International Journal of Research in Agronomy 2025; 8(12): 448-453

E-ISSN: 2618-0618
P-ISSN: 2618-060X

NAAS Rating (2025): 5.20
www.agronomyjournals.com
2025; 8(12): 448-453
Received: 06-11-2025
Accepted: 09-12-2025

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Impact of ultrasound as a pretreatment on the malting properties of Ragi and foxtail millet

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DOI: https://www.doi.org/

Abstract
Ultrasound pretreatment of cereal grains has been shown to have positive effects on their malting properties in the literature. As millets are highly nutritious and climate-resilient crops, this study focuses on using ultrasound pretreatment to enhance malting of *Eleusine coracana* (ragi) and *Setaria italica* (foxtail millet). Soaking kinetics and germination efficiency were evaluated after treating the samples with ultrasound using a 25kHz probe sonicator (6mm probe diameter) at amplitudes of 20% and 40% for 60s and 120s, respectively, with a pulse of 3s on and 6s off at 298K, corresponding to power densities between 597 and 1195 W/L^{-1}. Soaking kinetics were modelled using the Peleg, Page, Weibull, and Midilli empirical models, where the Midilli model gave the best fit ($R^2 > 0.98$). Ultrasound reduced soaking time by 20-30% compared to untreated control seed samples. This enhanced mass transfer can be attributed to the micropores created by ultrasound. Germination also improved with enhanced seed viability and germination capacity after ultrasonication. Ragi treated with a 40% amplitude for 60 seconds showed a maximum GR of 71.11% and dormancy of 28.89%. Similarly, foxtail millet also showed the best improvement, with a GR of 75.56% under the same treatment combinations. Among all the treatment conditions, moderate ones (40%, 60s) effectively enhanced soaking and germination compared to treatments of longer durations (120s). This validates ultrasound as a sustainable, non-thermal technology for improving the overall malting and functional qualities of millet grains, which require further research and investigation.

Keywords: Ultrasound, soaking, germination, millets, pretreatment

1. Introduction

Research on millets, specifically Finger millet or Ragi (*Eleusine coracana)* and Foxtail millets or Kangni (*Setaria italica*), has gained popularity due to their high nutritional value and suitability for developing healthy foods rich in dietary fibre, bioactive compounds, antioxidants, and other minerals, while also demonstrating climate-resilient production [1-5]. Malting improves nutrient bioavailability, protein digestibility, phenolic content and antioxidant activity. However, a longer soaking time causes the leaching of nutrients and promotes microbial growth [6-8].The tough seed coats and antinutrients of millet increase soaking time, affect germination and reduce nutrient bioavailability [9-11]. To tackle these limitations, ultrasound pretreatment emerged as a clean and green novel technology that is effective in accelerating the hydration and germination of seeds. Ultrasound works through acoustic cavitation, where the formation and collapse of microbubbles create high-pressure, high-temperature zones, enhancing mass transfer, softening the seed coat, increasing membrane permeability, and stimulating early metabolic and enzymatic activity [12-16]. In Barley, 20 kHz sonication improved germination yield by 4-6.5% reducing germination time by 45% [17]. Milk thistle seeds treated with a 24kHz, 400W probe system showed nearly double root length and significantly improved vigour indices [18]. Studies also showed improved germination in wheat, mung bean, lentil, adzuki bean, tomato, kidney bean, chickpea, peanut and soyabean under bath frequencies of 25-45kHz due to increased permeability and enzyme activation [19-23]. Ultrasound pretreatment of the millet seeds thus has the potential to affect the hard seed coats and improve hydration and germination. To study hydration, empirical models such as the Peleg, Page, Weibull, and Midilli models are widely used in food grains [24-27]. These models are used extensively to estimate hydration rate constants, equilibrium moisture uptake, and the entire hydration behaviour of many grains;

however, limited scientific work is available on ultrasound-assisted hydration and malting of ragi and foxtail millet, where a probe sonicator is used for pretreatment. Therefore, this study aims to investigate the influence of ultrasound pretreatment of millet seeds using a probe sonicator and to study the hydration and malting behaviour using different kinetic models, as well as analysing germination traits, such as germination, dormancy, and root-shoot development, to identify the optimal ultrasound treatment under our experimental design.

2. Materials and Methods

Finger Millets (Ragi) and Foxtail Millets (Kangni) were collected from a local farmer in Jajpur, Odisha, and Uttar Dinajpur, West Bengal, India, respectively. The initial moisture content of finger millet was found to be 6.5%, and that of foxtail millet was 5.5%, as calculated using a moisture analyser (Aczet MB-50). The millets were treated with ultrasound using a probe sonicator (PRO Scientific, Model PRO656, Touchscreen Series, USA), as shown in Fig. 1, equipped with a 6mm titanium probe and operating at a frequency of 25kHz. A total of eight treatments, as shown in Table 1, were designed using two amplitudes (20% and 40%) and two treatment times (60 and 120 seconds), applied in a pulsed manner (3 seconds on and 6 seconds off) mode. Seeds (0.005kg) in 0.08 L of distilled water were treated in a beaker at a temperature of 298 K. The distance between the probe tip and the samples was maintained at more than 4 cm, and the probe was immersed 2 cm into the water. For amplitudes of 20% and 40%, the input power was 130W and 260W, respectively. The change in temperature was 95.59 K for 60s and 49.79 K for 120s. The power densities were 1194.84 W/L for a 60s treatment and 597.42 W/L for a 120s treatment, showing that short treatments delivered higher energy for this experimental design. Output acoustic power and power densities were quantified calorimetrically using temperature rise during treatment and treatment time [28]. Ultrasound-pretreated seeds were soaked (12h) and germinated (7 days). During soaking, changes in weight were checked at 2-hour intervals until 12 hours using an analytical balance. The 24th hour reading was also taken for analysis. For model fitting, the moisture content at each interval on a dry basis% was calculated using the mass balance method [29], considering the initial weight (5g) and initial moisture contents. This study employed the empericals models-the Peleg Model, $M_t = M_0 + \frac{t}{K_1 + K_2 t}$, the Page model $MR = \exp(-K_3 . t^n)$, the Weibull model $MR = \exp\left(-\left(\frac{t}{\alpha}\right)^{\beta}\right)$, and the Midilli model $MR = a . \exp(-K_4 . t^n) + bt$ to explain the hydration behaviour and soaking time needed for the millets. Here, M_t is the moisture content at time t, M_0 is the initial moisture content, K shows the rate constant, M_e is the equilibrium moisture content, n is a dimensionless empirical exponent, α is the scale parameter (time to reach ~63.2% of total change), and β is the shape parameter. The moisture ratio (MR) was calculated as $MR = \frac{M_t - M_e}{M_0 - M_e}$, where M_e is the 24th hour moisture content. A non-linear least square method with a trust-region-reflective algorithm was used in MATLAB to estimate model parameters (Fig. 3). The treated samples were compared with the two control samples of Ragi (R) and Foxtail (F) millets. On the 7th day of germination, seed viability (SV), root length (RL), and shoot length (SL) were recorded, and the seeds were then kiln-dried at 45 °C for 6 hours. The seed weight (SW), root weight (RW) and shoot weight (SW) were collected for analysis. The entire data was collected in triplicate to minimise the errors. Table 2 shows the calculated germination rate (GR %), dormancy rate (DR %), germination capacity (GC%), malting loss (ML%), malting yield (MY%) and seed vigour indexes (SVI-I AND SVI-II) [30, 31].

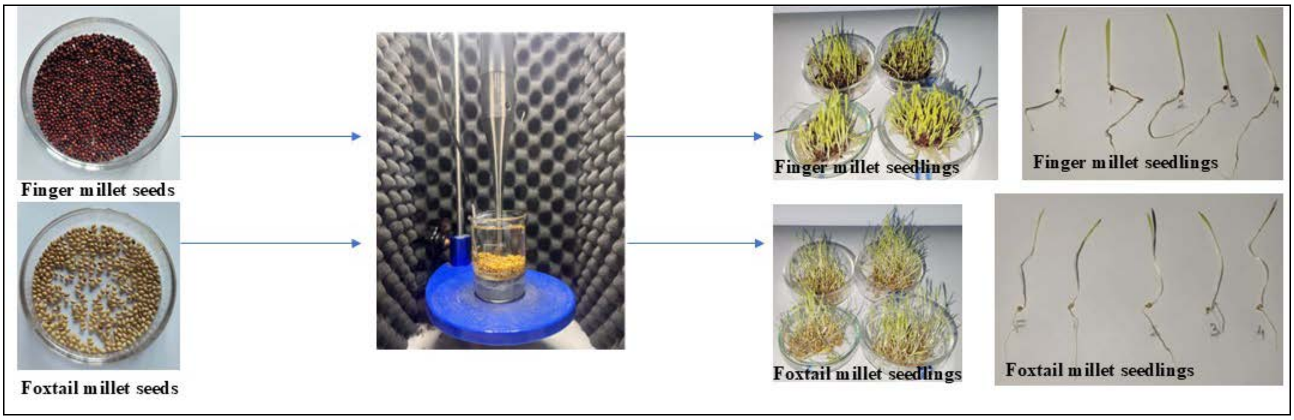


Fig 1: The figure illustrates the method of ultrasound treatment using a probe and germination.

3. Results and Discussions

Empirical Model Analysis

Both millets exhibited an initial rapid uptake, followed by slower hydration towards equilibrium (Fig. 3). Ultrasound pretreatment enhanced the kinetic behaviour observed in the analysis of the empirical model fits. Table 1 shows that the Midilli model outperformed others with R^2 (0.9972 to 0.99996) and RMSE (0.0017). The parameters K_4 decreased markedly under optimal conditions from 0.957 in the control sample of Ragi to 0.0586 in Treatment 2, and from 0.8058 in the control foxtail to 0.338 in Treatment 6, indicating faster moisture uptake. Diffusion. The exponent n, within the range of 0.49-0.78, indicated a mixed Fickian and non-Fickian transport mechanism, with ultrasound yielding higher values of n, indicating faster hydration. The Peleg parameters supported the acceleration of initial hydration with ultrasound, reducing K_1 from 1.936 in the R-control to the lowest value of 1.580 in Treatment 3, and in foxtail from 0.475 in the F-control to 0.475-0.798 across all treatments, confirming the enhancement of initial water uptake. K_2 of 0.294 in F-control to 0.249 in Treatment 8 indicated a faster approach to equilibrium. In the page model, K_3 increased under ultrasound from 1.329 in Treatment 3 to 0.814 in Treatment 7, and discussion exponents were higher in treated seeds (n = 0.71-0.78 in foxtail, showing improved water uptake. The Weibull shape parameters (α) decreased in the most responsive treatments (e.g., α = 0.88 in 3-20%120s, α = 1.15 in F-control, α = 1.27-3.86 in treated foxtail), consistent with faster early-phase hydration under acoustic cavitation and structural modification. Hence, these model parameters show that the ultrasound pretreatment accelerates both the initial absorption phase (lower Peleg K_1, higher Page K_3) and the later diffusion-controlled phase (higher Midilli n, lower Peleg K_2). The exceptionally high Midilli R^2 values (>0.998 for most treatments and 0.999956 for F-8) confirm that this model most effectively captures the combined exponential and linear transport behaviour induced by ultrasound.

Using the Midilli model and defining hydration completion as 95% of equilibrium moisture (MR = 0.05), the model gave the lowest time to reach 95% hydration at Treatment 3, where t_{95} =5.1609 represents a 28.075% reduction compared to the control ragi, and for foxtail greatest reduction was for 7-20%120s, where t_{95}=7.4224 gave a 29.89% reduction.

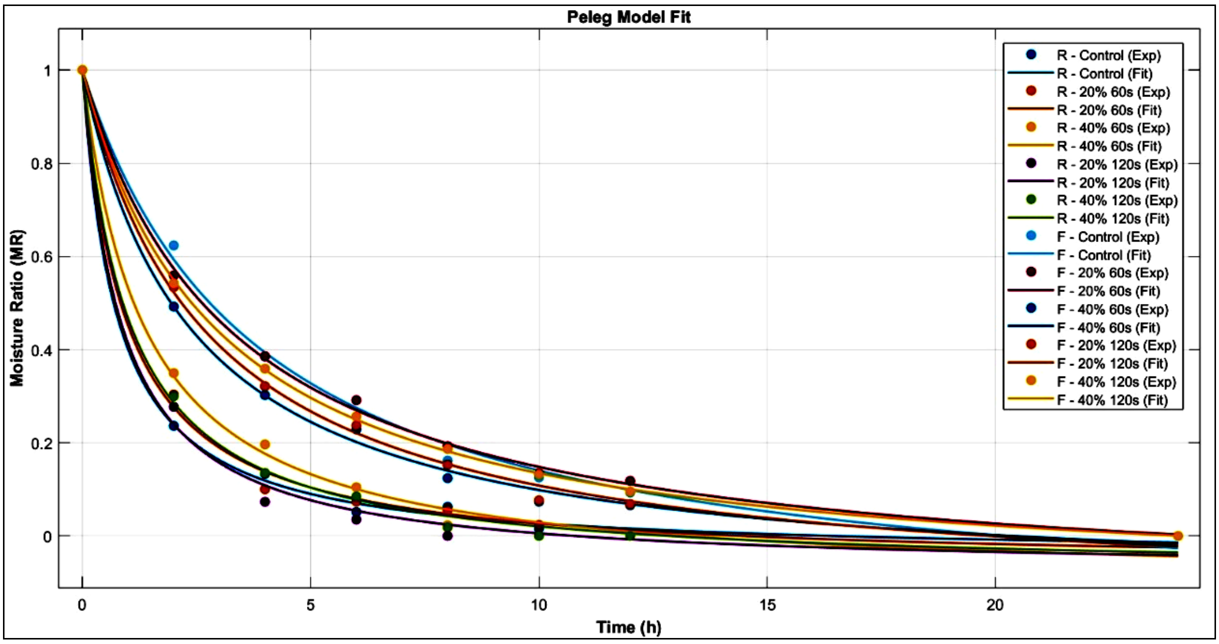
Germination Analysis

Depending on exposure time and amplitude, ultrasound enhances the germination performance (Table 2). Treatment 2 produced the best germination performance, with GR% increasing from 51.11% in the control to 71.11%, while reducing dormancy from 48.89% to 28.89%. This increased the GC% from 2.22% to 42.22%, accompanied by the highest SVI-I (590.22) and SVI-II (0.144), indicating better seedling development. A comparable response was observed in foxtail millet, where Treatment 6 enhanced the germination rate from 63.33% to 75.56%, reduced dormancy by 12.22 percentage points, and yielded the maximum germination capacity (51.11%), with the highest SVI-I of 414.93, indicating better seedling growth and mass. Thus, the 60s treatment consistently performed better, suggesting that short-time, moderate-intensity sonication pulses can also be used to enhance germination and soaking of seeds under the stated experimental conditions for Ragi and Foxtail millet seeds.

Fig 2: The figure shows the germinated seedlings after 7th day.

Table 1: Summary of the empirical models.

Models	Parameters	R-Control	1-20%60s	2-40%60s	3-20%120s	4- 40%120s	F-Control	5-20%60s	6-40%60s	7-20%120s	8-40%120s
Peleg	K_1	1.93689	2.33094	3.12662	1.58036	2.09044	0.475108	0.798357	1.68212	1.14745	0.47558
	K_2	2.59939	2.47393	2.311	0.69153	1.21785	0.294705	0.761147	1.15394	0.633185	0.249366
	R^2	0.998169	0.996223	0.994574	0.999131	0.998508	0.999781	0.999473	0.999031	0.999231	0.999781
	RMSE	0.004977	0.007404	0.009256	0.003351	0.004901	0.001215	0.00202	0.002956	0.002143	0.001215
Page	K_3	0.944435	0.733475	0.578673	1.32929	0.886586	0.8058	0.338379	0.575459	0.814244	0.359008
	n	0.588243	0.739301	0.805159	0.489099	0.60082	0.536225	0.776872	0.714653	0.629247	0.752333
	R^2	0.998317	0.997904	0.996943	0.999721	0.998844	0.99868	0.99868	0.998049	0.998629	0.999313
	RMSE	0.012966	0.014551	0.017723	0.00736	0.011645	0.003518	0.004115	0.005518	0.003008	0.00788
Weibull	α	1.10206	1.52084	1.97267	0.880781	1.21291	1.15119	3.86227	2.39947	1.27972	3.9026
	β	0.588243	0.739301	0.805159	0.489099	0.60082	0.536225	0.776872	0.714653	0.629247	0.752333
	R^2	0.998317	0.997904	0.996943	0.999721	0.998844	0.99868	0.99868	0.998049	0.998629	0.999313
	RMSE	0.012966	0.014551	0.017723	0.00736	0.011645	0.003518	0.004115	0.005518	0.003008	0.00788
Midilli	a	0.999883	1.0004	0.999038	1.00002	1.00007	1.00007	1.00035	1.00022	1.0001	1.00004
	K_4	0.957058	0.730463	0.586604	1.32929	0.886586	0.8058	0.338379	0.575459	0.814244	0.371207
	n	0.570211	0.745208	0.78414	0.489096	0.600826	0.536218	0.776872	0.714653	0.629246	0.716872
	b	-0.00037	0.00011	-0.00062	-0.00029	-0.00065	-0.00071	-0.00113	-0.0011	-0.00087	-0.00113
	R^2	0.998415	0.997914	0.997263	0.999721	0.998844	0.998194	0.999131	0.99831	0.998629	0.999956
	RMSE	0.012584	0.014516	0.016772	0.00736	0.011645	0.003635	0.001743	0.004976	0.003008	0.001985


Peleg Model Fit
Moisture Ratio (MR)
Time (h)
R - Control (Exp)
R - Control (Fit)
R - 20% 60s (Exp)
R - 20% 60s (Fit)
R - 40% 60s (Exp)
R - 40% 60s (Fit)
R - 20% 120s (Exp)
R - 20% 120s (Fit)
R - 40% 120s (Exp)
R - 40% 120s (Fit)
F - Control (Exp)
F - Control (Fit)
F - 20% 60s (Exp)
F - 20% 60s (Fit)
F - 40% 60s (Exp)
F - 40% 60s (Fit)
F - 20% 120s (Exp)
F - 20% 120s (Fit)
F - 40% 120s (Exp)
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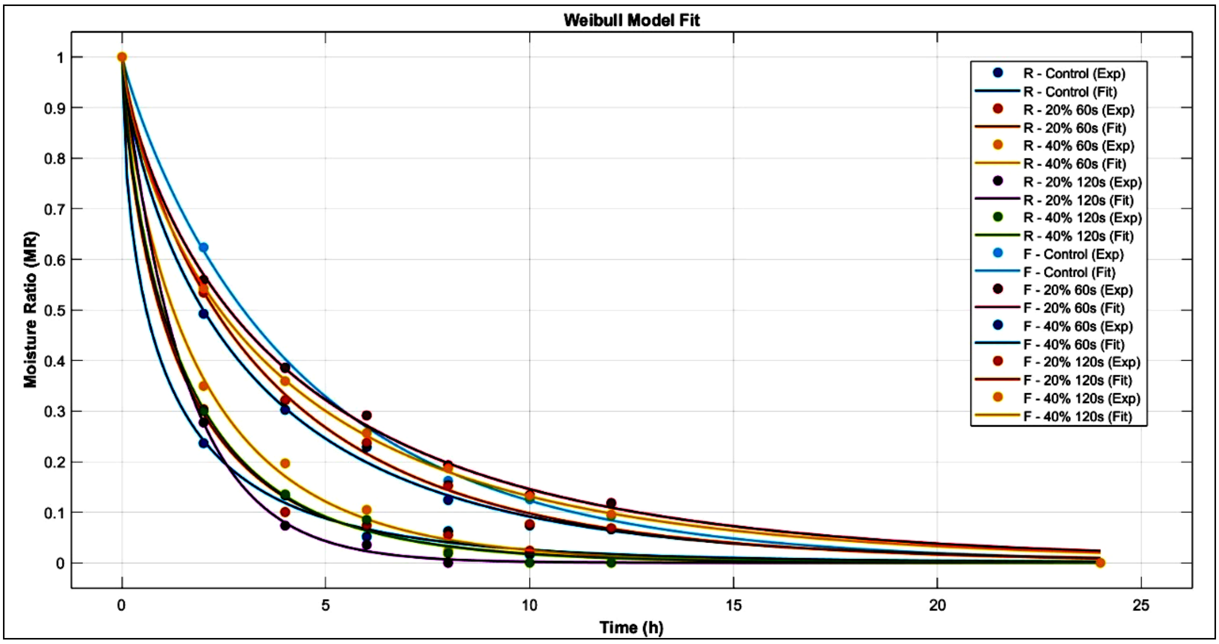
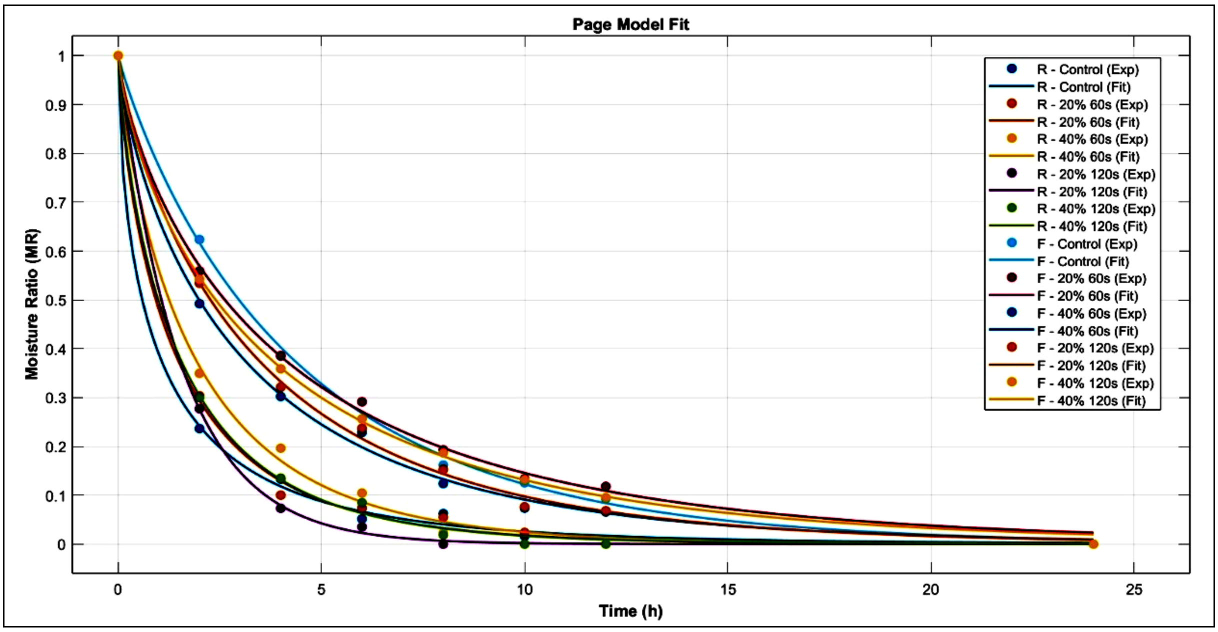

Weibull Model Fit
Moisture Ratio (MR)
Time (h)
R - Control (Exp)
R - Control (Fit)
R - 20% 60s (Exp)
R - 20% 60s (Fit)
R - 40% 60s (Exp)
R - 40% 60s (Fit)
R - 20% 120s (Exp)
R - 20% 120s (Fit)
R - 40% 120s (Exp)
R - 40% 120s (Fit)
F - Control (Exp)
F - Control (Fit)
F - 20% 60s (Exp)
F - 20% 60s (Fit)
F - 40% 60s (Exp)
F - 40% 60s (Fit)
F - 20% 120s (Exp)
F - 20% 120s (Fit)
F - 40% 120s (Exp)
F - 40% 120s (Fit)


Page Model Fit
Moisture Ratio (MR)
Time (h)
R - Control (Exp)
R - Control (Fit)
R - 20% 60s (Exp)
R - 20% 60s (Fit)
R - 40% 60s (Exp)
R - 40% 60s (Fit)
R - 20% 120s (Exp)
R - 20% 120s (Fit)
R - 40% 120s (Exp)
R - 40% 120s (Fit)
F - Control (Exp)
F - Control (Fit)
F - 20% 60s (Exp)
F - 20% 60s (Fit)
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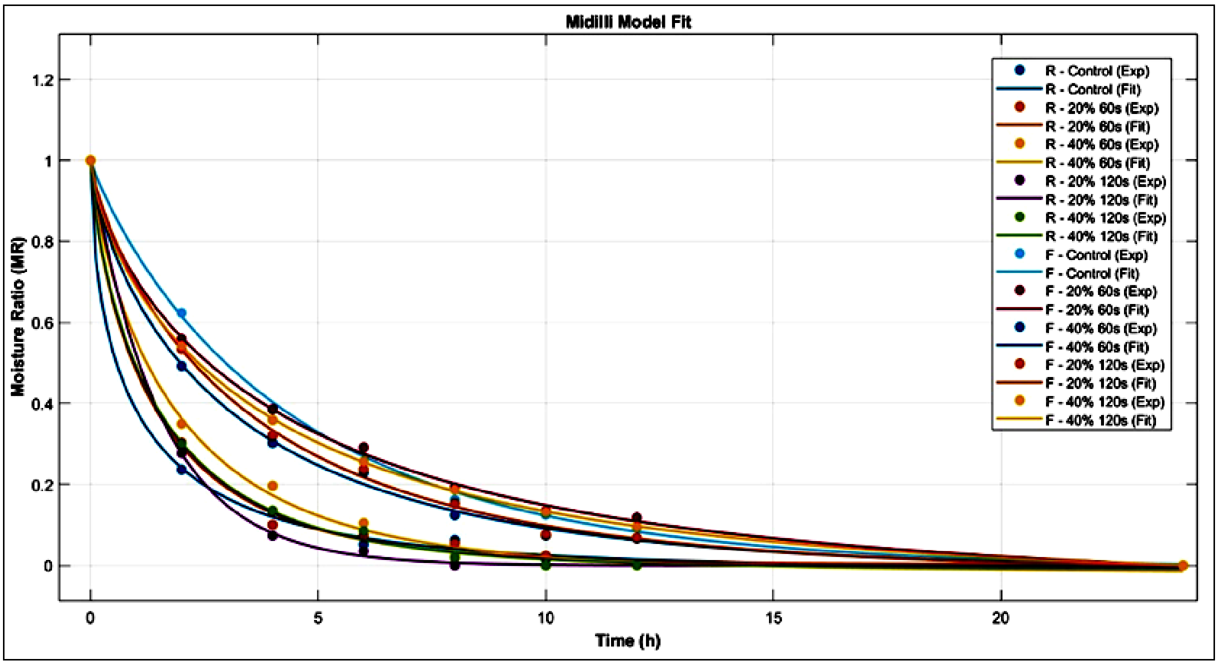

Fig 3: The graphs show the Peleg, Page, Weibull and Midilli empirical model fit curves for all eight treatments and two control samples.

Table 2: Summary of the parameters of Germination showing GR%, DR%, GC%, ML%, MY%, SVI-I, SVI-II

Samples	Total Treatment Time (s)	Amplitude (%)	Germination Rate%	Dormancy Rate%	Germination Capacity%	Malting Loss%	Malting Yield%	Seed Vigour Index- I	Seed Vigour Index- II
R	0	0	51.11111111	48.88888889	2.222222222	32.45135479	67.54864521	345.8518519	0.1122222222
1	60	20%	62.22222222	37.77777778	24.44444444	51.28205128	48.71794872	470.8148148	0.1366666667
2	60	40%	71.11111111	28.88888889	42.22222222	57.26495726	42.73504274	590.2222222	0.1444444444
3	120	20%	54.44444444	45.55555556	8.888888889	43.58974359	56.41025641	390.1851852	0.1155555556
4	120	40%	58.88888889	41.11111111	17.77777778	51.70940171	48.29059829	432.2444444	0.1188888889
F	0	0	63.33333333	36.66666667	26.66666667	51.147343	48.852657	299.7777778	0.04966666667
5	60	20%	65.55555556	34.44444444	31.11111111	53.92512077	46.07487923	323.7351852	0.05844444444
6	60	40%	75.55555556	24.44444444	51.11111111	60.26570048	39.73429952	414.9259259	0.05744444444
7	120	20%	67.77777778	32.22222222	35.55555556	54.89130435	45.10869565	299.1259259	0.04977777778
8	120	40%	72.22222222	27.77777778	44.44444444	60.62801932	39.37198068	344.8611111	0.05211111111

4. Conclusions

This study explains how ultrasound pretreatment can be used as a rapid, chemical-free method to non-thermally treat seeds, thereby enhancing soaking and germination during the malting of minor millets, including Finger and Foxtail. Empirical modelling revealed an acceleration of water uptake by reducing Peleg constants and improving Weibull α, confirming faster hydration under the 60s treatment of our experimental design. These improvements further enhanced germination performance with 40% amplitude and 60s treatments giving the highest GR and strongest SVI for both ragi and foxtail. The convergence of empirical modelling and germination outcomes demonstrated that moderate intensity, a short pulse of treatment, and a short time are practical and scalable pretreatments for seeds, reducing soaking time and enhancing germination, which will clearly benefit millet processing and sustainable agriculture.

5. Acknowledgement

I acknowledge the School of Community Science and Technology, IIEST, for providing the laboratory research facilities and the Indian Institute of Engineering Science and Technology, Shibpur, Howrah, West Bengal, for providing the fellowship.

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