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Microwave-assisted parboiling of high moisture paddy: A comparative study based on energy utilization, process economy and grain quality with conventional parboiling



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ABSTRACT

Parboiled rice (PBR) is extremely popular in South Asian nations however, the conventional process of parboiling performed for PBR production is energy and time intensive. In the present work, a unique approach of parboiling is proposed in which high moisture freshly harvested paddy was taken as the raw material for parboiling and the conventional hot water soaking (HWS) was replaced by microwave-assisted soaking (MWS). An in-depth comparative assessment was carried out between the conventional parboiling (CP) and the microwave-assisted parboiling (MWP) based on actual and theoretical energy consumption and feasibility of the MWP was ascertained given process economy and PBR qualities into account. An overall energy saving of 20.48% was achieved through MWS as compared to HWS. The specific energy consumption for steaming during MWP was found to be 78.22 kJ kg^{-1} which is 48.47% lower as compared to the CP. Moreover, the overall processing time and cost of processing were reduced by 6.91 h and 1583 INR/ton for MWP in comparison to CP. From the quality point of view, MWP resulted in a lower broken percentage, higher grain whiteness and lower cooking time of the PBR produced.

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1. Introduction

Rice (*Oryza sativa* L.) is one of the most consumable crops in the world. The worldwide paddy production in 2017 was reported at 769.65 million metric tonnes (MMT), cultivated over an agricultural land of 167.25 million hectares [1]. It is assessed that half of the world's population consumes rice every day [2] however, the pattern of rice cooking and criteria of consumption is found to be of a wide range [3]. Predominantly rice is consumed either in two ways i.e. raw rice or parboiled rice with the latter being extremely popular in South Asian nations. An estimated 130 MMT of harvested paddy is processed globally to produce parboiled rice [4], which is expected to expand further, driven by the nutritional and physical characteristics of parboiled rice [5].

To produce parboiled rice, the paddy has to undergo three

essential steps i.e. hydration, gelatinization and dehydration. This multistep hydrothermal treatment is an energy and time-intensive process. Previous studies revealed that the specific energy consumption (SEC) during paddy parboiling ranges between 5860 kJ kg^{-1} [6] to $18700\text{--}34800 \text{ kJ kg}^{-1}$ [7] depending on the method of processing and type of fuel used. Considering the above facts, the global energy consumption per year for paddy parboiling would be approximately 443 TW-hours. Along with high energy demand, another prime concern with paddy parboiling is the selection of raw material where stored paddy (SP) is taken instead of the high moisture freshly harvested paddy (FHP). The conventional choice of raw material includes drying of the FHP and its storage before the parboiling treatment that could have been side-stepped provided FHP was considered as the raw material for parboiling. Drying of FHP is highly energy-intensive as the SEC per kg of water evaporated was found to be as high as $4630\text{--}5260 \text{ kJ kg}^{-1}$ [8] to $6800\text{--}43200 \text{ kJ kg}^{-1}$ [9]. As reviewed by Defraeye [10], industrial drying may consume as high as 25% of the national energy use. Although drying of FHP has been attempted by numerous

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Nomenclature

BP	Broken percentage (%)	<i>c</i>	pre-cleaning
C	Cost (INR)	<i>da</i>	drying air
C	Specific heat ($\text{kJ kg}^{-1} \text{°C}^{-1}$)	<i>d</i>	dry grain
CP	Conventional parboiling	<i>dr</i>	dryer
EC	Energy consumption	<i>HR</i>	head rice
E_{T-dr}	Theoretical energy absorbed by FHP during drying (kJ)	<i>hsk</i>	soaking
E_{d-dr}	Energy absorbed by the dry mass during drying (kJ)	<i>ht</i>	Heating element
E_{w-dr}	Energy absorbed by the wet mass during drying (kJ)	<i>in</i>	insulation
E_{e-dr}	Energy required to remove moisture from the FHP (kJ)	<i>IN</i>	investment
E_{T-hsk}	Theoretical energy absorbed by the SP during HWS (kJ)	<i>M</i>	milling
E_{d-hsk}	Energy absorbed by the dry mass of SP during HWS (kJ)	HY	Head rice yield (%)
E_{w-hsk}	Energy absorbed by the wet mass (grain moisture + soaking water) during HWS (kJ)	INR	Indian rupees
E_{e-hsk}	Energy used in evaporating moisture from soaking water (kJ)	mc_{fh}	Moisture content of FHP (% wb)
E_{T-msk}	Theoretical energy absorbed by FHP during MWS process (kJ)	MC	Moisture content (decimal wb)
E_{d-msk}	Energy absorbed by the dry mass of FHP during MWS (kJ)	MMT	Million metric tonnes
E_{w-msk}	Energy absorbed by the wet mass (grain moisture + soaking water) during MWS (kJ)	MWP	Microwave-assisted parboiling
E_{e-msk}	Energy used in evaporating moisture from soaking water (kJ)	MWS	Microwave-assisted soaking
E_{sk}	Energy absorbed by the soaking water, before adding to FHP (kJ)	MY	Milling yield (%)
E_{T-st}	Energy absorbed by the soaked paddy (SKP) during steaming (kJ)	PBP	Parboiled paddy
E_{d-st}	Energy absorbed by the dry mass of SKP (kJ)	PBR	Parboiled rice
E_{w-st}	Energy absorbed by the wet mass during steaming (kJ)	P_M	Microwave power (W)
E_{T-drst}	Theoretical energy absorbed by the steamed paddy during drying (kJ)	SEC	Specific energy consumption (kJ kg^{-1})
E_{e-drst}	Energy required to remove moisture from the steamed paddy (kJ)	SP	Stored paddy
E_{drst}^r	Reserved energy in steamed paddy capable of removing moisture (kJ)	STP	Steamed paddy
E_{d-drst}^r	Reserved energy in the dry mass of STP which dissipated before convective drying (kJ)	T	Temperature (°C)
E_{w-drst}^r	Reserved energy in the wet mass which dissipated before convective drying (kJ)	t	Time (h)
FHP	Freshly harvested paddy	T_b	Grain bed thickness (cm)
f_u	fraction of husk used for heating	V_a	Air velocity (ms^{-1})
h_{bm}	Latent heat of vaporization of bound moisture present in the FHP (kJ kg^{-1})	W:G	Water to grain ratio
h_{vs}	Heat of vaporization at soaking temperature (kJ kg^{-1})	W_{d-dr}	Weight of dry mass in FHP (kg)
HRE	Head rice equivalent	W_{w-dr}	Weight of wet mass in FHP (kg)
HWS	Hot water soaking	W_{fh}	Initial weight of FHP taken for drying (kg)
		W_{e-dr}	Weight of moisture evaporated from FHP during drying (kg)
		W_{d-hsk}	Weight of dry mass in SP (kg)
		W_{e-hsk}	Weight of moisture evaporated from soaking water during HWS (kg)
		W_a	Weight of water absorbed by SP (kg)
		W_r	Weight of water remaining after HWS (kg)
		W_{d-st}	Weight of dry mass in SKP (kg)
		W_{w-st}	Weight of wet mass during steaming (kg)
		W_{e-drst}	Weight of moisture evaporated from STP during drying (kg)
		W_{w-drst}	Weight of wet mass in STP (kg)
		W_{d-drst}	Weight of dry mass in STP (kg)
		ME	mechanical energy
		RC	Recovered from by-product
		RM	raw material
		st	steaming
		ST	storage
		T	theoretical
		TE	thermal energy
Greek letters			
		η	efficiency
		ω_R	Uncertainty in the overall result
		$\omega_1, \omega_2, \dots, \omega_n$	Uncertainties in independent variables
		$x_1, x_2, \dots, x_n$	Independent variables
Subscripts			
aa	Ambient air		
A	Actual		
B	Bagging		
BO	bran used for oil extraction		

researchers in the past, the energy demand, environmental impact, cost and time requirements of drying have never been discussed in combination with parboiling.

Moreover, the use of lower-grade fuel during paddy parboiling and releasing of polluted water from the soaking unit of the parboiling plant causes significant environmental nuisance. In the current scenario, a major proportion of paddy is parboiled on a rural scale where husk or wood are used as a chief source of fuel which has poor energy conversion efficiency [11] and on burning they release undesirable particulate materials to the environment [12]. As the global energy demand is expected to see around a 40% hike by 2030 [13] an alternative energy source is of foremost interest, which needs to be economical, reliable and could reduce on-site emissions for a cleaner processing environment [14]. In the last two decades, the use of microwave in food processing sector has taken a lead over conventional heating methods due to its advantages like volumetric or bulk heating [15], instantaneous control over the power temperature response [16], less (20–35%) floor space requirement, resulting in no combustible pollutants [17], and effective rapid heating of materials having low thermal conductivity [15]. The unique and effective heating methods of microwave energy resulted into various novel applications in the field of food processing and preservation, waste management, metallurgy, mineral extraction, etc [18–20].

In industrial paddy parboiling, hot water soaking (HWS) is commonly used which constitutes about 38% of the total parboiling energy [21] and also causes an environmental hazard by discharging the leftover water after soaking into nearby water bodies or barren land. To counter this issue, authors in their previous work have attempted microwave-assisted soaking (MWS) of SP [22] and FHP [unpublished data] and found promising outcomes as compared to the conventional HWS. In the previous studies by the authors, it has optimized the MWS method for SP and FHP and found that the MWS was superior to HWS in term of moisture gain, leaching losses, grain whiteness and time consumption. Parboiling being the combination of soaking, steaming and drying it would be interesting to discover the impact of MWS on the overall parboiling process. However, the implications of the MWS on the overall energy usage, processing cost and quality of parboiled rice have not been covered before.

In the present study, a unique approach of parboiling (Fig. 1) is proposed in which FHP was taken as the raw material for parboiling

and conventional HWS was replaced by MWS. This approach is expected to cover multiple important aspects such as energy expenses due to drying of FHP, post-harvest management of high moisture FHP, accelerated ageing of FHP to improve the cooking quality of rice and the detrimental effect on the environment due to burning of fuels for drying. Thus, the current study aims to carry out a comparative assessment between conventional parboiling (CP) and microwave-assisted parboiling (MWP) based on actual and theoretical energy consumption during different stages of parboiling and establish the practicality/feasibility of MWP given process economy and final grain qualities such as milling yield, whiteness index and cooking qualities into account.

2. Material and methods

Paddy variety IR36 was considered for the parboiling experiments. The overall experimental flow is summarized in Fig. 2. The two experimental differences between MWP and CP were the selection of raw material and the soaking method. For CP low moisture stored paddy (SP) was taken and HWS was adopted whereas, for MWP high moisture FHP was taken and MWS was performed which is an extension of our previous study [unpublished data]. Due to the high moisture content of FHP, the grains were sealed in air-tight and moisture-proof packages weighing 0.5 kg each and stored in refrigerated condition (below 4 °C). Before conducting the experiments, the packages were kept at room temperature for 6 h to attain equilibrium. Only sound grains were taken for the experimental trials.

2.1. Experimental design

The experimental parameters and their respective values for CP and MWP are presented in Fig. 3. An in-depth energy estimation was carried out for each processing step i.e. soaking, steaming and drying involved in both the parboiling techniques. Moreover, the overall energy consumption and process economy in producing parboiled paddy (PBP) were evaluated for the comparative assessment between MWP and CP. Finally, the quality aspect of the PBP produced through both methods was also discussed which included milling yield, whiteness index of polished parboiled rice (PBR), and cooking qualities (i.e. cooking time and gruel loss).

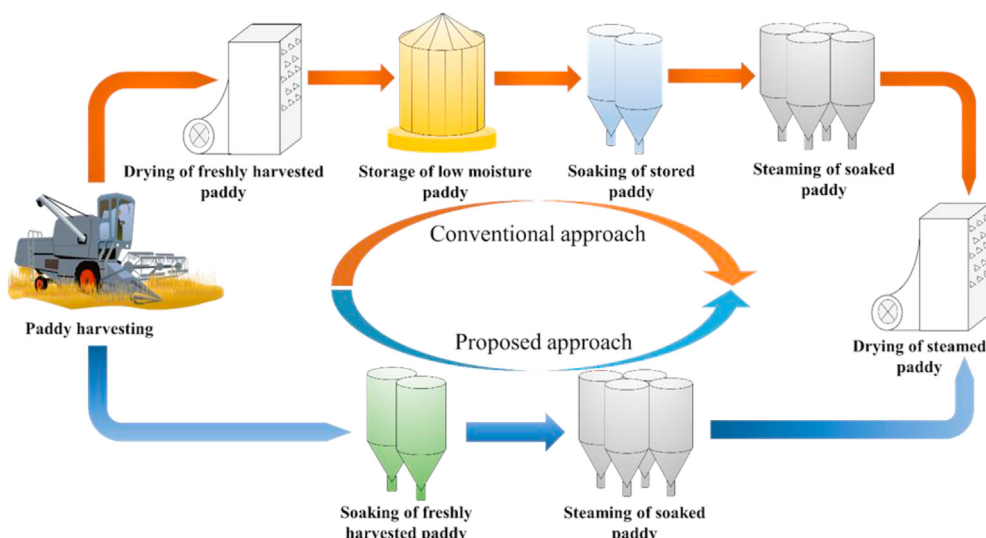


Fig. 1. The schematic diagram of proposed approach for paddy parboiling.

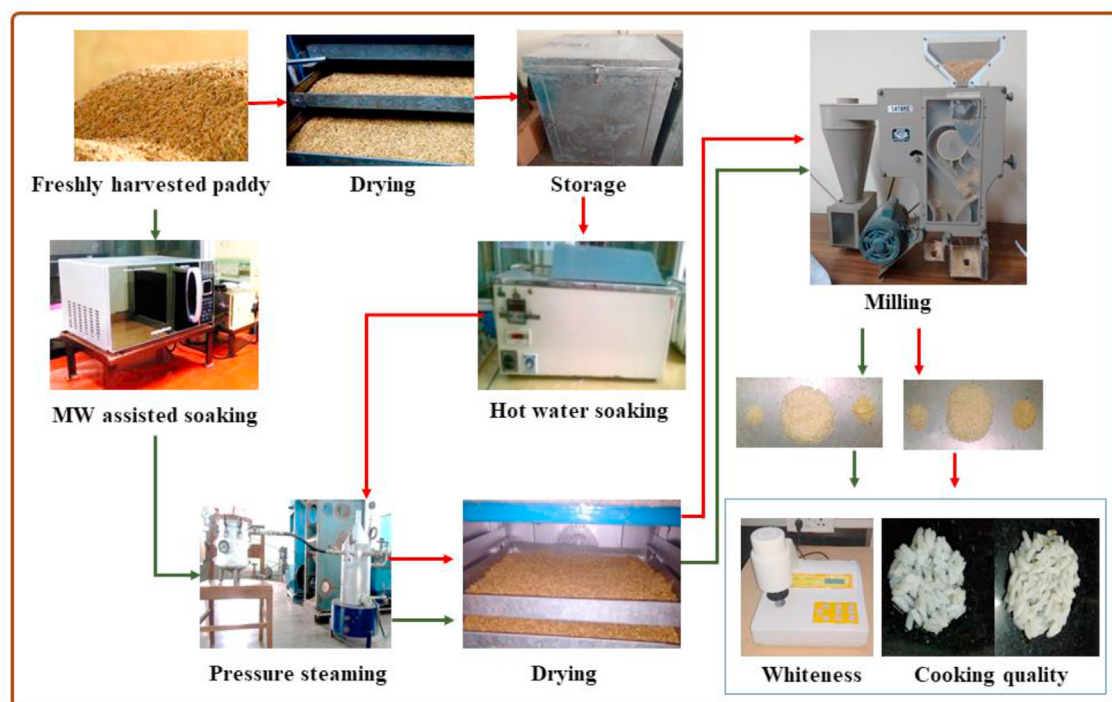


Fig. 2. Pictorial presentation of experimental flow adopted in the current study.

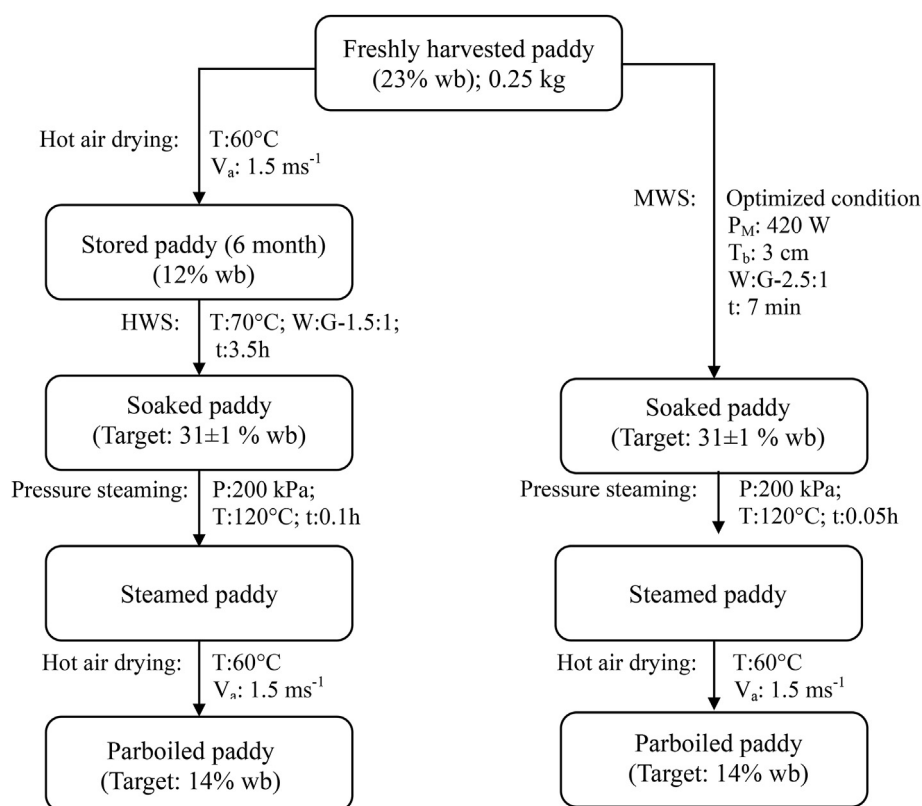


Fig. 3. Flow diagram of experiments conducted for CP and MWP

N.B. T - temperature, V_a - air velocity, W:G - water to grain ratio, t - time, P - pressure, T_b - bed thickness, P_M - microwave power.

2.2. Thermal energy calculation

Energy consumption was analysed using two approaches that are theoretical and actual aspects by considering the empirical equations and efficiency factors, respectively. Steaming and drying of steamed paddy were kept identical in both CP and MWP.

2.2.1. Theoretical energy analysis

2.2.1.1. Drying of FHP. Drying of the FHP has been carried out in a cabinet tray dryer (M/s Macro Scientific Works Pvt. Ltd., New Delhi; 25–180 °C, accuracy: ± 1 °C). The energy required for hot air drying of FHP in conventional parboiling (Fig. 3) is calculated as per the following formulation:

$$E_{T-dr} = E_{d-dr} + E_{w-dr} + E_{e-dr} \quad (1)$$

where E_{T-dr} is theoretical energy absorbed by FHP during drying (kJ); E_{d-dr} is energy absorbed by the dry mass during drying (kJ) [Eq.(2)]; E_{w-dr} is energy absorbed by the wet mass during drying (kJ) [Eq.(4)]; E_{e-dr} is energy required to remove moisture from the FHP (kJ) [Eq.(6)]

$$E_{d-dr} = W_{d-dr} \times C_d \times (T_{da} - T_{aa}). \quad (2)$$

$$W_{d-dr} = W_{fh} \times (1 - MC_{fh}). \quad (3)$$

$$E_{w-dr} = W_{w-dr} \times C_w \times (T_{da} - T_{aa}). \quad (4)$$

$$W_{w-dr} = W_{fh} - W_{d-dr} \quad (5)$$

$$E_{e-dr} = W_{e-dr} \times h_{bm} \quad (6)$$

$$W_{e-dr} = W_{fh} \times \left(\frac{MC_{fh} - MC_{sr}}{1 - MC_{sr}} \right) \quad (7)$$

$$h_{bm} = 319351 \times mc_{fh}^{-1.446} \quad (8)$$

where, W_{d-dr} is weight of dry mass in FHP (kg); T_{da} is drying air temperature (°C); T_{aa} is ambient air temperature (°C); C_d = specific heat of dry mass of paddy ($1.109 \text{ kJ kg}^{-1} \text{ °C}^{-1}$); W_{w-dr} is weight of wet mass in FHP (kg); C_w = specific heat of water ($4.185 \text{ kJ kg}^{-1} \text{ °C}^{-1}$); W_{fh} is initial weight of FHP taken for drying (kg); MC_{fh} = initial moisture content of FHP (wb; decimal); W_{e-dr} is weight of moisture evaporated from FHP during drying (kg); MC_{sr} is final moisture content of FHP after drying, kept for storage (wb; decimal); h_{bm} is latent heat of vaporization of bound moisture present in the FHP (kJ kg^{-1}) [15]; mc_{fh} is moisture content of FHP (% wb).

2.2.1.2. Hot water soaking. Hot water soaking was performed in a temperature controlled shaking water bath (RSB-12, Remi Elektrotechnik Limited, India). The energy required for hot water soaking after drying process was determined using the following formulations:

$$E_{T-hsk} = E_{d-hsk} + E_{w-hsk} + E_{e-hsk} \quad (9)$$

where, E_{T-hsk} is theoretical energy absorbed by the SP during HWS (kJ); E_{d-hsk} is energy absorbed by the dry mass of SP during HWS (kJ) [Eq.(10)]; E_{w-hsk} is energy absorbed by the wet mass (grain moisture + soaking water) during HWS (kJ) [Eq.(12)]; E_{e-hsk} is energy used in evaporating moisture from soaking water (kJ) [Eq.(14)]

$$E_{d-hsk} = W_{d-hsk} \times C_d \times (T_{hsk} - T_{aa}) \quad (10)$$

$$W_{d-hsk} = W_{sr} \times (1 - MC_{sr}) \quad (11)$$

$$E_{w-hsk} = W_{w-hsk} \times C_w \times (T_{hsk} - T_{aa}) \quad (12)$$

$$W_{w-hsk} = W_{sr} \times [1 + (W : G)] - W_{d-hsk} \quad (13)$$

$$E_{e-hsk} = W_{e-hsk} \times h_{vs} \quad (14)$$

$$W_{e-hsk} = W_{hsk} - (W_a + W_r) \quad (15)$$

$$W_a = W_{sr} \times \left(\frac{MC_{hsk} - MC_{sr}}{1 - MC_{hsk}} \right) \quad (16)$$

where, W_{d-hsk} is weight of dry mass in SP (kg); T_{hsk} is soaking temperature (°C); W_{sr} which is " $W_{fh} - W_{e-dr}$ " is weight of SP taken for soaking (kg); W_{w-hsk} is weight of wet mass (grain moisture + soaking water) during HWS (kg); W_{hsk} is weight of water taken for HWS (kg); $(W : G)$ is water to grain ratio (by mass) during HWS (1.5:1); W_{e-hsk} is weight of moisture evaporated from soaking water during HWS (kg); h_{vs} is heat of vaporization at soaking temperature (2333 kJ kg^{-1}); W_a is weight of water absorbed by SP (kg); W_r is weight of water remaining after HWS (kg); MC_{hsk} is final moisture content of paddy after HWS (wb; decimal).

2.2.1.3. Microwave-assisted soaking. Microwave assisted soaking was done using a domestic microwave (Morphy Richards- 25CG, 2450 MHz, output power- 900 W, capacity- 25 l) in which the paddy sample was taken in a cylindrical glass container (Borosilicate, capacity- 1 l). Microwave-assisted soaking (MWS) was done with the optimized experimental condition obtained from our study [unpublished data] using the following equation:

$$E_{T-msk} = E_{d-msk} + E_{w-msk} + E_{e-msk} + E_{sk} \quad (17)$$

where E_{T-msk} is theoretical energy absorbed by FHP during MWS process (kJ); E_{d-msk} is energy absorbed by the dry mass of FHP during MWS (kJ); E_{w-msk} is energy absorbed by the wet mass (grain moisture + soaking water) during MWS (kJ); E_{e-msk} is energy used in evaporating moisture from soaking water (kJ); E_{sk} is energy absorbed by the soaking water, before adding to FHP (kJ).

The optimized condition was achieved at 420 W power soaked for 7 min with a bed height of 3 cm. All the expressions except E_{sk} were determined using similar formulation as mentioned in equations (10), (12) and (14). While the energy absorbed by soaking water, before adding to FHP was calculated with:

$$E_{sk} = W_{sk} \times C_w \times (T_{sk} - T_{aa}) \quad (18)$$

where W_{sk} is weight of soaking water that is calculated considering the water to grain ratio (2.5:1).

2.2.1.4. Steaming. Steaming of the soaked paddy was carried out inside an airtight pressure chamber (custom made, capacity- 10 l, maximum steam pressure 5 kg cm^{-2}) in which desired pressure was achieved using steam, supplied from a steam generator. The pressure steaming process (Fig. 3) was common for both conventional and microwave-assisted parboiling. Therefore, similar formulations were considered to determine the energy consumption during each process as mentioned below:

$$E_{T-st} = E_{d-st} + E_{w-st} \quad (19)$$

where, E_{T-st} is energy absorbed by the soaked paddy (SKP) during steaming (kJ); E_{d-st} is energy absorbed by the dry mass of SKP (kJ) [Eq. (20)]; E_{w-st} is energy absorbed by the wet mass during steaming (kJ) [Eq. (22)].

$$E_{d-st} = W_{d-st} \times C_d \times (T_{st} - T_{skp}) \quad (20)$$

$$W_{d-st} = W_{sk} \times (1 - MC_{sk}) \quad (21)$$

$$E_{w-st} = W_{w-st} \times C'_w \times (T_{st} - T_{skp}) \quad (22)$$

$$W_{w-st} = W_{sk} \times \left[MC_{sk} + \left(\frac{MC_{st} - MC_{sk}}{1 - MC_{st}} \right) \right] \quad (23)$$

where, W_{d-st} is weight of dry mass in SKP (kg); T_{st} is steaming temperature ($^{\circ}\text{C}$); T_{skp} is SKP temperature ($^{\circ}\text{C}$); W_{w-st} is weight of wet mass during steaming (kg); C'_w is specific heat of water at steaming temperature ($4.243 \text{ kJ kg}^{-1} \text{ }^{\circ}\text{C}^{-1}$); MC_{st} is final moisture content of SKP after steaming (wb; decimal).

2.2.1.5. Drying of steamed paddy. The same dryer used in case of drying FHP was also used for drying of steamed paddy (STP). Drying of STP was the last step in the complete conventional and microwave-assisted parboiling process, respectively.

$$E_{T-drst} = E_{e-drst} + E_{drst}^r \quad (24)$$

where, E_{T-drst} is theoretical energy absorbed by the steamed paddy during drying (kJ); E_{e-drst} is energy required to remove moisture from the steamed paddy (kJ) [Eq. (25)]; E_{drst}^r is reserved energy in steamed paddy capable of removing moisture (kJ) [Eq. (29)].

$$E_{e-drst} = W_{e-drst} \times h_{bm} \quad (25)$$

$$W_{e-drst} = W_{st} \times \left(\frac{MC_{st} - MC_{pb}}{1 - MC_{pb}} \right) \quad (26)$$

$$W_{st} = W_{sk} \times \left(1 + \frac{MC_{st} - MC_{sk}}{1 - MC_{st}} \right) \quad (27)$$

$$h_{bm} = h_{vd} + 291 \quad (28)$$

$$E_{drst}^r = E_{d-drst}^r + E_{w-drst}^r \quad (29)$$

$$E_{d-drst}^r = W_{d-drst} \times C_d \times (T_{st} - T_{da}) \quad (30)$$

$$W_{d-drst} = W_{st} \times (1 - MC_{st}) \quad (31)$$

$$E_{w-drst}^r = W_{w-drst} \times C_w \times (T_{st} - T_{da}) \quad (32)$$

$$W_{w-drst} = W_{st} - W_{d-drst} \quad (33a)$$

where, W_{e-drst} is weight of moisture evaporated from STP during drying (kg); h_{bm} is heat of vaporization of bound moisture present in STP (kJ kg^{-1}) [23]; MC_{pb} is moisture content of parboiled paddy (wb; decimal); h_{vd} is heat of vaporization of free water at drying temperature (2358 kJ kg^{-1}); E_{d-drst}^r is reserved energy in the dry mass of STP which dissipated before convective drying (kJ); E_{w-drst}^r

is reserved energy in the wet mass which dissipated before convective drying (kJ); W_{w-drst} is weight of wet mass in STP (kg); T_{st} is STP temperature ($^{\circ}\text{C}$); T_{da} is drying air temperature ($^{\circ}\text{C}$); W_{d-drst} is weight of dry mass in STP (kg).

2.2.2. Actual energy calculations

The actual energy consumption at each step was determined by dividing the efficiency factor by theoretical consumptions. All the equipment used in the current study were operated with an energy meter connected to the main power supply hence the power consumption and energy consumption (in term of kWh) in every single stage of CP and MWP were recorded at the no-load and full load conditions (not mentioned for the sake of brevity) and subsequently the efficiency factors were determined. The necessary efficiency factors and the actual energy formulation is described in Table 1.

2.3. Specific energy consumption

The SEC for each step was determined for both theoretical and actual scenarios. The specific consumption was evaluated by dividing the energy (theoretical or actual) with sample weight taken during each step of the parboiling processes. The formulation for estimating actual SEC is presented in Table 1. The theoretical value of SEC was calculated by omitting the efficiency terms used in the actual SEC equations (Table 1).

The overall energy required for the production of 1 kg of PBP through MWP and CP were evaluated using Eq. (33) and Eq. (34) respectively.

$$SEC_{pb}^{mw} = \frac{1}{W_{pb}^{mw}} \times (SEC_{msk}^{mw} \times W_{fh} + SEC_{st}^{mw} \times W_{sk} + SEC_{drst}^{mw} \times W_{st}) \quad (33b)$$

$$SEC_{pb}^c = \frac{1}{W_{pb}^c} \times (SEC_{dr}^c \times W_{fh} + SEC_{sk}^c \times W_{sr} + SEC_{st}^c \times W_{sk} + SEC_{drst}^c \times W_{st}) \quad (34)$$

where, SEC_{pb}^{mw} is specific energy consumption for production of 1 kg of PBP by MWP (kJ kg^{-1}); SEC_{pb}^c is specific energy consumption for production of 1 kg of PBP by CP (kJ kg^{-1}); W_{pb}^{mw} and W_{pb}^c are weight of PBP produced through MWP and CP (kg) which is " $W_{st} - W_{e-drst}$ "; rest of the values were taken from previous sections.

Table 1

Actual energy and SEC formulations used for each step of parboiling.

Steps	Actual energy (kJ)	Actual SEC (kJ kg^{-1})
Hot air drying	$\frac{E_{T-dr}}{\eta_{dr}}$	$\frac{E_{T-dr}}{\eta_{dr} \times W_{fh}}$
Hot water soaking	$\frac{E_{T-sk}}{\eta_{ht} \times \eta_{in}}$	$\frac{E_{T-sk}}{\eta_{ht} \times \eta_{in} \times W_{sr}}$
Microwave-assisted soaking	$\frac{E_{T-msk}}{\eta_{gen} \times \eta_{abs}}$	$\frac{E_{T-msk}}{\eta_{gen} \times \eta_{abs} \times W_{fh}}$
Steaming	$\frac{E_{T-st}}{\eta_{ht} \times \eta'_{in}}$	$\frac{E_{T-st}}{\eta_{ht} \times \eta'_{in} \times W_{sk}}$
Hot air drying of steamed paddy	$\frac{E_{T-drst}}{\eta_{dr}}$	$\frac{E_{T-drst}}{\eta_{dr} \times W_{st}}$

Where, η_{dr} is energy efficiency of dryer (0.27); η_{ht} is electrical to thermal energy conversion efficiency of the heating element (0.95); η_{in} is insulation efficiency of the soaking unit (0.85); η_{abs} is microwave absorption efficiency (0.57, unpublished data); η_{gen} is microwave generation efficiency (0.65, unpublished data); η'_{in} is insulation efficiency of the steaming unit (0.9).

2.4. Experimental uncertainty

The experimental uncertainties are inevitable during measurement executions that involves random electronic fluctuations or various influences of friction in the instrument or apparatus. Therefore, uncertainty analysis for individual equipment was carried to observe the randomness in the measured data using eq. (35) [24] and the total uncertainties of measured and calculated parameters are depicted in Table 2.

$$\omega_R = \left[\left(\frac{\partial R}{\partial x_1} \omega_1 \right)^2 + \left(\frac{\partial R}{\partial x_2} \omega_2 \right)^2 + \left(\frac{\partial R}{\partial x_3} \omega_3 \right)^2 + \dots + \left(\frac{\partial R}{\partial x_n} \omega_n \right)^2 \right]^{1/2} \quad (35)$$

2.5. Economic assessment

The cost analysis for the production of 1 tonne of PBP and the corresponding amount of PBR through MWP and CP was evaluated using the following equations. The value of electricity cost taken in this study was as per the state West Bengal, India which happens to be the highest paddy producing location of the country [25]. For industrial applications, the average cost per unit of electricity was 5.7 INR (kWh)⁻¹ [26].

$$C_{IN} = C_{RM} + C_{TE} + C_{ME} \quad (36)$$

$$C_{RM} = (W_{FH} \times C_{FH} + V_W \times C_W) \quad (37)$$

$$C_{TE} = \frac{W_{PB} \times SEC_{pb}}{3.6} \times C_{EU} \quad (38)$$

$$C_{ME} = (W_{FH} \times EC_C + W_{PB} \times EC_M + W_{HR} \times EC_B) \times C_{EU} \quad (39)$$

where, C_{IN} is cost of investment (INR); C_{RM} is cost of raw material (INR); C_{TE} is cost of thermal energy used during parboiling (INR); C_{ME} is cost of mechanical energy used during parboiling (INR); W_{FH} is weight of paddy taken for parboiling (tonne); C_{FH} is cost of FHP (14000 INR tonne⁻¹); V_W is volume of water taken for soaking (l); C_W is cost of water (0.35 INR l⁻¹); W_{PB} is weight of PBP produced (tonne); SEC_{pb} is refer to Eq.(33) and Eq.(34); C_{EU} is cost per electricity unit (5.7 INR kWh⁻¹); EC_C is energy consumption in pre-cleaning (kWh tonne⁻¹) [27]; EC_M is energy consumption in milling (kWh tonne⁻¹) [27]; W_{HR} is weight of head rice (tonne); EC_B is energy consumption in bagging (kWh tonne⁻¹) [27].

The net energy consumed during overall processing was evaluated using Eq. 40

$$C_{Net} = C_{IN} - C_{RC} \quad (40)$$

$$C_{RC} = C_{HE} + C_{BO} \quad (41)$$

$$C_{HE} = \left(\frac{W_H \times f_u \times \eta_{ht} \times HV}{3.6} \right) \times C_{EU} \quad (42)$$

$$C_{BO} = W_B \times C_B \quad (43)$$

where, C_{Net} is net cost invested (INR); C_{RC} is cost recovered from by-products (INR); C_{HE} is cost of thermal energy supplemented by husk as fuel (INR); C_{BO} is cost of bran to be used for oil extraction (INR); W_H is weight of husk produced after milling (0.22 times dry mass of paddy) [28]; f_u is fraction of husk used for heating (0.513) [29]; η_{ht} is efficiency of the heating unit (0.41) [30]; HV is heating value of husk (14,000 kJ kg⁻¹) [31]; W_B is weight of bran (tonne); C_B is cost of bran (17,500 INR tonne⁻¹).

Production cost for 1 tonne of PBR was evaluated using Eq.(44).

$$C_{PR} = \frac{C_{Net}}{HRE} \quad (44)$$

$$HRE = W_{PB} \times (HY \times 10 + MY \times BC \times 0.04) \quad (45)$$

where, C_{PR} is cost of production for 1 tonne of PBR; HRE is head rice equivalent (tonne); HRE is calculated considering the price of broken as 40% of that of head rice.

2.6. Grain quality assessment

2.6.1. Milling recovery

Parboiled paddy was dehulled using a laboratory model rubber roll sheller (Satake Engineering Co., Ltd., Tokyo, Japan). The milled kernels having at least 3/4th of the average kernel length were considered as head rice and the rest were considered as broken [32]. Separated fractions of head rice and broken grains were weighed individually. Milling yield (MY), head rice yield (HY), and broken percentage (BP), were calculated using Eq.(46), Eq.(47) and Eq.(48), respectively. Each experiment was conducted in triplicates.

$$MY = \frac{W_m}{W_p} \times 100. \quad (46)$$

$$HY = \frac{W_h}{W_p} \times 100. \quad (47)$$

$$BP = \frac{W_b}{W_m} \times 100. \quad (48)$$

where, W_m is weight of milled rice (kg); W_p is weight of PBP taken for milling (kg); W_h is weight of head rice (kg); W_b is weight of broken (kg).

2.6.2. Whiteness index

The whiteness index of the PBR kernels obtained through CP and MWP was determined by Digital/Fluorescence Whiteness Meter (WSB-3A, Arotek Scientific Instruments Pvt. Ltd., Thane, Maharashtra). The instrument was calibrated first with a standard black and white tile. The corresponding value for black tile was set at zero, whereas for white tile a pre-calibrated value (83) was set. Before analysis, the sample holder was overfilled and then compacted and levelled up to the brim by removing the surplus grains with the help of a levelling plate. The whiteness value of the sample was compared to understand the impact of the parboiling method on the whiteness of the kernel.

Table 2

Uncertainties of the measure quantities and calculated experimental parameters.

Parameter	Unit	Uncertainty
Temperature (drying unit)	°C	±0.20
Temperature (soaking unit)	°C	±0.12
Temperature (Steamer)	°C	±0.10
Microwave power	W	±3.68
Air velocity	ms ⁻¹	±0.14
Energy meter	kWh	±0.002
Pressure gauge (steamer)	kPa	±0.51
Moisture metre	%	±0.23
Whiteness metre	%	±0.36
Weighing balance	g	±0.001

2.6.3. Cooking quality

In the current study, two cooking qualities were considered i.e. cooking time and gruel loss. Optimal cooking time for the rice samples obtained from FHP and SP was estimated by the method described by Ref. [33]. 10 g of rice was cooked in water (grain to water ratio of 1:10) maintained at 95 °C (Water bath shaker RSB-12, Remi Elektrotechnik Limited, India). Five grains were removed at 1 min intervals and pressed between two glass slides to check the presence of any white core. The disappearance of the white core indicates the end of the cooking process. The gruel loss was analysed corresponding to the optimized cooking time. The remaining water after straining out the cooked rice was used for determining the gruel loss. 25 ml of cooking water was taken in a pre-weighed flask and kept in a hot air oven set at 65 °C for 24 h. After attaining a stable weight, the flask was reweighed. The percentage of gruel loss was calculated using the following equation [34]:

$$\text{Gruel loss (\%)} = \frac{\text{Weight of dried flask} - \text{Weight of empty flask}}{\text{Initial grain weight taken for cooking}} \times 100. \quad (49)$$

2.7. Statistical analysis

One-way analysis of variance (ANOVA) of the mean responses was conducted using Microsoft Excel 2010 (Microsoft Corporation, Washington, USA). The response values were presented as mean $\pm$ standard deviation of three replications of individual treatments.

3. Results and discussion

3.1. Thermal energy consumption assessment for MWP and CP

3.1.1. Soaking

The theoretical specific energy consumed in drying of FHP was 492.2 kJ kg⁻¹, but as mentioned in the introduction, supplied energy (actual energy consumption) may go higher by changing the drying condition and drying method. In the current study, the actual SEC value was 3.7 times higher than that of the theoretical value for hot water soaking (Table 3). The energy required in the drying of FHP is considered as an additional expense when parboiling is targeted further. The drying cost is expected to reduce by 30% by decreasing the harvesting moisture content of paddy from 22 to 17% wb [35]. Therefore, while calculating the energy consumption up to soaking (HWS) both initial drying of FHP and soaking of SP were considered. The theoretical and actual SEC for HWS were 466.8 and 578.08 kJ kg⁻¹, respectively. Whereas, the corresponding values for MWS were 1027.8 and 1872 kJ kg⁻¹ (for FHP). Even though the initial moisture content of paddy in both the soaking methods was different, the final moisture contents were targeted to be similar. The reasons for which SEC in the case of MWS is higher is due to the energy required in heating of water before MWS and lower conversion efficiency from supplied electrical energy to effective thermal energy (36.56%) [36]. An additional reason for the same could be a lower hydration rate in FHP as compared to SP [37]. The husk layer in FHP is expected to be the reason behind the slower diffusion, as earlier reporting suggested an increase in cooking time of rice due to ageing [38]. A comparative presentation of energy consumed to produce 1 kg of SKP is shown in Fig. 4 (a). An overall energy saving of 20.48% was achieved through MWS.

3.1.2. Steaming

Values of SEC for steaming are shown in Table 3. Even though the same steaming treatment was given on SKP obtained from both the soaking method, the energy requirement differed because of the difference in temperature of SKP when steaming was initiated. The SKP obtained through MWS possesses a higher temperature due to the volumetric heating phenomena of microwave heating [15]. Therefore, the steaming time required during MWP was reduced by almost 50%. Moreover, the SEC for steaming during MWP was found to be 78.22 kJ kg⁻¹ which is lower than the previously reported SEC values for steaming in the range of 88–270.57 kJ kg⁻¹ (Table 3). As compared to the CP, the energy required for steaming was reduced by 48.47% in the case of MWP. However, an overall energy savings of 22.1% was achieved in the MWP up to steaming (Fig. 4 (a)).

3.1.3. Drying

The energy consumption data obtained from drying of STP is presented in Table 3. A decrease in SEC for drying of STP (during CP) was observed as compared to SEC for drying of FHP that can be attributed to increased husk permeability in the former case. However, in MWP the SEC for drying of STP was comparable to SEC for drying of FHP. This might be due to a higher degree of gelatinization in STP that hinders moisture migration and/or a lesser degree of increase in husk permeability in FHP. Obtained values of SEC for drying of STP in the current study fall in the range proposed by Rao et al. [39]. The overall energy consumption in producing dried parboiled paddy using MWP decreased by 10.1% as compared to CP (Table 3). Moreover, the overall processing time reduced from 11.31 h to 4.40 h (Fig. 4(b)). Even the time required in initial drying was eliminated, there was a 43.22% decrease in processing time in the case of MWP.

3.1.4. Parboiling

The SEC for parboiling was higher for CP than MWP (Table 3). Elimination of initial drying and higher temperature of SKP before steaming were responsible for the decrease in SEC. However, the decrease is in the range of ~10% but, it also depends on the scale of production and instrumental efficiencies. Additionally, the husk produced during rice milling may also be utilized for partial fulfilment of thermal energy requirement (sub-section 3.3.1). It can be assumed that if 50% of the globally produced FHP are parboiled using the proposed method, the calculated saving in energy will be around 9.25×10^3 GWh. A corresponding decline in CO₂ emission will be expected due to a decrease in electricity generation [40].

3.2. Economic assessment of MWP and CP

The cost of energy supplied for parboiling may vary from country to country depending upon source and availability of energy, conversion efficiency of primary energy into thermal energy, and local taxes. In the current study, electrical energy is taken as the primary energy and hence the number of electrical units required for CP and MWP will be universally persistent. The number of electrical units (kWh) required to produce, and process 1 tonne of parboiled paddy was calculated to be 1453 and 1311 for CP and MWP respectively. The overall cost of investment and recovery are given in Table 4. A total saving of 1583 INR per tonne of PBR production was achieved in the proposed method as compared to the conventional practice. A yearly saving of around 102.89 billion INR (~1.38 billion USD) can be achieved, even if half of the existing parboiling practice is modified to MWP. However, the recovery cost from the by-products can additionally be expanded by utilizing bran and husk for biodiesel production [46] biogas production [47], respectively. For adopting the proposed method on an industrial

Table 3
Specific energy consumption in different stages of paddy parboiling.

Processing step	CP		MWP		Previous study	
	SEC _T (kJ kg ⁻¹)	SEC _A (kJ kg ⁻¹)	SEC _T (kJ kg ⁻¹)	SEC _A (kJ kg ⁻¹)	SEC (kJ kg ⁻¹)	Reference
Drying (FHP)	492.2	1822.96				
L.S.U. dryer (husk fired)					977.7	[27]
Deep bed convective drying					649–4126	[9]
Horizontal rotary dryer					17,000–53,860*	[41]
Semi-industrial microwave dryer					49,780*	[42]
Soaking	466.8	578.08	1027.8	1872		
Hot water soaking					360	[42]
Pressure soaking					251.31	[43]
Hot water soaking (fuel wood)					210–1500	[21]
Hot water soaking (husk fired)					1898	[27]
Steaming	129.78	151.79	66.88	78.22		
Boiler steaming (husk fired)					88	[27]
Atmospheric pressure steaming					270.57	[27]
Open kettle steaming					276	[43]
Boiler steaming					105	[31]
Drying (STP)	474.59	1757.65	490.27	1815.54		
Hot air drying					573.34	[27]
LSU dryer					826	[23]
Hot air drying (theoretical)					574	[31]
Convective air drying					1770–2229	[39]
Parboiling	1787.64	5079.15	1876.89	4567.08		
Boiler less parboiling					1450–2440	[44]
Industrial parboiling					1260–3310	[45]
Boiler less parboiling					5862	[6]
Three stone fire parboiling					15303	[7]

N.B. SEC- specific energy consumption per kg of paddy, FHP- freshly harvested paddy, STP- steamed paddy.

#- SEC (kJ per kg of moisture evaporated).

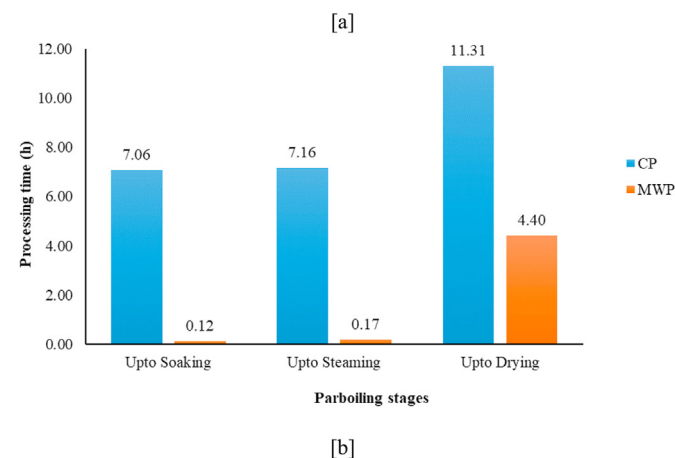
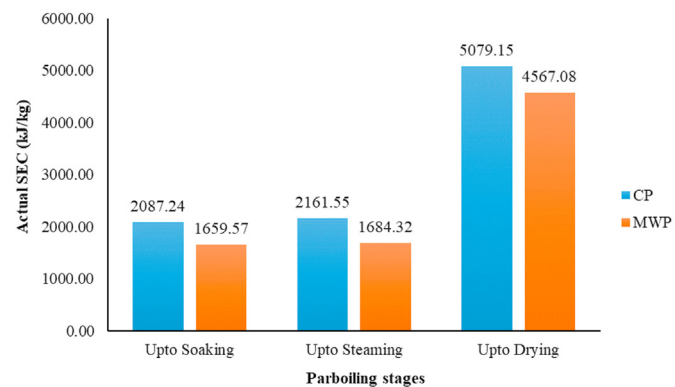


Fig. 4. Comparison of (a) Actual SEC and (b) processing time between MWP and CP.

Table 4
Economic assessment of parboiled rice production in CP and MWP.

Parameters	Values	
	CP	MWP
Raw material cost (INR)		
Freshly harvested paddy	15,638	15,638
Water	525	875
Mechanical energy cost (INR)		
(pre-cleaning, milling, bagging)	241.53	241.88
Thermal energy cost (INR)		
(Parboiling)	8,042	7,231
Recovery cost from by-products (INR)		
Energy from husk	958.57	957.17
Bran	827.75	812
Net investment (INR)	22,660	22,216
Head rice equivalent (tonne)	0.705	0.727
Production cost of parboiled rice (INR tonne ⁻¹)	32,142	30,559

N.B. Cost of different parameters are per processing of 1 tonne of FHP.

scale, high MW efficiency [69] and less manpower requirement (owing to lesser processing steps) will further reduce the production cost. Besides, due to a higher whiteness (sub-section 3.3.2) index, the selling price of PBR is also anticipated to increase. Hence, the profit margin will be significantly higher for PBR produced through MWP.

3.3. Quality assessment of grains produced through MWP and CP

3.3.1. Milling recovery

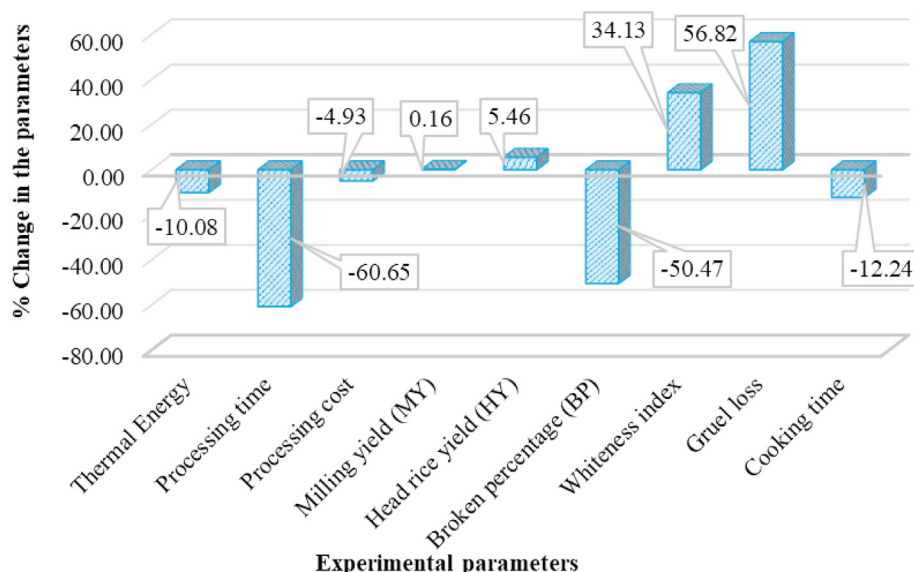
In the present study, there was not much difference in MY but higher HY and lower BP was observed in case of MWP (Table 5). The significant reduction in the BP value in the case of MWP can be attributed to the MWS step which is expected to induce more uniform moisture distribution within the rice kernel as compared to the conventional HWS. Another strong supporting explanation

Table 5

Values of different processing parameters in MWP and CP.

Method	MY (%)	HY (%)	BP (%)	Whiteness	Cooking time (min)	Gruel loss (%)
CP	74.71 ^a ±0.90	67.62 ^b ± 0.69	9.49 ^d ± 0.11	13.36 ^f ±0.06	24.5 ^h ± 0.50	2.20 ⁱ ±0.01
MWP	74.83 ^a ±1.13	71.31 ^c ±0.36	4.70 ^e ±0.064	17.92 ^g ± 0.17	21.5 ⁱ ±0.50	3.45 ^k ±0.02

N.B. Values of MY, HY, BP, whiteness, cooking time and gruel loss are presented as mean ± standard deviation. Same letter within the row indicating non-significant difference between the treatments; different letter within the row indicating significant difference between the treatments.

**Fig. 5.** Percentage change in various parameters for MWP as compared to CP.

for the same could be the inherently lower hardness of FHP as compared to the SP [38] which were taken as the raw material for MWP and CP respectively. It was reported that the internal cracks that remain after soaking, stay even after steaming if gelatinization is incomplete and reappear during drying [48]. However, complete gelatinization is not required to get maximum HY as reported by Marshall et al. [49] and Taghinezhad et al. [50]. From the current observation, it can be concluded that volumetric heating and partial gelatinization of rice starch during MWS are the two most important reasons behind the superior milling quality of parboiled paddy obtained through MWP.

3.3.2. Whiteness index

The whiteness value of PBR obtained through CP and MWP are presented in Table 5. PBR, in general, has a low whiteness index, attained in three phases i.e. long-term storage, soaking, and steaming [51–53]. In the present study, PBR obtained through MWP had shown 34.13% higher whiteness value than that of CP. The reason for the same is the short soaking duration in MWS that causes limited migration of pigments from bran and hull and secondly, elimination of storage step in case of FHP. Even if the overall parboiling time is considered then the paddy has short exposure to thermal treatment in the case of MWP as compared to CP. As discussed earlier (subsection 3.2) the lighter colour of the PBR would fetch additional profit due to higher consumer preference.

3.3.3. Cooking quality

Rice obtained from FHP gets deformed at a lower cooking time before attaining the desired texture whereas parboiled rice takes longer cooking time to achieve higher swelling index as compared to raw rice. Therefore, optimum cooking time is considered as a useful indicator of cooking quality of cooking quality [22,54]. The

overall comparison of cooking qualities between CP and MWP are shown in Table 5. There was a significant decrease in the cooking time of PBR produced through MWP whereas, the gruel loss was found to be lower for that of CP. One of the prime reasons for the same could be the existing variability in the paddy as raw material due to aging [38]. For instance, the gruel loss during cooking of rice obtained from untreated FHP and SP were $10.65 \pm 0.03\%$ and $3.60 \pm 0.041\%$ respectively [36]. This indicates the remarkable improvement in cooking quality due to MWP even without storing the paddy. However, if the untreated stored rice and PBR (through MWP) were compared then the difference in gruel loss was insignificant which implies the possibilities of using the proposed method for accelerated aging of FHP. As compared to their untreated counterparts, the percentage increase in cooking time for MWP and CP was 43.33% and 32.43%, respectively. Although there is a higher increase in cooking time due to MWP, it is important to note here that the untreated rice from FHP deformed before it was cooked properly [36]. Apart from this the cooked rice colour was darker for the one processed through CP, which could be related to the whiteness value of PBR demonstrated in subsection 3.3.2.

4. Conclusions

In the current work, a unique approach of parboiling is proposed in which FHP was taken as the raw material for parboiling and conventional HWS was replaced by MWS. For CP low moisture stored paddy was taken and HWS was adopted whereas, for MWP high moisture FHP was taken and MWS was performed. An overall energy saving of 20.48% was observed when the HWS was replaced by MWS. Moreover, the soaked paddy obtained through MWS possesses higher temperature due to the volumetric heating phenomena of microwave treatment hence, required lower steaming

time during MWP. Based on the energy consumption and economic requirement observed in the current study, it can be assumed that if 50% of the globally produced FHP are parboiled using the MWP, energy savings of approximately 9.25×10^3 GWh and financial savings of around ~1.38 billion USD can be achieved per year.

From the quality point of view, there was not much difference in MY but higher HY and lower BP was observed in the case of MWP. The PBR obtained through MWP had shown a 34.13% higher whiteness value than that of CP. There was a significant decrease in the cooking time of PBR produced through MWP whereas, the gruel loss was found to be lower in the case of CP. The percentage change in the various parameters is presented in Fig. 5 when the MWP was replaced by CP.

It is pretty clear from the current study that, with the replacement of initial drying of FHP and use of a cleaner and energy-efficient heating technique like microwave, the developed parboiling would be eco-friendly and a feasible alternative to the CP methods.

Credit author statement

Brajesh Kumar Panda: Conceptualization, Methodology, Investigation, writing original draft. Gayatri Mishra: experimental support, literature review. Shubham Subrot Panigrahi: literature review and editing. Shanker Lal Shrivastava: Project administration.

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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