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Influence of Magnetic Induction Power on Physico-Chemical and Microbial Quality of Milk

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The study aimed to assess the quality of milk heated using a laboratory-scale batch-type Magnetic Induction Heating (MIH) system. Magnetic induction heating is an electromagnetic non-contact heating method which is being efficiently utilized in food processing nowadays. But the possibility to heat milk and other dairy products using MIH is yet to be explored. The study employed seven adjustable induction powers, and milk was heated from 10 to 90°C. The results revealed that heating time gradually decreased from 187 to 114 s as the induction power increased from 500 to 2000 W. The levels of fat, Solid Not Fat (SNF), and protein were statistically similar before (3.96% fat, 8.46% SNF, and 3.34% protein) and after heating (3.93–3.98% fat, 8.37–8.41% SNF and 3.34–3.40% protein). However, microbial parameters exhibited significant variability ($p < 0.05$) depending on the applied induction power. Since MIH can save energy by eliminating the need for steam and its associated auxiliary components, this technology has emerged as a potential alternative to heat milk with shorter time and minimum quality degradation.

Keywords: Cow milk, Induction heating, Methylene blue reduction test, Physico-chemical properties, Standard plate count

Introduction

Milk is a naturally nutritious food that provides all the necessary nutrients for a mammalian offspring. However, cow's milk is consumed by humans of all ages, from newborn to geriatric. The composition of cow's milk includes 87.3% water, 3.7% fat, 3.4% protein, 4.8% carbohydrates, and 0.7% minerals as major components, while vitamins, enzymes, phospholipids, pigments, and other minor components also contribute to its nutritional value.[1] Due to its high nutrient and water content, milk is a highly perishable commodity that is susceptible to spoilage by microorganisms. Consumption of milk contaminated with pathogenic microorganisms can result in foodborne illnesses.[2] Spoilage of milk is caused by psychrotrophic bacteria and their heat-stable enzymes.[3] As a result, preserving the original quality of milk is a challenge for the dairy sector, and thermal treatments are necessary to destroy these microbes.

Heating plays a critical role in the dairy and food industry, particularly in ensuring the safety of milk for consumption and extending its shelf life. A variety of thermal treatments are employed to achieve these objectives. To accomplish proper thermal treatment, various types of heat exchangers are employed, such as scraped surface, plate, and tubular heat exchangers. However, these methods require a significant amount of energy to function efficiently. The primary goal of these treatments is to reduce the moisture content and microbial load in milk. By lowering the moisture content, the growth of microorganisms that cause spoilage and disease is prevented. Additionally, these treatments aid in the preservation of flavor, texture, and nutritional content of the milk. It is important to note that different types of milk require different thermal treatments to achieve optimal safety and preservation.

The conventional heating methods are not very energy efficient and can also affect the nutritional quality of the final food product.[4] Elliott *et al.*[5] investigated the properties of commercially directly and indirectly heated UHT milks after heating and reported that the indirectly heated UHT milks had sustained more heat damage than the directly heated UHT milks. In the dairy and food industry, various alternative technologies such as radio frequency, microwave, infrared, pulsed electric field, ohmic heating, and Magnetic Induction Heating (MIH) have emerged to overcome these drawbacks. Magnetic

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induction heating has become increasingly popular due to its numerous advantages, such as faster heating rate, higher production rate, flexibility, uniformity in temperature, homogeneous product quality, improved safety, good nutritional quality, environmental friendliness, hygiene, and cost-effectiveness.[6] In comparison to traditional heating methods, MIH can save energy by eliminating the need for steam and its associated auxiliary components. This process, which utilizes high-frequency electricity to heat electrically conductive materials, is a complex interplay of electromagnetic, thermal, and metallurgical phenomena. Moreover, being a non-contact heating process MIH eliminates the risk of food contamination.[7]

MIH is based on the principle of combining Joule heating and electromagnetic induction. According to Faraday's law, when an alternating electrical current passes through a conducting material, an alternating magnetic field is generated. If a conducting material is placed within a magnetic field, it will induce an electric current, resulting in heating due to Joule heating.[7] MIH has been used in various industries, including non-food industries like metallurgy, surgical applications in medicine, and food applications like pasteurization and cooking.[8] The technique provides an energy-efficient heating in a shorter period of time.[9] The efficiency and heating pattern of MIH depend on the design of the induction coil and input power properties.[10] A highly efficient flow-through induction heating system was designed using a plastic pipe embedded with a metal shell (AISI 420) as a work-piece.[6] The air gap in the magnetic circuit induction heating affects the heating pattern, as a larger air gap results in lower magnetic flux density and *vice versa*.[11] Uneven heating patterns may occur along the work-piece wall if the height of the work-piece is equal to or less than the height of the coil.[12] From an electronic standpoint, an induction heating system consists of four parts: rectifier, capacitive filter, high-frequency inverter, and resonant load.[13]

Kittiamornkul *et al.*[14] utilized MIH to pasteurize six-litre coconut juice, using three different induction powers (1200, 1600, and 2000 W) to achieve a temperature range of 25 to 90°C, with heating times of 66, 64, and 32 min, respectively. Lamo *et al.*[15], pasteurized guava juice using a 1500 W induction pasteurizer and varying time-temperature combinations. Jin *et al.*[16] achieved a heating time-temperature combination (93.7°C and 400 s) for grapefruit juice using an induction heater under 2700 V induced voltage and 300 Hz frequency. MIH was also found to be a promising method for liquid whole egg pasteurization[17], with optimal time-temperature combinations of 60°C for 210 s and 68°C for 60 s to maintain its functional properties. Hence the scope of MIH in fruit juice pasteurization has been explored by researchers. Also, in the previous studies, the potential of magnetic induction heating units for heating milk in terms of the energy efficiency were analyzed.[18,19] However, there is no literature available mentioning the application of MIH to heat milk and its impact on milk quality. Therefore, the present study for the first time uses a batch-type laboratory scale MIH unit to heat milk at different applied induction powers and assess its physico-chemical and microbial quality parameters. Hence the main objective of this study is to assess the quality of magnetic induction heated milk at various applied induction powers.

Materials and Methods

Cow milk was collected from the Experimental Dairy, ICAR-NDRI, Karnal. A laboratory-scale batch-type MIH system consisting of an electrical circuit, induction coil, sample holder and associated accessories was used to study the effect of MIH on milk (Fig. 1). The sample holder (AISI 304) was placed inside the induction coil (Litz copper coil with 15 layers, 5 m long, 26 turns, 10.5 cm height, 1.3 mm thickness and 9.6 cm inner diameter). Sample holder dimensions were 12.6 m in height, 7.7 m inner diameter and 0.6 m in thickness.

Heat Treatments of Milk Samples

Each trial of 400 mL cow milk was heated using seven different induction powers (i.e. 500, 800, 1000, 1300, 1600, 1800 and 2000 W) to achieve a temperature from 10 to 90°C. Temperature variation of milk was recorded using 8 channel temperature

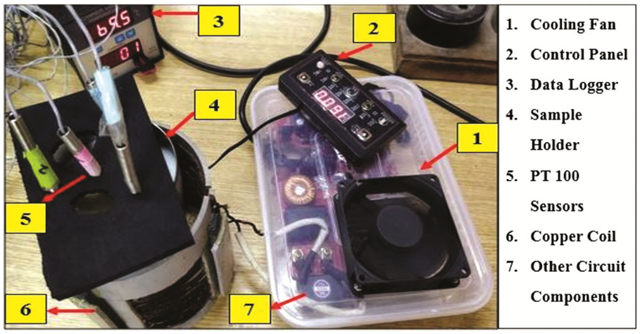

Fig. 1 — Laboratory scale MIH unit

sensor (PT-100) data logger (M/s Countronics, India; sensors: J/K/R Thermocouples, 3 wire PT100 and 4–20mA input user selectable; resolution: 1°C for thermocouples, 0.1°C for PT100 and user selectable for 4–20 mA; scanning rate: User settable from 1–99 seconds; logging rate: 1 second to 99 Mins 59 seconds; accuracy: ±1°C ± 1 Least Significant Digit for Thermocouples and ±0.1°C ± 1 Least Significant Digit for PT100) at an interval of 10 s. The various operating conditions of the MIH unit were selected for the treatment of milk as given in Table 1.

Quality Analysis of Raw and Treated Milk

Titratable Acidity

Titratable acidity was determined by using the titration method. [20]

Titratable acidity (% lactic acid) = $\frac{9\,V_1 N}{V_2}$

where, V_1 = Volume of NaOH (mL)
N = Normality of NaOH
V_2 = Volume of milk sample (mL)

Fat, Solid Not Fat (SNF) and Protein

Fat, SNF and protein were analyzed by a milk analyser (Milko-screen™, IndiFOSS, 3809), based on Fourier Transform Infra-red Technology (FTIR). Twenty millilitres of each milk sample (25 to 28°C) were taken in the cuvette and the same was introduced into the sample chamber of the milk analyser. The values were obtained within 45 sec for each sample and noted.

Methylene Blue Reduction Test (MBRT)

The MBRT test was done by adding 1 mL methylene blue solution to 10 mL treated milk in a test tube. Then the test tube was placed in a thermostatically maintained water bath at 37 ± 0.5°C.[20] Time was noted after the milk sample turned white from the blue.

Alkaline Phosphatase Test

Five millilitres of phosphatase buffer solution was taken in a test tube and 1 mL milk was added to it and then kept in a thermostatically maintained water bath at 37 ± 0.5°C.[21] Time was noted till the sample colour turned yellow from white.

Table 1 — Operating parameters selected for MIH treatment of milk

Parameters	Operating values
Induction power	500, 800, 1000, 1300, 1600, 1800, 2000 W
Supplied voltage	200 – 220 V
Frequency	50 – 60 Hz
Input current	AC

Standard Plate Count (SPC)

Dilutions were prepared and transferred 1 mL of appropriate dilution (1:10000 for raw milk and 1:100 for treated milk) to the sterile Petri plate. Then 15 mL of nutrient agar was poured into a Petri plate, mixed and allowed to solidify. This test was conducted in a vertical laminar airflow cabinet (Airstream®, CLASS-II BSC, ESCO Life Sciences Group, India). Then Petri plates were kept at 37°C in a bacteriological incubator. Counts were noted after 48 h and multiplied by the dilution factor.[22,23]

Coliform Count

One millilitre of each treated un-diluted milk sample was transferred directly to a Petri plate while raw milk was diluted (1:10) and transferred to a Petri plate. Then violet-red bile agar (15 mL) was poured into the Petri plate. This test was conducted in a vertical laminar airflow cabinet. After proper mixing, agar was allowed to solidify and kept at 37 ± 1°C in a bacteriological incubator. Counts were noted down directly after 24 h.[22–24]

Yeast and Mould Count

Dilutions were prepared and transferred 1 mL of appropriate dilution (1:10 for both raw milk and treated milk) to a sterile Petri plate. Acidified potato dextrose agar (15 mL) was poured into a Petri plate and allowed to solidify. This test was conducted in a vertical laminar airflow cabinet. After solidification Petri plates were kept at 25 ± 1°C in a BOD incubator. Counts were taken after 96 h and recorded the number of yeast and mould per mL after multiplying with the dilution factor.[25]

Statistical Analysis

Statistical analysis of the data was done using IBM SPSS Statistics Version 23. Significant differences between means were determined by Tukey's Multiple Comparison using One-Way ANOVA ($p<0.05$).

Results and Discussion

Effect of Applied Induction Powers on the Exposure Time

The milk exposed to the maximum induction power (2000 W) showed a faster temperature rise from 10 to 90°C compared to the milk exposed to the minimum induction power (500 W) at a fixed exposure time of 3 min 7 sec. (187 sec). Although the heating rate increased with increasing induction power, no significant difference in temperature change was observed between 500 and 800 W at different time durations and also between 1000 and

1300 W. When milk was heated at 1300 W for 1.5 min, its temperature change was not significantly different from milk heated at 1600 W. However, significant differences were observed among milk temperatures at different time intervals when the induction power was 1600, 1800, and 2000 W. Therefore, an increasing trend was observed in heating temperature with increasing induction power, and significant differences ($p < 0.05$) were observed between the temperatures of different milk samples treated by different powers for 1, 1.5, and 2 min (Table 2). A similar finding was reported by Kittiamornkul *et al.*[14] in their study of coconut juice pasteurization using an MIH-based system, where exposure time decreased with an increase in induction power.

Effect of Applied Induction Powers on Milk Temperature

Different induction powers were applied to heat milk using MIH, and the time taken to reach set temperatures of 63, 72, and 90°C from the initial temperature of 10°C varied. It is evident from Table 3 that lower induction power (500 W) required more time to achieve the set temperature, while higher induction power (2000 W) required less time. Generally, the exposure time needed to reach a specific milk temperature decreased with an increase in induction power. Specifically, milk heated with 2000 W induction power required 1.5 min 24 sec (114 sec) to reach 90°C, while the milk heated with 500 W induction power required 3 min 7 sec (187 sec) to reach the same temperature. Similar findings were reported by Kittiamornkul e*t al.*[14] who observed that lower exposure time was required with higher induction power to reach 90°C from a 25°C temperature of coconut juice treated in an MIH unit. They heated about 6L of coconut juice with 2000, 1600, and 1200 W induction powers and reported that the juice reached 90°C in 32, 64, and 66 min, respectively.

Table 2 — Temperature of milk at different induction powers and exposure time

Power (W)	Temperature (°C) of milk after heating		
	1 min	1.5 min	2 min
500	28.8 ± 0.7^{a}	42.2 ± 1.1^{a}	56.8 ± 0.7^{a}
800	30.7 ± 0.9^{a}	44.9 ± 2.5^{a}	60.3 ± 2.5^{a}
1000	32.9 ± 1.6^{b}	46.9 ± 2.5^{b}	68.4 ± 3.3^{b}
1300	34.6 ± 1.4^{b}	51.8 ± 2.7^{bc}	70.1 ± 3.4^{b}
1600	37.6 ± 1.2^{c}	55.1 ± 2.3^{c}	77.1 ± 3.4^{c}
1800	41.8 ± 1.0^{d}	63.0 ± 1.2^{d}	85.6 ± 0.6^{d}
2000	44.2 ± 0.8^{e}	70.6 ± 2.7^{e}	91.8 ± 0.7^{e}

n=5; Mean values with the same superscript letters within the same column do not differ significantly ($p > 0.05$). Initial temperature of milk was constant in all cases and was 10°C

Quality Analysis of Raw and Treated Milk

Studies on magnetic induction heating of milk and its effects on milk quality are not reported yet in detail. But the researchers reported the advantages of induction heating of milk in terms of its energy efficiency. Hence the present study results were compared with other novel techniques like ohmic heating.

Titratable Acidity

There was no significant change in the titratable acidity of milk after MIH processing at different powers and temperatures (Table 4), indicating that the heating conditions used were not severe enough to disrupt the equilibrium state of the colloidal/ soluble calcium in the milk. Elhasan *et al.*[26] reported that raw and low pasteurized (at 68°C for 30 min) cow milk had similar values (0.144 ± 0.01). Lee *et al.*[27] also reported no change in the titratable acidity of milk heated up to 65°C using pulse electric field. However, the extensive heating causes irreversible migration of soluble calcium to the colloidal side, resulting in increased acidity.[1]

Fat (%)

The fat content of milk treated with different induction powers was found to be statistically similar to that of raw milk (Table 4). Previous studies have shown that traditional heat treatments such as pasteurization and boiling do not affect the fat content of milk.[26] Similarly, the fat content of raw milk and ohmic-heated milk were observed similar.[28]

SNF (%)

The treated milk showed no significant difference in SNF content compared to the raw milk (Table 4). This result is consistent with previous studies by Elhasan *et al.*[26], which found that boiling did not

Table 3 — Milk heating time at different induction powers

Power (W)	Heating time (s) required		
	63°C	72°C	90°C
500	131.5 ± 1.9^{f}	148.1 ± 2.0^{e}	187.2 ± 0.5^{g}
800	123.8 ± 3.4^{e}	139.4 ± 3.9^{d}	171.2 ± 5.0^{f}
1000	112.4 ± 4.8^{d}	127.3 ± 5.5^{c}	159.3 ± 4.9^{e}
1300	108.7 ± 5.5^{d}	124.4 ± 5.2^{c}	149.6 ± 4.3^{d}
1600	101.1 ± 3.9^{c}	109.6 ± 3.9^{b}	137.7 ± 0.1^{c}
1800	90.0 ± 1.7^{b}	100.4 ± 1.0^{a}	127.8 ± 0.3^{b}
2000	81.6 ± 2.7^{a}	94.8 ± 2.6^{a}	114.3 ± 5.3^{a}

n=5; Mean values with the same superscript letters within the same column do not differ significantly ($p > 0.05$)

Table 4 — Chemical and microbial data of raw and treated milk

Milk	Chemical and microbial quality					
	Fat (%)	SNF (%)	Protein (%)	Acidity (% LA)	MBRT (min)	SPC (log cfu/mL)
Raw milk	3.96 ± 0.07^a	8.46 ± 0.05^a	3.34 ± 0.06^a	0.122 ± 0.005^a	179 ± 5.8^a	5.70 ± 0.01^h
Treated milk 1 (500W)	3.98 ± 0.06^a	8.40 ± 0.08^a	3.36 ± 0.04^a	0.122 ± 0.005^a	374 ± 3.7^b	3.62 ± 0.01^g
Treated milk 2 (800W)	3.95 ± 0.08^a	$8.4\ 5 \pm 0.04^a$	3.34 ± 0.05^a	0.122 ± 0.005^a	382 ± 2.4^{bc}	3.56 ± 0.01^f
Treated milk 3 (1000W)	3.96 ± 0.07^a	8.37 ± 0.11^a	3.35 ± 0.04^a	0.122 ± 0.005^a	390 ± 3.2^{cd}	3.49 ± 0.01^e
Treated milk 4 (1300W)	3.93 ± 0.70^a	8.38 ± 0.10^a	3.36 ± 0.05^a	0.122 ± 0.005^a	397 ± 2.4^{de}	3.45 ± 0.01^d
Treated milk 5 (1600W)	3.98 ± 0.60^a	8.39 ± 0.12^a	3.35 ± 0.06^a	0.122 ± 0.005^a	404 ± 3.7^{ef}	3.42 ± 0.02^c
Treated milk 6 (1800W)	3.98 ± 0.70^a	8.39 ± 0.08^a	3.35 ± 0.03^a	0.122 ± 0.005^a	410 ± 5.5^f	3.38 ± 0.01^b
Treated milk 7 (2000W)	3.96 ± 0.07^a	8.41 ± 0.06^a	3.40 ± 0.02^a	0.122 ± 0.005^a	414 ± 8.6^f	3.31 ± 0.02^a

n =5; Mean values with the same superscript letters within the same column do not differ significantly ($p > 0.0$)

affect the SNF content of cow milk. Similarly, Bakry *et al.*[29] reported no significant difference in the SNF content of milk treated with microwave heating.

Protein (%)

The protein content of raw and treated milk showed no significant difference regardless of the induction powers used (Table 4). In a study conducted by Gökmen *et al.*[30] on the quality parameters of various milk samples subjected to heat treatments, it was found that boiling did not significantly alter the total protein content of raw cow milk. However, pasteurization caused a notable change in the protein level. Similarly, Ul Haq *et al.*[31] reported that while thermization and sterilization had no significant effect on the protein content of skimmed milk, pasteurization had a remarkable impact on the protein content. Similarly, ohmic heating-based pasteurization was not found to significantly affect protein content.[32] Also, Wang *et al.*[17] from their study observed no egg protein coagulation after pasteurization of liquid eggs using MIH.

MBRT

Both raw and treated milk samples turned completely white after 3 h and minimum of 6 h to a maximum of 7 h respectively. The MBRT time of the treated milk samples significantly increased ($p<0.05$) with an increase in induction power, as shown in Table 4. Milk heated at 500W had an MBRT time of 6.2 h, while milk heated at 2000W had an MBRT time of 6.9 h. Thania and Ibrahim[33] classified milk quality based on the MBRT time as excellent (>8 h), good (6–8 h), fair (2–6 h), and poor (<2 h). Jain *et al.*[34] found that the MBRT time for raw milk is less than 2 h, and for pasteurized milk, it is 3 to 4 h. According to the FSSAI[35] regulations, the minimum MBRT for processed milk should be at least 5 h.

Alkaline Phosphatase Test

Even after 7 h, all the treated milk samples exhibited negative results, indicating that the alkaline phosphatase enzyme was destroyed by induction heating. Jain e*t al.*[34] also found a negative result for pasteurized milk after 3 to 5 h of heating. As per FSSAI[35] guidelines, the phosphatase test must be carried out immediately after pasteurization, and the result should be negative. Meshaan and Alhaji[28] observed a negative phosphatase result after ohmic heating of milk as well.

Standard Plate Count (SPC)

The SPC of the treated milk samples showed significant differences ($P<0.05$) depending on the induction power applied. Raw milk had an SPC of 5.70 log cfu/mL, which decreased with increasing induction powers (Table 4). The milk heated at 1800 and 2000 W had the least SPC, which were statistically similar, while the milk heated at 500 W had an SPC of 3.61 log cfu/mL. Agarwal *et al.*[2] reported an SPC of 6.35 log cfu/mL in raw milk and 4.49 log cfu/mL in boiled milk. Metwally *et al.*[36] found that the microbial count decreased from 9.30 log cfu/mL to about 2.95 log cfu/mL after boiling the milk for 15 sec. Nur *et al.*[23] reported an SPC of 3.34 to 3.58 log cfu/mL for pasteurized milk, while Kumar and Puranik[7] observed a 4.15 to 4.49 log cfu/mL SPC count in pasteurized milk. According to FSSAI[35], the SPC of pasteurized milk should be 4.48 to 4.7 log cfu/mL. Bakry *et al.*[29] analyzed the SPC of raw cow and buffalo milk as well as their microwave-treated counterparts. They reported that the SPC decreased from 5.30 (raw buffalo milk) to 1.75 log cfu/mL (microwave-treated buffalo milk) and from 5.18 log cfu/mL (raw cow milk) to 1.67 log cfu/mL (microwave-treated cow milk) by microwave treatment for 180sec. Al-Hilphy[32] also observed a reduction in SPC from 5.19 to 3.80 log cfu/mL by applying electrical fields of 55 V/cm for ohmic pasteurization of milk. Wang *et al.*[17] used MIH for pasteurization of liquid eggs and reported A 7.6 log reduction of *Salmonella* Enteritidis.

Coliform Count

The initial coliform count of raw milk was 2.70 log cfu/mL, but it was not detected in any of the MIH-treated samples. According to FSSAI[35], pasteurized milk should have a coliform count of less than 1 log cfu/mL. Kumar and Puranik[7] reported no coliform count in their pasteurized milk samples, while Nur *et al.*[23] found a coliform count ranging from 0.30 to 0.48 log cfu/mL. Bakry e*t al.*[27] investigated the quality of microwave-heated milk and reported no coliform count after microwave treatment. Similarly, Al-Hilphy[32] and Meshaan and Alhaji[28] observed no coliform count after ohmic heating of milk.

Yeast and Mould Count

The initial yeast and mould counts of raw milk were 2.45 log cfu/mL, but they were absent in all treated milk samples. In the study by Bakry e*t al.*[29], microwave treatment for 1.5 min reduced the yeast count of buffalo milk from 4.51 to 1.12 log cfu/mL and the mould count from 3.22 to 2.52 log cfu/mL. No yeast or mould count was observed in buffalo milk after 2 min of microwave treatment. For cow milk, the researchers reported that the yeast count decreased from 4.46 to 4.05 log cfu/mL and the mould count decreased from 3 to 2.52 log cfu/mL after 1 min of microwave treatment. After 1.5 min of microwave treatment, there was no yeast or mould count observed in cow milk. According to the FSSAI[35], pasteurized milk should have an absence of yeast and mould count. Kumar and Puranik[7] also reported the absence of yeast and mould count in pasteurized milk.

Conclusions

This study investigated the impact of different induction powers on the heating time, physicochemical and microbiological characteristics of milk. The results revealed a significant variation in milk heating time across the different induction powers. However, the fat, SNF, and protein content of the magnetic induction heated milk samples were similar to that of raw cow milk. Moreover, the microbial load of the milk was significantly reduced with increasing induction powers. The results of the study recommend the potential usefulness of magnetic induction heating as a feasible alternative to the traditional milk heating process in milk processing plants. For future research, one could think about a continuous magnetic induction heating unit which could be incorporated into a milk pasteurization unit or any other milk heating unit. However, the scaling up of the unit especially the electrical circuit and the compatibility of different food grade metals to the induction circuit needs to be studied thoroughly.

Conflict of Interest

The authors declare that they have no conflict of interest.

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