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RESEARCH ARTICLE

COMPREHENSIVE EVALUATION OF AERATED SOAKING FOR PADDY PARBOILING IN AN ECO-FRIENDLY MANNER

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ABSTRACT

Aerated soaking of paddy is a simple novel technique to utilize water effectively. Therefore, automated water circulation was maintained in the aerated soaking systems using a motor and timer. The timer was set with 70 minutes on-time and 20 minutes off-time. Hence, aerated soaking systems with operating cycles of 70 minutes on-time and 20 minutes off-time were developed based on dissolved oxygen profile in soaking water. The quality parameters of soaking water and rice were analyzed and compared with the conventional soaking process. In addition, moisture absorption pattern was also studied in aerated soaking systems and compared with the conventional soaking system. Results revealed that the aerated soaking of paddy improved hydration rate and reduced soaking time with a considerable reduction in effluent quality in terms of BOD. The moisture contents of conventional soaking, submerged aerated soaking and exposed aerated soaking were 27.84±0.01%, 30.41±0.01% and 31.48±0.01% respectively after 24 hours of soaking. The BOD values of conventional soaking, submerged aerated soaking and exposed aerated soaking were 1575 mg/l, 600 mg/l and 472 mg/l respectively after the end of soaking. The higher DO resulted in the germination of paddy grain which in turn reduced the head rice yield. The values of pH, total dissolved solids, total solids and electrical conductivity of conventional soaking were highly different compared to submerged and exposed aerated soaking systems. The values of head rice percentage (HR-79.15±1.15%) and broken rice percentage (BR-20.84±1.15%) of conventional soaking were almost similar to submerged aerated soaking (HR-79.51±1.62% and BR-20.49±1.63%), but remarkably different from exposed aerated soaking (HR-60.74±2.00% and BR-39.25±1.99%). The use of a submerged aerated system yielded a positive outcome related to hydration rate, reduction in terms of BOD (975 mg/l) value with reasonable milling yield profile in terms of head rice percentage. Hence, the system of submerged aerated soaking can be considered as a viable initiative for an eco-friendly parboiling process.

Keywords: Aeration, Cold-water, Evaluation, Paddy parboiling, Submerged aerated soaking.

INTRODUCTION

Rice (*Oryza sativa*) is one of the world's three most important edible starchy cereal crops. It plays a vital role in meeting global food demands. Approximately, half of the world's population consumes rice as a primary source of nutrition and it contributes 20% of the calories (Kubo and Purevdorj 2004). Consumption of rice increases with population growth. A substantial increase in the population is expected in the 21st century (Kubo and Purevdorj 2004). Moreover, rice is the staple food grain in Sri Lanka with an annual per capita intake of 108.6 kg (Kumari *et al.* 2014a). Rough rice is processed in two forms, raw rice and parboiled rice. Parboiled rice is a hydrothermally treated rice to tune physiochemical properties for better consumption (Itoh *et al.* 1985). However, parboiled rice accounts for around 55% of total rice consumption in Sri Lanka (Kumari *et al.* 2014a) and it contributes to nearly 50% of the energy and 40% of the protein in the daily diet of people in Sri Lanka (Sartaj and Suraweera 2005).

The method of parboiling consists of three stages such as soaking, steaming and drying (Igathinathane *et al.* 2005; Kannan *et al.* 2012; Kumari *et al.* 2014b). The main aim of soaking is to facilitate quick gelatinization of

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the paddy grains and to reduce energy consumption during steaming. The grain moisture content should be increased to at least 30% (wb) to have the perfect steaming process of parboiling (Kannan 2015; Kumari *et al.* 2014a; Wimberly 1983). For different grains, there are three soaking methods in use; cold soaking, hot soaking and vacuum soaking (Kumari *et al.* 2014a). The rate of moisture absorption is largely determined by the moisture gradient, environmental conditions and grain properties (Thakur and Gupta 2006).

The most common practice is soaking paddy in stagnant cold water for 36 - 72 hours at room temperature. Because of the long duration of the cold soaking method, the microorganisms consume all of the dissolved oxygen in the soaking water and fermentation of starch, resulting in anaerobic conditions (Kumari *et al.* 2014a). This results in an odor in both the soaking water and the soaked paddy. To avoid these issues, it is a common practice to change the soaking water at regular interval 10 - 12 hours (Rathnayake *et al.* 2010). For the manufacturing of parboiled rice, the soaking process uses a large volume of water and it is around 1.3 times the weight of paddy (Kannan 2015; Wimberly 1983). The volume of wastewater generated from the parboiling site is 0.4 to 0.52 l/kg of paddy processed. Wastewater contains a high concentration of organic and inorganic substances causing significant polluting effects (Sayanthan and Thusyanthy, 2018). In Sri Lanka, small and semi-modern mills are with higher production costs and limited milling output, resulting in low profitability. As a result, such millers commonly release wastewater into the environment without any treatment (Kumari *et al.* 2014a). The continual discharge of effluent into the environment causes several environmental problems (Thushyanthy *et al.* 2016). Moreover, effluent should be treated to come into the permissible level before disposal. Discharging effluent indiscriminately into the environment can make soil pollution, water pollution and air pollution by releasing noxious gases (Senanayake *et al.* 2001).

Hence, there is a need to modify the commonly used soaking process to solve such environmental consequences. Therefore, a simple aerated soaking system is considered to be helpful to reduce the microbial population, increase the water usage efficiency, reduce the oxygen demand, reduce effluent quantity and strength in terms of Biological Oxygen Demand (BOD) and increase the milling yield (head rice percentage) in an eco-friendly manner. It further created a piece of new knowledge about Dissolved Oxygen (DO) dynamics in soaking water during the simple aeration cycle of the aerated soaking system. As there are limited research works carried out on aerated soaking of paddy, this novel strategy and its investigations are helpful to propose eco-friendly soaking systems for paddy parboiling. Hence, this study was set to investigate the effect of submerged and exposed aerated soaking systems on effluent quality, paddy hydration and milling yield with an intention of proposing an eco-friendly strategy for the paddy parboiling process.

MATERIALS AND METHODS

The experiment was conducted at the Department of Agricultural Engineering, Faculty of Agriculture, University of Jaffna, Kilinochchi.

Long paddy grain variety Bg 251 was selected for this study. Newly harvested dried paddy (moisture content - 13.4% wb) was obtained from Paddy Research Institute, Paranthan, Kilinochchi. Impurities and foreign materials were removed from the paddy sample before the experiment.

Simple aerated soaking system and its design

Three PVC pipes of 1.5 m height and 100 mm diameter were used as the testing soaking tanks to represent conventional soaking (CS), exposed aerated soaking (EAS) and submerged aerated soaking (SAS) as shown in Fig. 1. A water pressure pump (ARPICO 90W 230V/50Hz) was used to circulate the water through the PVC column. A 25 mm PVC pipe was used to circulate the water in the aeration unit. The pump was fixed with the SAS column and EAS column. A showerhead with fine holes of a diameter less than 1 mm was used to sprinkle water. The showerhead was kept 0.35 m above the top of the paddy soaking PVC pipes of EAS and SAS systems. A similar PVC column was made for traditional cold water soaking. Furthermore, in the SAS column, paddy was always submerged in water.

However, in the EAS column, paddy grains were exposed to the environment when water was circulated. Moreover, an automated water circulation system was maintained in the SAS and EAS systems using the pump and timer. It was programmed with 70 minutes on-time and 20 minutes off-time based on the Dissolved Oxygen (DO) of soaking water. This cycle was started after 12 hours of soaking and continued until the 30% (wb) moisture content of the paddy. The moisture content was measured by the oven-dry method to check the moisture profile to regulate the soaking cycle.

The experiment was designed to study the effect of aerated soaking systems (SAS and EAS) on effluent quality and paddy grain quality. They were then compared with CS. Each experiment was conducted two times (two replicates).

The collected water quality parameters and paddy grain parameters of cold soaking were compared graphically with SES and EAS. A correlation analysis was done for checking the relationship between total dissolved solids (TDS) and dissolved oxygen (DO) and pH and DO. After obtaining 30% (wb) moisture content, paddy grains from all three soaking methods were steamed and dried (14% wb) properly for a better milling process. Milling yield analysis for head rice yield, broken rice yield, whitebelly percentage, heat-damaged grains and whiteness values of polished grains were analyzed at the end. In addition, a correlation analysis was done with six values to check the regression analysis between whitebelly and whiteness value and whitebelly and heat-damaged grains. This study involved the determination of physical characteristics of paddy before and after soaking, soaking

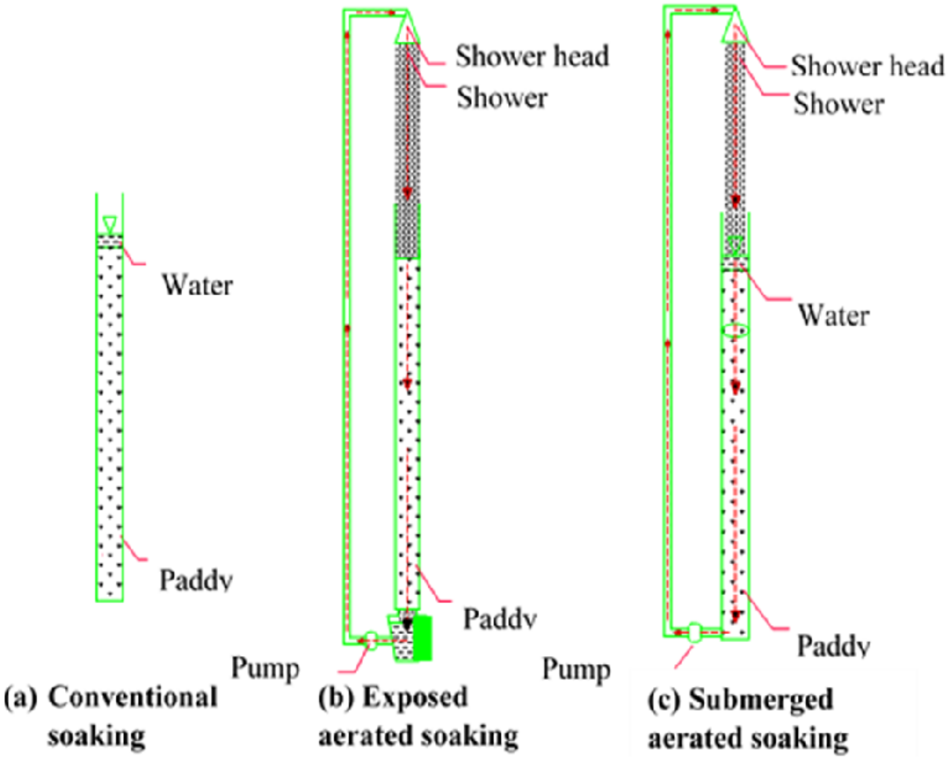

Figure 1: Drawings of CS (a); EAS (b); SAS (c) systems

effluent characteristics and milling yield analysis. The instrumentation and measurement procedures are described below.

Moisture content

The standard oven-dry method was used to determine the moisture content of the paddy. Accurately measured 5 g of sample was kept in the oven overnight at 105 °C. After drying, the final weight was measured (AOAC, 2000). Moisture content was calculated by the Eqn 1 (Kannan *et al*. 2012).

Aspect ratio

Length (mm) and width (mm) of randomly selected paddy samples were measured using vernier calliper with a reading error of 0.01 mm (Model: KANON E-PITA 20 Digital). The aspect ratio was calculated by the Eqn 2 (Nadvornikova *et al*. 2018; Varnamkhasti *et al*. 2008).

True density

It was determined by the toluene displacement method (Ravi and Venkatachalam 2014). Since paddy absorbs toluene more slowly than water, toluene (C_7H_8) was used instead of water. The preweighed paddy sample was placed into the known volume of toluene in a measuring cylinder. Toluene displacement was noted as volume (ml).

Bulk density

It was determined using the mass/volume relationship (Ravi and Venkatachalam 2014). Therefore, paddy was filled into the empty container of predetermined volume and

$$\%\ \text{Moisture content}\ (\text{wb}) = \frac{\text{Initial weight (g)} - \text{Final weight (g)}}{\text{Initial weight (g)}} \text{ x } 100 \qquad \text{(Eqn 1)}$$

$$\text{Aspect ratio} = \frac{\text{Width of paddy (mm)}}{\text{Length of paddy (mm)}} \qquad \text{(Eqn 2)}$$

$$\text{Porosity (\%)} = 1 - \frac{\text{Bulk density}}{\text{True density}} \text{ x } 100 \qquad \text{(Eqn 3)}$$

$$\text{Elongation percentage} = \frac{\text{Final length (mm)} - \text{Initial length (mm)}}{\text{Initial length (mm)}} \text{ x } 100 \qquad \text{(Eqn 4)}$$

$$\text{Germination percentage} = \frac{\text{Number of seed germinated}}{\text{Total number of seeds taken}} \text{ x } 100 \qquad \text{(Eqn 5)}$$

$$\text{Total Solids } (g/l) = \frac{\text{Final weight of beaker (g)} - \text{Initial weight of beaker (g)}}{\text{10 ml}} \text{ x 1000 ml} \qquad \text{(Eqn 6)}$$

$$\text{Milling recovery (\%)} = \frac{\text{Weight of milled rice (g)}}{\text{Weight of paddy sample used (g)}} \text{ x } 100 \qquad \text{(Eqn 7)}$$

$$\text{Head rice (\%)} = \frac{\text{Head rice weight (g)}}{\text{Sample weight (g)}} \text{ x } 100 \qquad \text{(Eqn 8)}$$

$$\text{Broken rice (\%)} = \frac{\text{Broken rice weight (g)}}{\text{Sample weight (g)}} \text{ x } 100 \qquad \text{(Eqn 9)}$$

$$\text{Heat damaged grains (\%)} = \frac{\text{Weight of heat damaged rice (g)}}{\text{Sample weight (g)}} \text{ x } 100 \qquad \text{(Eqn 10)}$$

$$\text{Weightbelly (\%)} = \frac{\text{Weight of whitebelly (g)}}{\text{Sample weight (g)}} \text{ x } 100 \qquad \text{(Eqn 11)}$$

weight. Finally, a container containing the paddy sample was weighed and bulk density was determined.

Porosity

Bulk density (g/cm^3) and true density (g/cm^3) of randomly selected paddy samples were determined using standard methods. The values of the test characteristics were obtained and the porosity of the paddy sample was estimated using Eqn 3 (Ravi and Venkatachalam 2014; Varnamkhasti *et al.* 2008).

Elongation percentage of paddy

Paddy length was measured initially and it was continued until the end of soaking at 12 hours interval using a vernier calliper with a reading error of 0.01 mm (Model: KANON EPITA 20 Digital). Elongation percentage was calculated by the Eqn 4.

Germination percentage of paddy

Paddy sample was mixed thoroughly and randomly selected 100 paddy grains were placed in the wetted tissue paper. Watch glass with soaked paddy was incubated at 27 °C in the dark (Kannan 2015). According to International Rice Research Institute (IRRI), the number of seeds germinated was counted at the end of the soaking from the first five days. Germination percentage was calculated by the Eqn 5.

Determination of parameters of soaking water

Total solids content in the soaking water was determined by using an oven drying method (Thupeeban and Kannan 2017). A beaker with a capacity of 50 ml was cleaned and placed into an oven for about three hours to remove all moisture. It was taken out and cooled in a desiccator at room temperature. The weight of the beaker was determined by standard analytical balance. A sample of 10 ml of the thoroughly mixed soaking water was placed into the beaker and the beaker was allowed to dry in the oven for three hours at 100 °C. It was taken out and cooled in a desiccator at room temperature. The TS values were calculated using the Eqn 6 (APHA 1992).

TDS (mg/l) was measured using a multimeter (Model: HACH HQ 40d). A portable DO meter (Model: DO 31P) was used to measure the DO (mg/l) content of the soaking water and the meter was pre-calibrated in air and saturated water to make accurate DO measurements. The pH was measured by a multimeter (Model: HACH HQ 40d). It was calibrated by 4, 7 and 10 standard pH solutions. The EC (mS/cm) of soaking water was measured by a multimeter (Model: HACH HQ 40d). All measurements (TS, TDS, DO, pH and EC) were taken at 2 hours intervals for soaking water of three different soaking methods until the paddy moisture content of 30% (wb). At the end of the soaking, BOD was measured by Winkler's titration method (APHA 1992).

Steaming of paddy

Steaming was done by an electric cooker (BR 910) and was completed as paddy grains were observed with split husk. It took 15-20 minutes to happen. Steaming was stopped as uniformly split husk had been observed (Hunt 2019).

Drying of paddy

Sun-drying was done. Paddy was spread on trays with 5 mm thickness. Paddy was turned up and down several times to make uniform drying. Paddy was dried to reach 12-14% moisture (wb) content to effective milling yield (Imoudu and Olufayo 1999).

Milling yield analysis of parboiled paddy obtained from different treatments

Milling yield analysis was done after dehusking and polishing. Analysis of milling yield in terms of head rice, broken rice, heat-damaged grains, whiteness value and whitebellies were determined using standard equations and methods used are given below.

Milling recovery

Milling was done in a small-scale rice mill located in Kilinochchi. After milling, bran and polished rice were weighed separately. The Eqn 7 was used to calculate the milling recovery percentage (Pokhrel *et al.* 2020).

Head rice percentage

Head rice percentage was done using Length Grader (Model: Grainman length grader 68). Polished rice of 300 g was kept in the grader. The time (50 Sec) and speed (45 rpm) were set before running the grader. Analysis was done two times to increase the accuracy. The Eqn 8 was used to calculate the percentage of head rice (Thupeeban and Kannan 2017).

Broken rice percentage

Broken rice percentage was measured using Length Grader (Model: Grainman length grader 68). At that same time, head rice and broken rice were separated. The Eqn 9 was used to calculate the broken rice percentage (Thupeeban and Kannan 2017).

Heat-damaged grains percentage

Paddy sample of 100 g was measured and hand separation was done based on observation of grains. As at least 10% of its surface area has been burnt, it was identified as heat-damaged grains (Mamadou *et al.* 2011). The Eqn 10 was used to calculate the heat damaged percentage.

Whitebelly percentage

Rice contains an internal white region that is referred to as whitebelly (Xi *et al.*, 2014). Paddy sample of 100 g was measured and hand separation was done. The Eqn 11 was used to calculate the whitebelly percentage (Thupeeban and Kannan 2017).

Whiteness value

The whiteness value of milled rice samples were measured by KETT Digital Whiteness Meter (Model: C-300-3). It was calibrated with ceramic to a value, 88.5. After that, paddy grains were placed. The displaced value was recorded as a whiteness value of samples placed.

RESULTS AND DISCUSSIONS

Physical properties of paddy

The initial moisture content of paddy was recorded as 13.4% (wb). According to the International Rice Research Institute (IRRI), normally after harvesting, dried paddy contains a moisture content lesser than 14% (wb) (Imoudu and Olufayo, 1999). Furthermore, the length (mm) and width (mm) of paddy grains were 7.82±0.01 and 2.64±0.06 respectively. It belongs to long grain under size classification and medium grain under shape classification (Chemetova 2013). The aspect ratio was calculated as 0.33. The porosity of paddy grain was calculated as 48.98±3.70%. Furthermore, bulk density and true density of long paddy grain are 0.59±0.02 g/cm^3 and 1.16±0.08 g/ cm^3 respectively. However, researchers reported porosity, bulk density and true density of paddy grains were to be 46 - 54%, 0.563 - 0.642 g/ml and 1.182 g/ml respectively (Bhattacharya *et al.* 1972). The information obtained in this section was highly useful to make a better scientific analysis of aerated soaking of paddy parboiling.

Moisture content change

Fig. 2 shows the relationship between the moisture content of paddy grains and soaking time of three different soaking methods. It is obvious from Fig. 2 that during the first 12 hours of soaking, a weighty rise in moisture content was observed in three different soaking methods due to the high moisture gradient that existed between paddy grain and soaking water environment (Kannan 2015; Thakur and Gupta 2006). However, moisture content changed very differently after 12 hours of soaking. Moreover, the rapid increase observed in the EAS and SAS compared to CS is due to the water circulation and aeration. Moisture content values for CS, SAS and EAS were 27.84±0.002%, 30.41±0.007% and 31.48±0.01% respectively after 24 hours of soaking. Both the aerated soaking systems were stopped after 24 hours due to the moisture content of 30% (wb). However, it took 48 hours to reach 30% (wb) moisture content in CS. This delay is due to the slow migration of moisture into paddy grains (Kannan 2015; Kumari *et al.* 2014a). During 24 - 48 hours, the rate of increasing moisture content was lower than the first 24 hours due to the formation of solid boundary around the paddy grain as the stagnant water prevailed. Moreover, this layer prevents the penetration of the water molecules inside the paddy grain. The same observation was

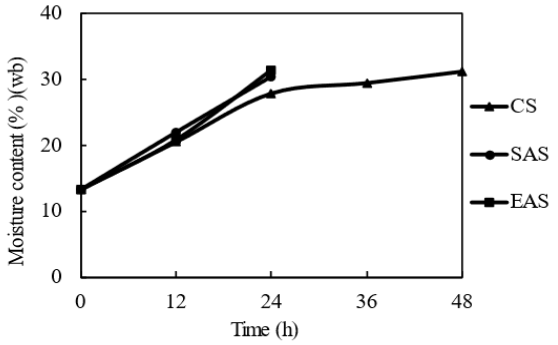

Figure 2: Effect of aeration on moisture absorption of paddy grains

reported already in aerated soaking of paddy (Kannan 2015; Kumari et al. 2014a).

Elongation percentage

Fig. 3 shows the elongation percentage of paddy during three different soaking methods. During the first 12 hours, elongation percentage increased linearly in all three different soakings due to a considerable big rise in the moisture content. The primary cause of the dimensional change was moisture gain during soaking. The starch granules found in endosperm swell after absorption of moisture, leading to dimensional transition (Kale *et al.* 2017). Another explanation is that when soaking paddy grains, cracks in the grain are filled and widened (Kale *et al.* 2017). However, the elongation percentage is very different after 12 hours of soaking. Moreover, a rapid increase in elongation was observed in SAS and EAS due to water circulation and rapid absorption of the moisture in paddy. Finally, CS, SAS and EAS paddy reached elongation percentages of 10.24, 10.36 and 10.56 respectively. During 36 - 48 hours of soaking, elongation of paddy was 0.13% in the CS. This value is highly different compared to the first 24 hours of soaking due to the obstruction given by husk to grains for swelling (Kale *et al.* 2017). However, after the removal of husk, during cooking, remarkable elongation does usually happen (Kale et al. 2017).

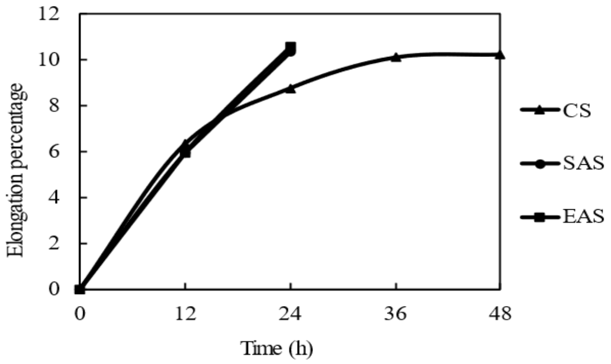

Figure 3: Effect of aeration on elongation of paddy grain

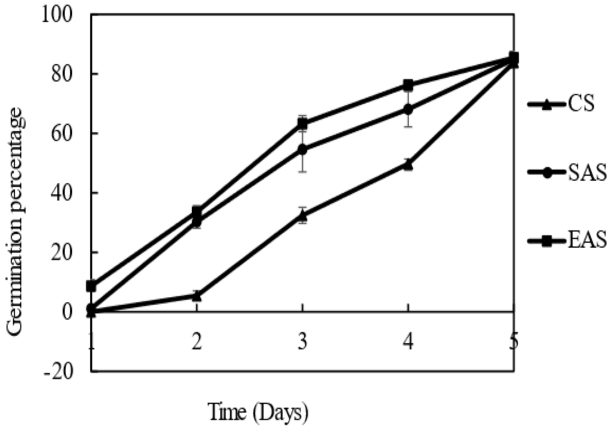

Figure 4: Germination of paddy after soaking

Germination percentage

Fig. 4 shows the germination percentage of three different soaking methods after reaching the moisture content of 30% (wb). The germination percentage reached 84.00±1.82%, 85.00±2.44% and 85.25±2.21% for CS, SAS and EAS respectively after 5 days. After soaking, 8.75±1.70% of germination was observed during the first day for the EAS. It was greatly higher during the second day. Germination percentages were observed to be 6.00±1.29%, 30.00±2.16% and 33.50±1.91% for CS, SAS and EAS respectively during the second day. These differences are due to different DO concentrations in different soaking methods. Paddy grain germination is induced when a favourable environment is provided by soaking water (Kannan, 2015). The high availability of oxygen in soaking water induces germination of the paddy grains (Panchan and Naivikul 2009).

Characterization of water

Tap water which was taken from the Department of Agriculture Engineering, Faculty of Agriculture was used to soak the paddy grains. Before using water, TS, DO, pH, TDS and EC values were determined. Initial values of pH, DO, EC, TDS and TS of used water were 7.53±0.08, 7.91±0.04 mg/l, 2470±98.99 µS/cm, 1088.5±21.92 mg/l and 1.2±0.01 g/l respectively. This piece of information is critical for analyzing changes in these parameters during different soaking methods.

Dissolved Oxygen (DO)

Fig. 5 shows the effect of aeration on DO of three different soaking methods. It is obvious from Fig. 5 that the DO value gradually decreased during the first 6 hours of three soaking methods due to the activation of aerobic microorganisms in the soaking water (Kannan, 2015). They utilized the DO in the water. After that, during 6 - 10 hours, a notable reduction of DO was observed in the soaking water. Researchers reported similar pattern as reported in this study because microbial activities are determinants of the DO and pH of soaking water based on the availability of the organic matter (Kannan 2015; Ramalingam and Raj 1996).

DO values for CS, SAS and EAS were 2.34±0.02 mg/l, 1.85±0.03 mg/l and 1.95±0.04 mg/l respectively after 12 hours of soaking. However, DO changes are very different after 12 hours of soaking in SAS and EAS due to the aeration process. Both aerated soaking systems were stopped after 24 hours of soaking which yielded 30% (wb) moisture content required for effective soaking. Therefore, SAS and EAS systems are set with no DO values after 24 hours.

However, it continued for CS up to 48 hours of soaking cycle by which required moisture content of 30 % (wb) was obtained and end of the soaking DO reduce to 0.89±0.01 mg/l. It has been reported that soaking water of CS exhibited DO values of 0.9 mg/l (Pradhan and Sahu 2004; Sayanthan and Thusyanthy 2018). A notable rise was observed during 12 to 14 hours of EAS and SAS because after 12 hours of soaking water circulation started. It lead to a rapid DO increase due to atmospheric diffusion.

During 14 to 24 hours of soaking, DO value decreased due to the dynamics of the aerobic microorganisms. The DO values of SAS, EAS and CS were 2.19±0.02 mg/l, 3.15±0.17 mg/l and 2.09±0.01 mg/l respectively after 24 hours of soaking. Both the SAS and EAS yielded higher DO than the CS system. However, the DO value of EAS is higher than the SAS system because of different mechanisms of oxygen addition. In the EAS system oxygen addition is through the atmosphere and paddy column. Hence, its values are always higher than other methods (Kannan 2015). Therefore, the observations made in this study are in line with reported findings.

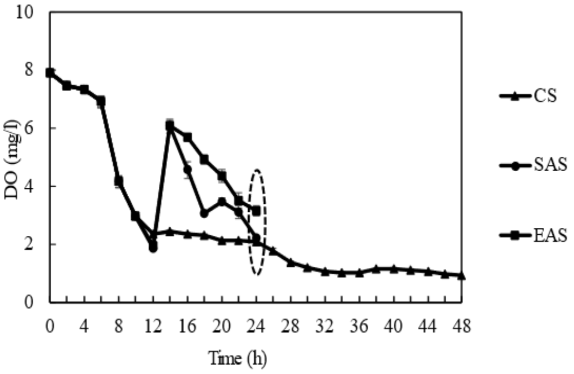

Figure 5: Effect of aeration on DO of three different soaking methods

Biological Oxygen Demand (BOD)

Fig. 6 shows the BOD value of three different soaking methods in mg/l. The values of BOD were 1575 mg/l, 600 mg/l and 472 mg/l for CS, SAS and EAS respectively. It has been reported that the BOD values of CS, SAS and EAS were 950 mg/l, 750 mg/l and 700 mg/l respectively (Kannan 2015). The prominent difference in BOD values has been observed in both aerated soaking systems compared to the CS method. The value of BOD was lower in both SAS and EAS compared to CS due to the artificial aeration provided in aerated soaking systems. Moreover, in EAS and SAS processes, DO addition was made by aeration which resulted in lower BOD values. The reason for the high BOD value in CS is the hydrolysis of organic materials presented in paddy grains.

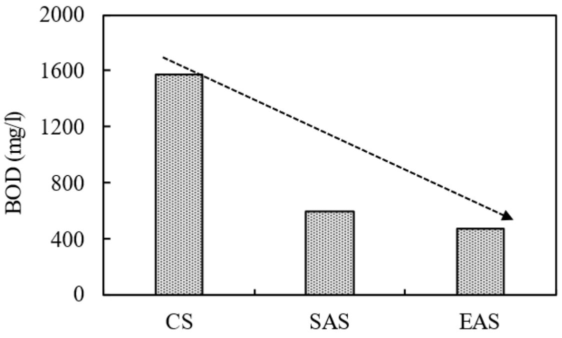

Figure 6: Effect of aeration on BOD value of three different soaking methods

These organic materials can be oxidized quickly in the aerated soaking system due to the addition of DO via aeration. Therefore, the demand for oxygen is less in SAS and EAS systems. The reduction of BOD value due to aeration has been reported in an aeration soaking environment (Kannan, 2015; Ouyang and Juan, 1995). Moreover, soaking durations of CS, SAS and EAS were 48 hours, 24 hours and 24 hours respectively. Furthermore, when the duration of soaking increased, it also induced the microbial population and their dynamics in both paddy and soaking water (Ramalingum and Raj 1996).

Total Dissolved Solids (TDS)

Fig. 7 shows the effect of aeration on TDS of three different soaking methods. It is obvious from Fig. 7 that the TDS concentration increased almost linearly during the first two hours of soaking for all three methods of soaking due to the higher concentration gradient of solid existed between grains and soaking water environment. This higher concentration gradient induced the movement of soluble solids into soaking water resulting in an increase of solid concentration in the soaking water. Moreover, during the period of soaking from 8 - 12 hours, TDS concentration again increased due to the degradation of soluble solids as a result of high microbial activity.

Moreover, the TDS value, 2800 mg/l for CS of paddy grains was obtained after the end of the soaking (Thushyanthy *et al.* 2016). However, TDS changes were very different after 12 hours of soaking in SAS and EAS systems compared to CS due to the influence of aeration on solids dynamics. The aerated soaking system was ceased after 24 hours of soaking as it reached a grain moisture content of 30% (wb) required for effective milling. Therefore, SAS and EAS were set have no value of TDS after 24 hours of soaking. However, the CS system took 48 hours to reach the grain moisture content of 30% (wb) required for effective milling. Therefore, it was able to get 1897.0±11.31 mg/l value for TDS after 48 hours of soaking. The highest TDS value observed for the SAS method was due to high suction force developed during aeration under the submerged condition of grains.

This highest suction force in SAS resulted in higher leaching rates. Furthermore, the degree of suction force is low for EAS compared to the SAS system. Therefore, the TDS concentration of the SAS system is high compared to the EAS system. The increasing trend in TDS concentration was observed for all three soaking systems due to the degradation of solids into soaking water by developed microbial colonies.

Electrical Conductivity (EC)

Fig. 8 shows the effect of aeration on EC of the three different soaking methods. An EC in water is caused by soluble ions. The EC of soaking water ranges from 1 - 6 mS/cm during the soaking time (Thushyanthy *et al.* 2016). The EC value of all three experimental

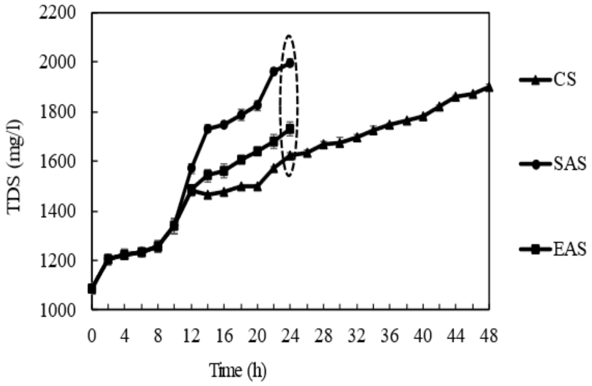

Figure 7: Effect of aeration on TDS of three different soaking methods

processes increased with the soaking period, but the increase was not gradual. EC of all three different soaking methods gradually increased up to 10 hours of soaking. However, EC changes are very different after 12 hours of soaking in SAS and EAS compared to CS due to the influence of aeration on solid dynamics. It was mixing the soluble ions in the soaking water.

The EC values in µS/cm for CS, SAS and EAS were 2995±21.21, 2940±56.56 and 2790±42.42 respectively after 12 hours of soaking. However, EC of the CS water is gradual because of the reduction in the concentration gradient of the soluble ions in the soaking water. After 12 hours, a notable rise was observed in SAS and EAS. The values of EC were 3680±56.56 µS/cm and 3165±21.21 µS/cm for after 14 hours of soaking of SAS and EAS respectively. Therefore, the circulation of soaking water increased the ability of soluble ions to be leached from paddy grain. This situation increases the soluble solid dynamics (Kannan 2015).

The EC value was 4005±7.07 µS/cm after 48 hours for CS. During the period from 12 hours of soaking to 24 hours of soaking, EAS and SAS showed an increasing trend in EC compared to CS. The highest EC value observed for the SAS method was due to high solute concentration due to the leaching of soluble solids.

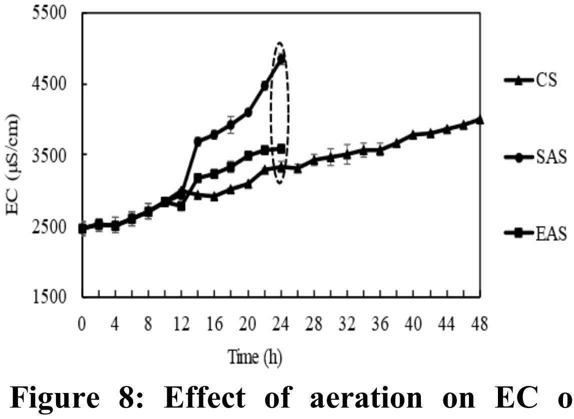

Figure 8: Effect of aeration on EC of three different soaking methods

This highest suction force in submerged aeration resulted in higher leaching rates. Furthermore, the degree of suction force is low for exposed aeration compared to submerged aeration system. Therefore, the EC of the submerged aeration system is high compared to exposed aeration system. A similar pattern has been observed for TDS concentration in three different soaking systems of this experiment. It has been reported that the TDS could be estimated from electrical conductivity (EC). The linear relationship between TDS and EC can be stated as TDS (mg/l) = k_e × EC (µS/cm). (k_e is a constant of proportionality) (Taylor *et al.* 2018). Therefore, the observation made in this study matches with reported findings.

pH

Fig. 9 shows the effect of aeration on the pH of the three different soaking methods. It is obvious from Fig. 9 that the pH value gradually decreased during the first 6 hours of soaking for all three soaking methods due to the activation of microbial dynamics between soaking water and paddy grains. After that, during 6 to 8 hours of soaking, an astonishing reduction in pH was observed in the soaking water due to the proliferation of microbial colonies, resulting in the formation of phenolic compounds in the soaking water (Kannan 2015; Senanayake *et al.* 2001). However, during 8 to 12 hours of soaking, again gradual decrease was observed due to the microbial activity. The pH values for CS, SAS and EAS were 6.51±0.06, 6.39±0.02 and 6.32±0.01 respectively after 12 hours of soaking.

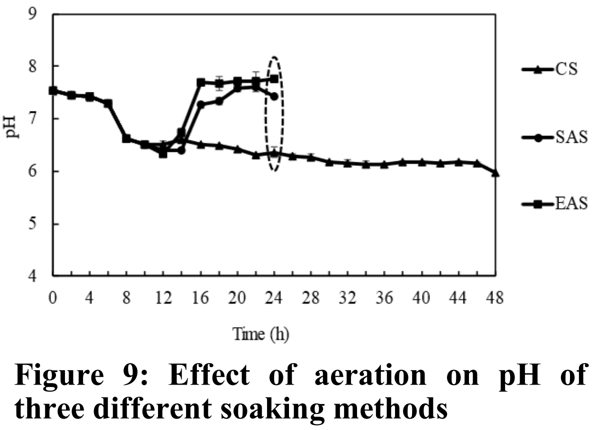

Figure 9: Effect of aeration on pH of three different soaking methods

However, pH changes are very different after 12 hours for SAS and EAS due to recirculation and aeration of the water. Both aerated soaking systems were stopped after 24 hours of soaking as they reached a moisture content of 30% (wb). The pH value of 5.97±0.05 was obtained in the CS system after 48 hours. During the period from 12 hours to 24 hours of soaking, EAS and SAS showed an increasing trend in pH compared to CS. SAS, EAS and CS systems had pH values of 7.42±0.01, 7.76±0.02 and 6.36±0.09 respectively after 24 hours of soaking. The highest pH value is observed in the EAS system due to high DO concentration than other soaking methods. DO values for CS, SAS and EAS were 2.09±0.01, 2.19±0.02 and 3.145±0.10 mg/l respectively after 24 hours of soaking. Therefore, aeration increased the pH value in soaking water (Ramalingam and Raj 1996).

Total Solids (TS)

Fig. 10 shows the effect of aeration on TS of the different soaking methods. It is obvious that the TS values curiously increased during the first 4 hours of soaking for all three methods due to the higher concentration of solid that existed between grains and soaking water. This concentration gradient induced the movement of solids into soaking water. Moreover, during 4 to 12 hours of soaking, TS values decreased gradually due to the microbial activity (Kannan 2015). The total solid increased in all three different soaking methods with different patterns.

The TS values for CS, SAS and EAS were 1.85±0.17 g/l, 1.86±0.18 g/l and 1.69±0.01 g/l respectively after 12 hours of soaking. However, TS changes were very different after 12 hours of soaking in submerged and EAS due to the recirculation of the water. During 12 to 14 hours of soaking substantial rise was observed in the TS value due to recirculation of the water, resulting in higher leaching of solids from the paddy grains. Moreover, the TS value includes both TDS and TSS (total suspended solid) (APHA 1992). During the period from 12 hours to 24 hours of soaking in EAS and SAS, an increasing trend in TS was observed, compared to CS. However, this increasing trend was observed in SAS. However, it was not gradual in EAS. SAS and EAS had TS values of 3.08±0.03 g/l, 3.06±0.01 g/l and 1.69±0.07 g/l respectively after 24 hours of soaking. The highest TS value was observed in SAS and EAS compared to CS. Moreover, both aerated soaking systems got the almost same value of TS content in soaking water at 24 hours of soaking. These changes are due to differences in the microbial population, which influenced the DO dynamics and TS in soaking water.

The relationship between TDS and DO of three different soaking methods

The relationship between TDS (mg/l) and DO (mg/l) of three different soaking methods, CS, SAS and EAS systems are shown in Fig. 11. It is obvious that different soaking systems have different degrees of relationships between TDS and DO. The conventional soaking system exhibited a better indirect relationship between TDS and DO. The TDS concentration in the soaking system was high as DO concentration was considered to be low. This scenario can be explained by considering the microbial population and organic substances degradation pattern with DO concentration in the soaking water. At high DO concentration, the aerobic microbes were active and the chemical degradation rate was also high, resulted in lower TDS concentration.

It is opposite to lower DO concentrations which were related to higher TDS in wastewater (Muigai *et al*. 2010). However, the

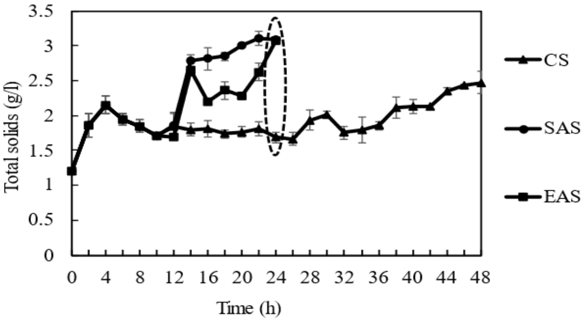

Figure 10: Effect of aeration on TS of three different soaking methods

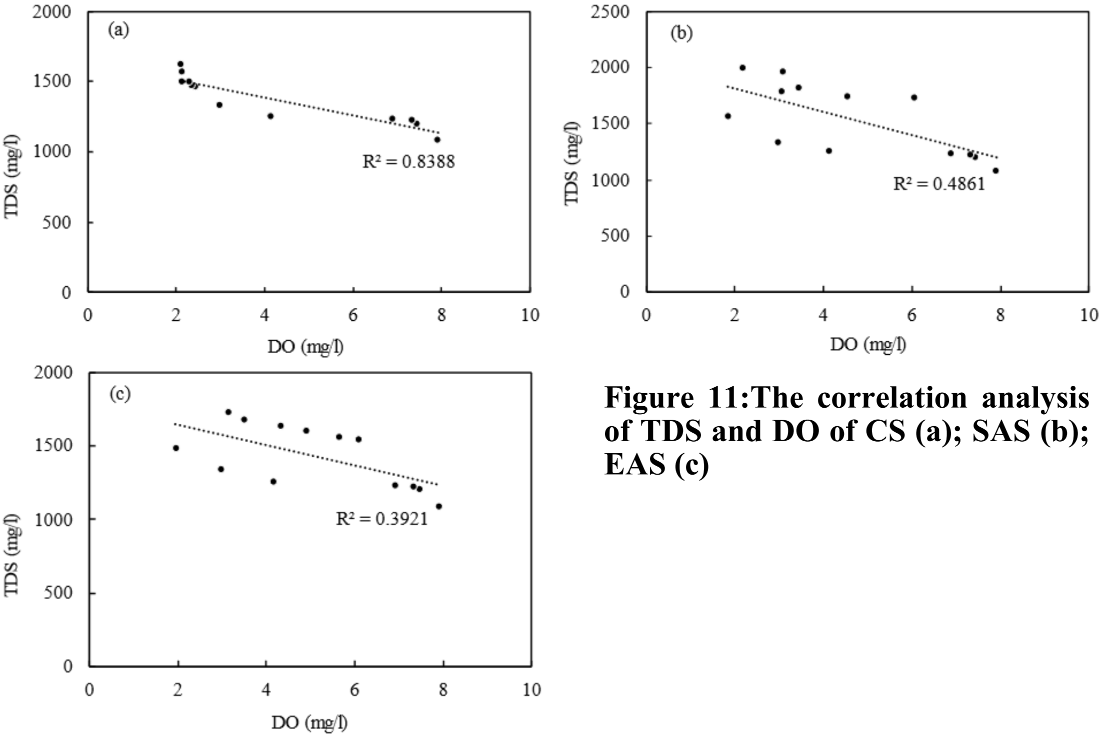

Figure 11:The correlation analysis of TDS and DO of CS (a); SAS (b); EAS (c)

relationship between TDS and DO for SAS and EAS system is not well correlated as of the influence given to DO profile of soaking water by deliberate aeration which made different patterns of soluble solids degradation. The R^2 value of SAS and EAS is 0.4861 and 0.3921 respectively, which show a weak relationship between TDS and DO. It has been reported that the TDS concentration of soaking water is influenced by DO concentration during soaking. The same observations were obtained in water eutrophication (Muigai *et al*. 2010).

The relationship between pH and DO of different soaking methods

The relationship between pH and DO (mg/l) of three different soaking methods, CS, SAS and EAS are shown in Fig. 12. The relationship between pH and DO is positively correlated. The CS system exhibited a direct relationship between pH and DO. The pH in the soaking system was low as DO concentration was low. This scenario can be explained by considering the microbial population and organic substances degradation pattern with DO concentration in soaking water. At high DO concentration, the aerobic microbes utilized dissolved oxygen. Therefore, the system is exposed to the anaerobic condition. Due to this anaerobic condition, fermentation of starch occurred, resulting in the formation of acid substances like volatile acids produced by anaerobic microbes in the soaking water environment (Kannan 2015).

Due to this microbial activity, pH was reduced when DO concentration was reduced. However, the relationship between DO and pH for SAS and EAS system is not well correlated as of the influence given to DO profile of soaking water by deliberate aeration which made different patterns of the microbial population. The soaking water environment was kept above 1 mg/l of dissolved oxygen value. The increasing trend in pH of soaking water with DO has been reported during paddy soaking (Kumari *et al*. 2014a).

The R^2 values of SAS and EAS are 0.0744 and 0.1255 respectively, which show the weak relationship between pH and DO. It has been reported that the pH of soaking water was highly influenced by DO concentration during soaking. Researchers reported the pH

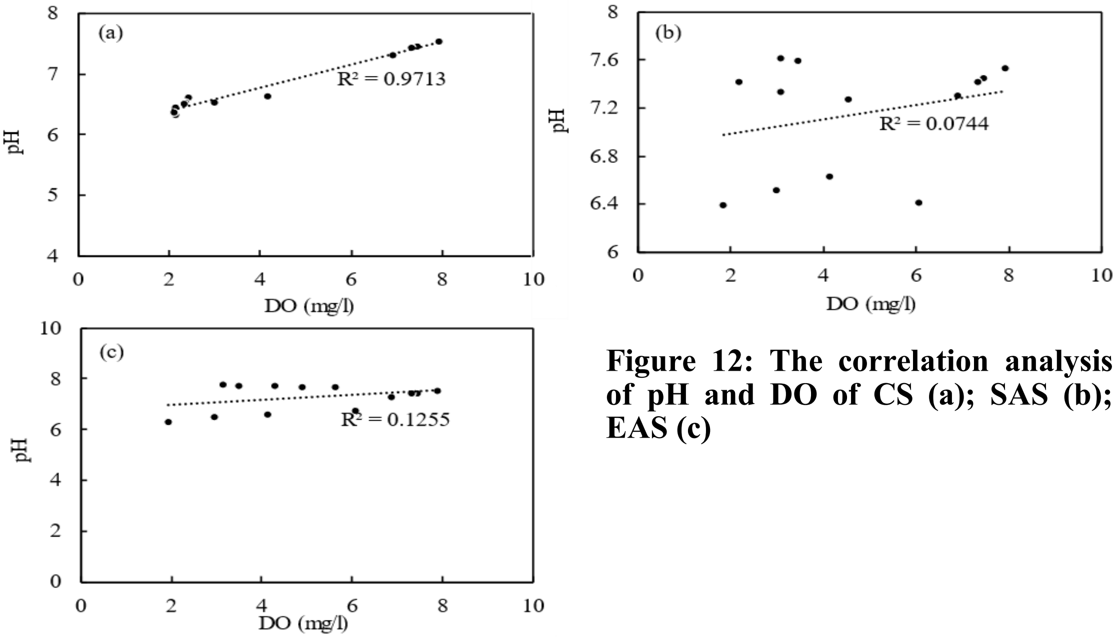

Figure 12: The correlation analysis of pH and DO of CS (a); SAS (b); EAS (c)

of soaking water had been influenced by microbial activities. Moreover, the DO and pH of soaking water influenced the availability of the organic matter (Kannan 2015; Kumari *et al*. 2014a; Ramalingam and Raj 1996).

Effect of aeration on milling yield of paddy

Long paddy grain samples, that were soaked by CS, SAS and EAS methods were steamed and sun-dried. Then, milling recovery, head rice percentage, broken rice percentage, heat-damaged grain percentage, whitebelly percentage and whiteness value of milled rice samples were analysed. The following sections are set to discuss outcomes obtained from milling yield analysis.

Milling recovery

Fig. 13 shows the milling recovery of three different soaking methods of Bg 251 paddy. There was no remarkable difference among the three different soaking methods in terms of milling recovery. Percentages of milled rice recovery of CS, SAS and EAS were 74%, 72.55% and 72.9% respectively after the removal of husk and bran. The amount of milled rice recovered during milling is determined by a number of factors, including the type of paddy, the amount of milling needed, the quality of the equipment used, and the operators (Dhankhar 2014). According to the above statement, the same amount of the same type of paddy was milled. Therefore, no notable changes were observed in milled rice, bran and husk in terms of yield.

Head rice and broken rice percentage

Fig. 14 shows the head rice percentage of different three soaking methods. There was no remarkable difference observed between CS and SAS in terms of head rice percentage. However, a considerable difference was observed between EAS and SAS in terms of head rice percentage due to paddy grain germination as of the higher DO concentration in the soaking water. Therefore, soaked paddy grains were exposed to the higher oxygen concentration in exposed aeration than the other two methods. It induced metabolic

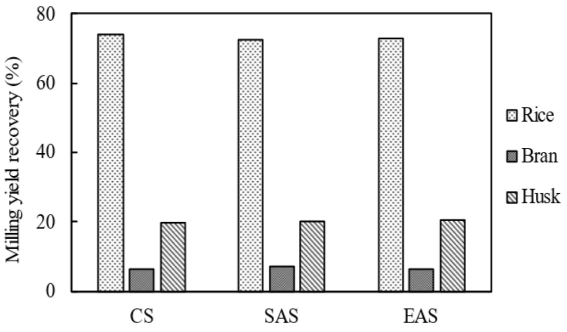

Figure 13: Milling recovery of different soaking methods

activities of paddy, resulting in germination. Due to this, the head rice percentage of EAS was reported to be low than the other two methods. The values of head rice percentage of CS, SAS and EAS were 79.15±1.15%, 79.51±1.62% and 60.74±2.00% respectively.

Furthermore, the broken rice percentage of EAS increased due to paddy germination. Germination of paddy reduced the milling yield percentage (Han *et al.*, 2016). The values of broken rice percentage of CS, SAS and EAS were 20.84±1.15%, 20.48±1.16% and 39.25±1.99% respectively. Broken rice percentage goes down as head rice percentage increases.

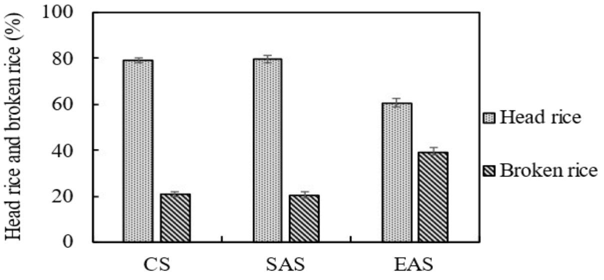

Figure 14: Head rice and broken rice percentage of different soaking methods

Regression analysis of white bellies, heat-damaged grains and whiteness value of parboiled rice

Fig. 15 (a, b and c) shows the whitebelly, whiteness value and heat damaged-grains of three different soakings of parboiled paddy grains. Fig. 15 (a) indicates the whitebelly percentages of CS, SAS and EAS 1.16±0.10%, 1.32±0.02% and 1.33±0.05% respectively. Fig. 15 (b) shows the whiteness value percentages of CS, SAS and EAS were 20.16±0.05, 20.76±0.37 and 20.83±0.30. Fig. 15 (c) displays the heat-damaged grains percentages of CS, SAS and EAS were 0.9±0.26, 1.36±0.04 and 1.65±0.23. The long time it took to reach the moisture content of 30% (wb) in the CS resulted in the uniform moisture migration to the centre of the paddy grains, which in turn turned into a lower whitebelly percentage. However, the quick moisture absorption in SAS and EAS systems left the centre of the paddy grain not hydrated with water, which produced a higher whitebelly percentage (Buggenhout *et al.*,

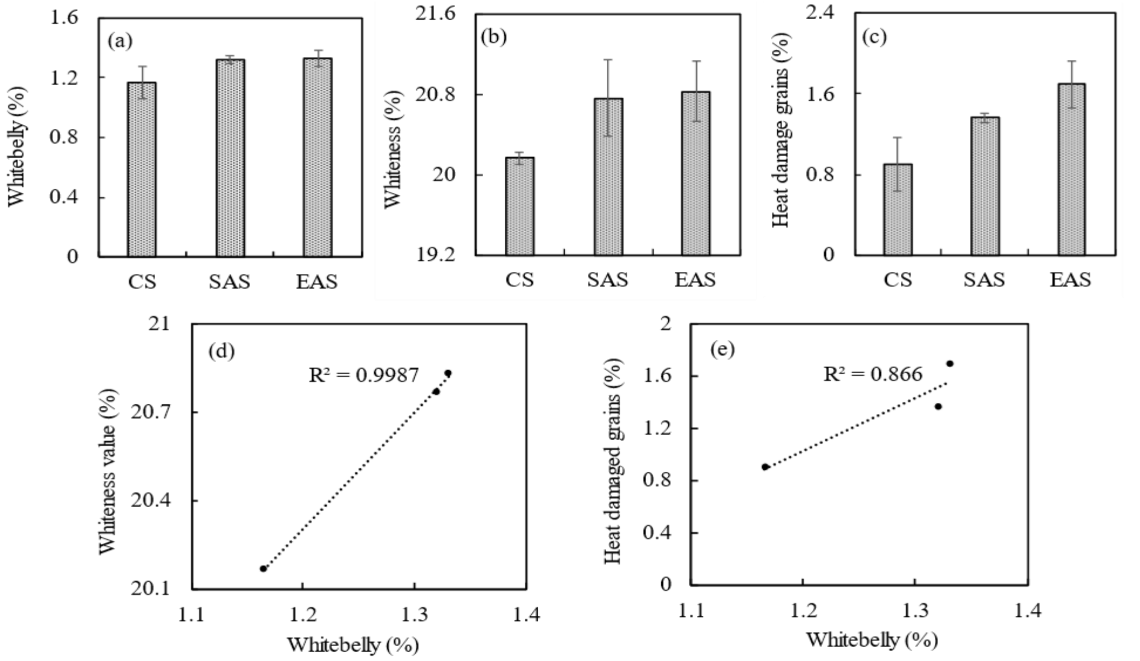

Figure 15: The scenario of whitebelly (a); whiteness value (b); and heat-damaged grains (c); and regression analysis of whiteness value and whitebelly (d); and heat-damaged grains and whitebelly (e) of three different soaking methods.

2014). Moreover, whitebellies are formed due to poor migration of moisture into paddy grains. Furthermore, whitebellies also influence the whiteness value of grains. This statement was supported by regression analysis of whitebelly and whiteness value as shown in the Fig. 15 (d). It is obvious from the Fig. 15 (d) that the whitebelly percentage and whiteness values are positively correlated (R^2- 0.9987).

In a research study, it has been reported that the whitebelly grains increased the value of whiteness percentage (Nagato *et al*. 1974). As the whitebellies are sensitive to heat damage, the percentage of heat-damaged grain is high in SAS and EAS systems as shown in the Fig. 15 (c). Moreover, a direct relationship was observed between the whitebelly percentage and heat-damaged grain percentage as shown in Fig. 5 (e) with the R^2 value of 0.866. In a research study, it has been reported that the moisture migration into paddy grain during soaking influences whitebelly percentage at the time of milling and the weakness of whitebellies is most likely due to air gaps or voids at the centre of grains (Buggenhout *et al*. 2014). Therefore, it is important to regulate the moisture migration into paddy grains for having a lower percentage of whitebellies.

CONCLUSION

This study investigated the effect of aerated soaking on the paddy parboiling process with an intention of proposing an effective way to reduce the quality and quantity of effluent to avoid unnecessary environmental consequences. Moreover, milling yield analysis was done to check the effect of aeration during the soaking process especially on the head rice yield. The effect of aerated soaking on the hydration rate of paddy is highly remarkable compared to CS. The moisture percentage of 30% (wb) was obtained by 24 hours of soaking in both SAS and EAS systems compared to CS. It therefore expressively reduced the number of water changes. The SAS and EAS systems were able to maintain positive DO in the soaking water. The DO profile in the EAS system was greater than the SAS system as of higher diffusion rates.

The higher DO maintain in the EAS system reduced head rice yield due to the breakage of germinated paddy grains during milling. The effect of SAS on the milling yield is unimportant. However, 1.32% of whitebelly was observed. It can further be improved by the changing of aeration cycles. This SAS system did not show considerable germination of grain and did not alter milling yield and head rice percentage compared to CS. Hence, the system of SAS is considered as a reliable option for soaking paddy during parboiling in an eco-friendly with a momentous reduction in effluent strength in terms of BOD.

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AUTHOR CONTRIBUTION

NC carried out the experiment, interpreted the data and developed the draft manuscript. NK developed the research concept, involved in critical discussion and interpretation of data, revised the manuscript and supervised the entire project (NC-Neshankine Chandraruban; NK-Dr. Nadarajah Kannan).

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