the present study in Table 2, could achieve a minimum energy saving of ~ 80 % on comparison with thermal drying (0.098 kWh/EO 30V dewatering of yogurt and 0.5 kWh/ thermal).

3.2. Evaluation of cost of energy usage and environmental impact

Using Equation 2, the total cost of the energy used per annum were calculated and are shown in Table 3. From the results, it is quite evident that electro-osmosis is a highly economical alternative to thermal drying method. For example, the cost of using 15 V osmotic dewatering on egg whites is as low as £ 1.40. It is also shown that at 30 V operation, costs incurred are higher than that at 15 V, the variations in prices among the various food materials are due to the difference in electrical resistances shown by each food materials and the amount of current (I), passed through the food material [2].

Table 3: Annual electric cost for electro-osmosis and thermal drying

Food material	Electro-osmosis dewatering cost per annum in GBP		Thermal drying electrical cost in GBP
	30 V	15 V	
Orange pulp	£ 10.63	£ 4.72	
Yogurt	£ 23.16	£ 6.14	£ 118.16
Egg whites	£ 3.07	£ 1.40	

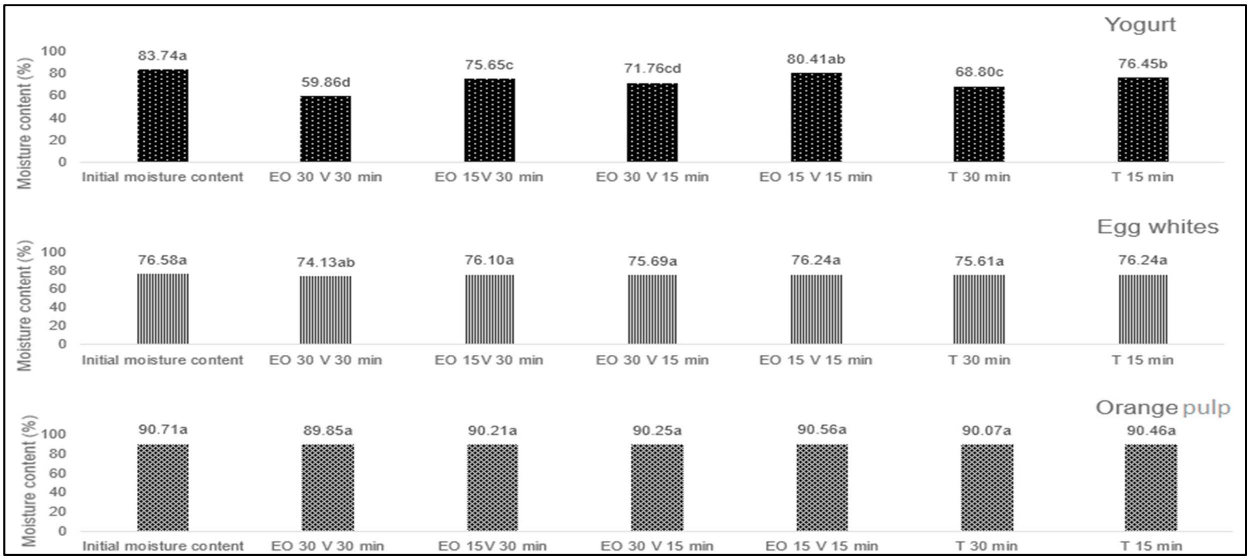
Carbon footprint were used to measure the environmental impact of electro-osmosis dewatering and thermal drying; emission conversion factor for electricity is 0.28307 (Table 1) and is multiplied by energy consumption values and the number of working days in year (253). The percentage differences in green-house gas emissions were calculated using Equation 4 and results are shown in Table 4. A minimum of 81 % less carbon emissions could achieved by using electro-osmosis, this proves that electro-osmosis has much lower environmental impact when compared to thermal drying, this has a huge impact as governmental mandate requires the green-house emissions for an enterprise to be maintained at a minimal level.

Table 4: Representation of kilograms of carbon dioxide equivalent emitted per year

Food material	Electro-osmosis dewatering – Carbon footprint		Thermal drying- Carbon footprint ($kgCO_2e$)
	30 V ($kgCO_2e$)/percentage difference (%)	15 V ($kgCO_2e$)/ percentage difference (%)	
Orange pulp	26.32/ 91	11.32/ 93	
Yogurt	56.04/ 81	14.71/ 95	286.46
Egg whites	7.35/ 97	3.39/ 99	

3.3. Effects on Moisture content and pH of food materials

Fig. 3, represents the moisture contents of food materials before and after electro-osmosis and thermal drying, respectively. The experimental data were analysed using one-way ANOVA (analysis of variance) and mean comparison using Duncan's multiple range test at 95% confidence level, using SPSS version 20 (IBM, USA). From literatures reported, a consistent decrease in moisture contents were noted with increased applied voltage for food samples [5], such a pattern is shown in the present study where moisture loss is higher at 30 V than 15 V and across exposure times of 15 min and 30 min. For example the average moisture loss in BSG samples were noted to be 7.15 % and 16.90 % for melon peel samples [5], the author justified the low electrical conductivity (0.1 s/m) of BSG samples on comparison with melon (0.4 s/m) for the differences in moisture losses. In the present study, both egg whites and orange pulp did not show any significant changes (p>0.05) in moisture contents in both electro-osmosis and thermal drying. For yogurt, the moisture content shows a significant difference (p<0.05) from the initial moisture content for all electro-osmosis trials except for 15 min at 15 V (80.41%). For electro-osmosis, the trials at 30 V shows a significant difference (p<0.05) from the trials conducted at 15 V (59.86 % / 75.76 % and 71.76 %/ 80.41 %, respectively). The free moisture availability in yogurt could have mediated a higher rate of diffusion within the food matrix to outside. It must also be taken into account that orange pulp and egg whites have more bounded (trapped within food matrix membrane) moisture when compared to yogurt. This is further justified from the results of thermal drying (for egg whites and orange pulp) where, no significant moisture losses (p>0.05) were noted from the initial moisture content and more energy (prolonged drying) would be necessary to mediate moisture diffusion. For example, work on electro-osmotic dewatering of tomato paste [6], showed a moisture loss of ~7 % after 30 min of operation and ~24% after 150 min of dewatering. This also proves that in electro-osmotic dewatering technology, the electrical conductivity of each food sample varies and might require a longer exposure time/ higher applied voltage to obtain a desired moisture content in dewatered food sample.



Mean values having a common letter within the same bar chart are not significant according to the Duncan's multiple range test at 5% level

Fig. 3. Moisture content of food samples for various dewatering methods

Fig. 4, presents comparsion between the pH values of various food materials for electro-osmotic dewatering of 30 V and 15V, respectively. Initialy looking at yogurt sample, it can be seen that for 30 V, the pH values recorded were higher than those at 15 V. It could be due to the electrolysis of moisture from the yogurt matrix due to the higher potential energy supplied for dewatering. Between 20-30 V, the living organisms namely; *Lactobacillus bulgaricus* and *Streptococcus thermophilus* are killed and could contribute to increasing the alkalinity of the food matrix [8]. It is interesting to note that the pH of orange pulp reduces after a slight increase, unlike other food products. This could be due to the moisture containing citric acid (acidic) is removed from within the pulp residues to outside. For egg whites especially at 30 V the pH increased subtaintially from 6 to 8, over the period of dewatering. This could be due to the protein and albumen contents in egg whites getting denatured due to higher potential difference (30V). Denaturation of proteins involves breakage of hydrogen bonds which directly contributes to the increase in pH values; increasing the alkalinity within the food matrix. For applications in food industries, the regulatory bodies such as departments of health are very particular about the pH of food materials. Due to the logarithmic nature of measurements, small changes in pH are significant, variations in pH can impact the flavour, consistency and shelf life. Dewatering at 15 V has shown not to affect the pH across all food materials after the drying process.

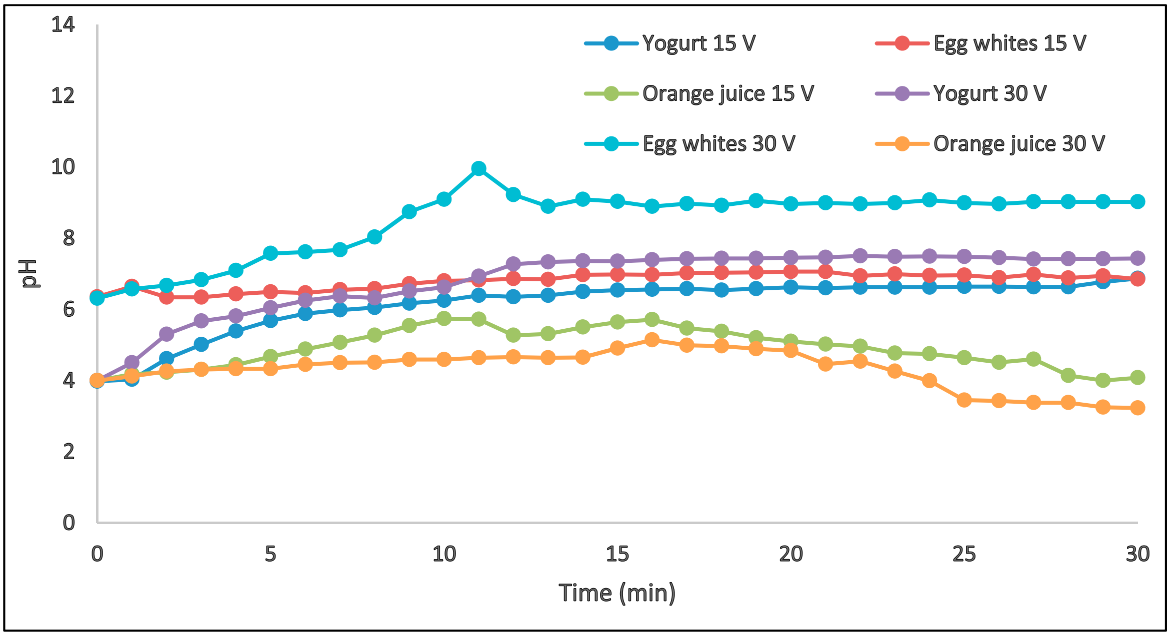


Fig. 4: Variation in pH of food materials during electro-osmotic dewatering

4. Conclusion

This study successfully designed and developed a purpose built electro-osmosis dewatering system. The system was used to characterise electro-osmosis dewatering at constant voltages of 15 V and 30 V, respectively. It was found that the magnitude of moisture removed from food samples increased from 15 V to 30 V. From the various food samples (yogurt, orange pulp and egg whites) analysed, the performance of dewatering varied due the electrical conductivity and free moisture availability of food material. The correlation between conductivity and current indicated that yogurt with a higher electric conductivity, encouraged a higher electro-osmotic flow within the food matrix to outside. Through experimental characterisation, the study was successfully able to establish that electro-osmosis is more energy efficient and economical to operate than thermal drying method. A minimum of 80 % reductions in carbon emissions could be achieved by implementing this technology over thermal drying. Electro-osmosis has a huge potential for application in food industries as an effective dewatering/pre-treatment method for food products.

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