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Impact of Radiofrequency and Microwave Heating on the Nutritional and Antinutritional Properties of Pulses: A Review

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ABSTRACT

Pulses, which are the dry seeds of legume crops, have gained global popularity, leading to a notable rise in their production. They are rich in protein, minerals, fibers, and low in fat content. However, they have some antinutrients that need to be removed. Novel techniques like radiofrequency (RF) and microwave (MW) heating can enhance pulse quality by reducing the antinutrients. The key mechanism behind this improvement is the rapid heating that disrupts the native structure of the pulses. These technologies offer several advantages, including speed, consistency, sustainability, and energy efficiency. The effectiveness of RF and MW processing depends on the heating conditions used and the kind of pulses being treated. This review highlights the mechanisms and influencing factors of RF and MW heating as well as their effect on the nutritional and antinutritional qualities of various pulses. Additionally, the limitations of these technologies are summarized, and future research prospects focusing on pulse processing are identified.

1 | Introduction

Pulses are a great source of various macronutrients and micronutrients, offering numerous health benefits. Because of their abundance, affordability, simplicity of processing, and productivity, they have been a part of the human diet since ancient times, typically serving as an additional source of protein along with staple foods (Divekar et al. 2017). They are eaten as whole seeds, dehulled split grain, and flour. All over the world, various pulses are produced and consumed. Among them, beans, chickpeas, dry peas, lentils, cowpeas, mung beans, urad beans, and pigeon peas are the most common (Rawal and Navarro 2019). On a global scale, the cultivation area for pulses has risen from 71.47 to 98.57 Mha between 2001 and 2022. This expansion in cultivation has seen a corresponding increase in production from 61.50 MT in 2001 to 100.82 MT in 2022. Over the same period, pulse productivity has also seen a rise, climbing from 234 to 268 T/ha (FAOSTAT 2024). The total increase in pulses production has been reflected in the individual rise of different pulses. As seen in Figure 1, total quantity of the common pulses has increased during this time. Over the years, peas and chickpeas have been two dominant pulses worldwide. India leads the world in pulse cultivation, covering 33.35 Mha, which is 35% of the global area. Despite this, India contributes about 26% of the total pulse production in the world. The global trade of pulses amounts to 19.01 MT, with Canada being the largest exporter at 5.70 MT and Australia coming in second with exports of 2.07 MT (Bhat et al. 2022).

Pulses are rich in protein along with essential vitamins, minerals, and dietary fiber. Their high nutrient makes them valuable

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dietary components, especially for those seeking alternatives to animal proteins. They are an affordable protein source and promote sustainable farming by fixing nitrogen in the soil that reduces the need for synthetic fertilizers (Lal 2017). Additionally, their versatility in culinary applications allows for a wide range of dishes, making them accessible and appealing to diverse populations worldwide. Due to their affordability, the highly nutritious proteins present in legumes and pulses are sometimes colloquially termed as "the protein of the poor" (Venkidasamy et al. 2019). With respect to nutritional suitability, pulses have different antinutritional compounds, which are basically bioactive substances that impact on the bioavailability of different nutrients (Sathe 2012). Pulses contain antinutritional compounds such as enzyme inhibitors, phytic acid, lectins, saponins, and allergens. These can hinder protein digestion and the absorption of essential minerals such as iron, zinc, and magnesium, potentially causing deficiencies (Parca et al. 2018). As a result, even though pulses are very nutritious, it is crucial to prepare them correctly to lower the antinutritional components and improve their digestibility and nutrient availability. Various traditionally practiced postharvest processing methods can reduce these antinutrients to a certain level.

Pulses undergo several postharvest operations to make them ready for preservation and consumption. These operations are also useful in reducing the postharvest losses, which is a major concern globally not only for securing food for all but also for reducing CO_2 emission. It has been reported that the postharvest loss of pulses is up to 30% in developing countries due to processing of pulses using traditional techniques (Sangeetha and Mohan 2021). The postharvest steps in processing pulses include cleaning, pitting, drying, conditioning, milling, and cooking. With the modernization of science and technology, various novel technologies have been invented and used in the processing of pulses. These emerging techniques not only reduce the postharvest losses but also improve their nutritional, functional, and antinutritional qualities (Ahmed 2021). They can be classified into two categories: electrotechnologies and nonthermal technologies. The electrotechnologies are the techniques of heating the pulses and other materials in the electromagnetic (EM) spectrum and include radiofrequency (RF) heating, microwave (MW) heating, and infrared heating. On the other hand, the nonthermal technologies do not elevate the temperature of the products but improve the qualities by modifying their chemical composition and structure, as well as inactivating the enzymes and microorganisms. Hydrostatic pressure, oscillating magnetic field, pulse light, ultrasound, cold plasma, and ozonization are examples of nonthermal technologies (Ahmed 2021; Ahmed et al. 2016). Among the EM technologies, MW and RF are very promising because of faster heat generation ability with high penetration depth, which results from molecular dipole rotation and ionic conductivity (Altemimi et al. 2019). Moreover, these techniques are energy efficient, cost-effective, and versatile for use in food processing. A number of applications have been developed for MW-based processing of pulses, which include disinfestation (R. Singh et al. 2012; Yadav et al. 2014), improvement of antinutritional qualities (Patterson et al. 2017), and cooking qualities (Ruisánchez et al. 2012). In contrast, RF heating is still underutilized for pulses. However, due to its longer wavelength, RF penetrates more into the food products compared to MW resulting in even heating (Altemimi et al. 2019). This technology has been applied to control *Salmonella enteria* in raw shelled almonds (Jeong et al. 2017), enzyme inactivation in green peas (C. Zhang et al. 2022), insect inactivation in walnut (Mitcham et al. 2004; S. Wang et al. 2001), stored grain (Shrestha et al. 2017; S. Wang et al. 2008; D. Yu et al. 2017), canola seeds (D. Yu et al. 2017), etc. Thus, this review will focus on the prospects of RF heating in pulse processing in comparison with MW heating. More specifically, the principles of RF and MW heating, factors affecting the heating behavior of RF and MW, and their effect on the nutritional and antinutritional quality of pulses will be summarized in the subsequent sections.

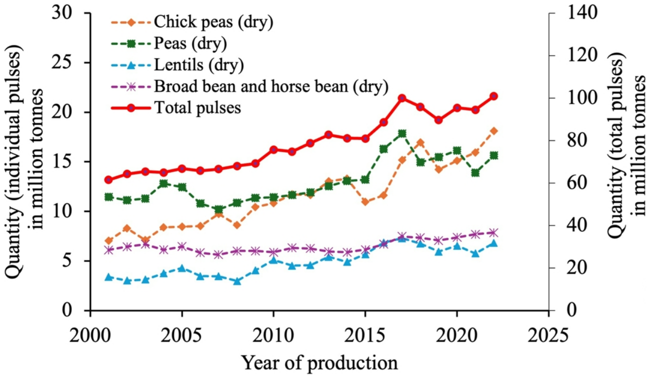

FIGURE 1 | Global pulse production from 2001 to 2022 (figure was generated based on data adapted from FAOSTAT 2024, using CC BY 4.0 license).

2 | Mechanism of RF and MW Heating

2.1 | Principle

This heating process, often referred to as dielectric heating or dielectric loss heating, occurs within dielectric materials. It results from molecular friction induced by high-frequency alternating electric fields (Jiao et al. 2014). RF and MW are distinguished based on their wavelength and frequency in the EM spectrum (Figure 2). MWs encompass the frequency range of 3000 MHz to 3000 GHz, whereas RF covers the range of 3 to 3000 MHz. Radar can pick up both MWs and RFs and can interfere with mobile phones as well as other communication systems. As a result, the US Federal Communications Commission (FCC) has limited the usage of broad ranges of MW or RF waves to only a

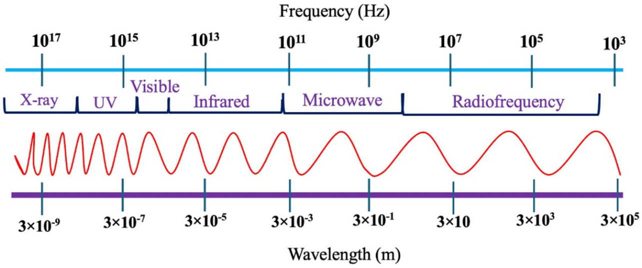

FIGURE 2 | Classification of electromagnetic waves based on frequency and wavelength in the electromagnetic spectrum (adapted with modification from Marra et al. 2009, with permission).

few specific frequencies. Medical, scientific, and industrial uses of RF are allowed at 13.56, 27.12, and 40.68 MHz, respectively (Y. Wang et al. 2011), whereas MWs are limited to frequencies of 915 and 2450 MHz (Jiao et al. 2014). Higher frequencies correspond to shorter wavelengths, as shown by Equation (1):

$$c = \lambda f \tag{1}$$

where, f = frequency (Hz), λ = wavelength (m), and c = the speed of light (m/s) ($c = 3 \times 10^8$ m/s). When comparing the penetration into foods, RF wavelengths are longer than MW, allowing RF waves to penetrate larger samples (Moirangthem and Baik 2021).

In dielectric heating, foods with polar molecules like water are subjected to an alternating electric field. These molecules, which have unevenly distributed charges, align with the field, causing polarization. Without the field, they are erratically arranged due to thermal agitation (Boutemtam et al. 2020) as shown in Figure 3a,b. When a fluctuating electric field is employed, polar molecules rotate to align with it, a process known as dipole rotation as shown in Figure 3c,d (Jiao et al. 2014; Marra et al. 2009). The EM energy is transformed into heat by the friction between nearby molecules, raising the temperature of the treated objects. In contrast to polar molecules, dissociative ions in food move when exposed to an applied electrical field. In a similar way, alternating electrical fields change the direction of motion. Additionally, the friction between molecules caused by the ions' forward and backward oscillation inside the materials also produces heat. This phenomenon is known as ionic conduction (Figure 3e,f). Basically, RF and MW heating occurs by both ionic conduction and dipole rotation (Jiao et al. 2014).

2.2 | Dielectric Properties

In RF and MW heating, essential dielectric properties are permeability, permittivity (or capacitance), and electrical conductivity. Permittivity significantly influences the dielectric constant, loss factor, and loss angle, which are critical for the efficiency of these heating methods (Piyasena et al. 2003). The complex permittivity (ε) of a dielectric material relative to free space is represented by the following equation:

$$\varepsilon = \varepsilon' + \varepsilon'' \tag{2}$$

where ε' = dielectric constant (real part) and ε'' = dielectric loss factor (imaginary part). The ε' defines energy storage in a dielectric material, and the ε'' defines the energy dissipation capability of a material by conductive loss of dipolar (ε''_d), ionic charges (ε''_σ), or through which energy from the electric field is transformed into heat within dielectric materials. Thus, ε' can also be present as by following Equation (3):

$$\varepsilon' = \varepsilon''_d + \varepsilon''_\sigma. \tag{3}$$

The relationship between ε' and ε'' is termed as tangent of loss angle (δ):

$$tan\ \delta = \frac{\varepsilon''}{\varepsilon'}. \tag{4}$$

The penetration depth, P_d (m), of an EM wave in a dielectric material depends on the frequency and the material's dielectric properties in free space. The equation to calculate P_d is as followed (Stratton 2007):

$$P_d = \frac{c}{2\pi f} \frac{1}{\sqrt{2\varepsilon' \left[\sqrt{1 + (\varepsilon'' + \varepsilon')^2} - 1 \right]}}. \tag{5}$$

The heat generation rate per unit volume, denoted as Q (W/m^3), at a specific point in the food during EM heating can be described by the following equation (Datta 2001):

$$Q = 2\pi f \varepsilon_0 \varepsilon'' E^2 \tag{6}$$

where E = intensity of electric field (V/m), and ε_0 = vacuum permittivity (constant) = 8.854×10^{-12} F/m.

Table 1 lists the dielectric properties of various pulse foods, highlighting the factors that can influence these properties in pulses. Also, the type of heating whether RF or MW, which resulted in different penetration depths is highlighted. Heating of pulses or other materials using RF or MW results in a rapid rise in temperature, triggering various chemical transformations like the Maillard reaction, starch gelatinization, and protein denaturation. These

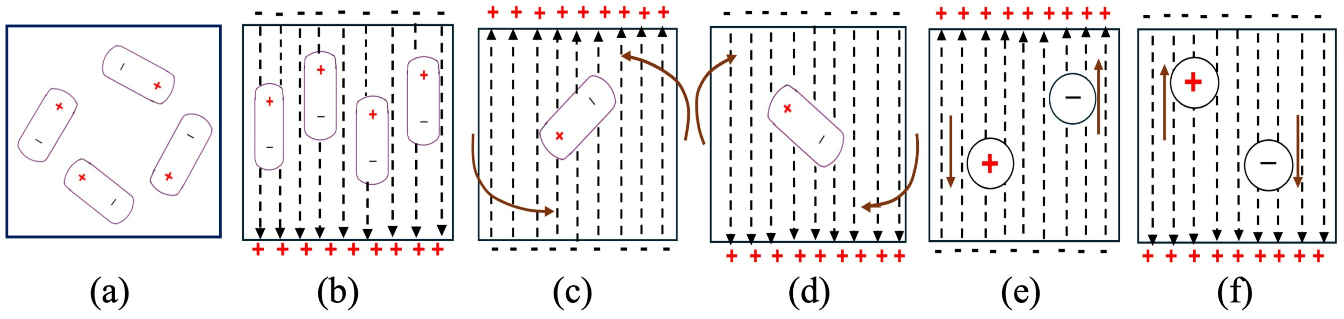

FIGURE 3 | Dielectric heating showing the response of polar molecules to different electric fields: (a) absence of electrical field; (b) continuous electrical field; (c, d) alternating electrical field (dipole rotation); (e, f) ionic conductivity (adapted with modification from Boutemtam et al. 2020, using Creative Commons Attribution 4.0 International license, and Moirangthem and Baik 2021, with permission).

TABLE 1 | Dielectric properties of some common pulses and products subjected to radiofrequency (RF) and microwave (MW) heating.

Product name	Moisture (%)	ε'	ε''	P_d	f (MHz)	Heating method	T (°C)	Source
Lentil flour	7.7	3.42	0.11	61.06 m	13.56	RF	30	A. Oke and Baik (2022)
	10.6	3.65	0.23	29.40 m				
Lentil seeds	13.0	3.67	0.20	34.25 m				
	15.0	4.37	0.39	19.08 m				
Chickpea (split)	13.2	3.80	0.22	31.79 m				
	15.8	5.21	0.72	11.19 m				
Chickpea flour	8.2	2.63	0.05	105.75 m				
	10.8	3.23	0.24	26.98 m				
Chickpea flour	—	2.26	0.11	0.37 cm	2450	MW	25	Alifakı and Şakıyan (2017)
Chickpea	11.8–19.8	~2.2–3.8	~0.1–1.0	14.61–5.72 cm	900–5800	MW	24–25	Taheri et al. (2018)
Chickpea flour	7.9	2.60	0.18	—	915	—	30	Guo et al. (2008)
Chickpea	7.9–20.9	Specific values are not provided. Both the dielectric constant and loss factor decrease as frequency increases and increase as temperature rises.		54.2–17.5 cm	915	MW	20	Guo et al. (2010)
				32.0–4.6 cm			60	
				8.6–1.9 cm			90	
Green pea	10.8–21.6			27.1–13.0 cm			20	
				11.7–4.9 cm			60	
				3.9–2.4 cm			90	
Lentil	8.4–21.5			47.4–16.5 cm			20	
				26.0–4.5 cm			60	
				6.7–2.0 cm			90	
Soybean	8.9–19.9			35.2–14.3 cm			20	
				17.5–5.4 cm			60	
				6.8–1.9 cm			90	

(Continues)

TABLE 1 | (Continued)

Product name	Moisture (%)	ε'	ε''	P_d	f (MHz)	Heating method	T (°C)	Source
Black-eyed pea	8.8	2.86	0.26	—	915	RF	30	Jiao et al. (2011)
	12.7	2.94	0.30	—				
Mung bean	10.2	2.71	0.36	—				
	14.4	3.25	0.41	—				
Peanut	10	6.00	0.82	524.85 cm	27	RF	25	S. Zhang et al. (2016)
	10	~4.5	~0.50	26.97 cm	915	MW		

processes modify the composition and structure of the treated substance and derived ingredients (Ahmed et al. 2022). Alterations in structure and chemical makeup impact the movement and behavior of small polar water molecules or ionic conduction, which in turn directly influence dielectric properties and the capacity to absorb EM waves (Heydari et al. 2022).

3 | Factors Affecting Dielectric Properties of Pulses

There are numerous factors that impact the dielectric heating behavior of pulses. Due to their hygroscopic nature, the amount of water present in the foods plays a key factor in affecting dielectric heating. Additionally, the frequency of the applied alternating electric field significantly impacts their dielectric characteristics. Other important factors include density, chemical composition, heating temperature, and structural features. The existence of mobile ions and fixed dipole moments, particularly those linked to water and other components, also greatly affects the dielectric behavior (Nelson and Trabelsi 2012). A few of the key factors affecting dielectric properties of pulses are described below.

3.1 | Moisture Content

Dielectric properties of different pulses in response to different moisture contents at a temperature of 30°C and frequency of 13.56 and 915 MHz are presented in Figure 4. It is evident that moisture content plays a significant role on both ε' (Figure 4a) and ε'' (Figure 4b) values. This can also be noticed in Table 1 that there is a substantial positive relationship between the dielectric constant and moisture content, while the connection with the loss factor is still not well understood. In a food matrix, water molecules interact with other chemical compounds, creating layers that affect the food's structure and properties (Piyasena et al. 2003). From Figure 4, it is also seen that both ε' and ε'' values are relatively low at a lower moisture level and increase sharply with a higher moisture level as also reported by Piyasena et al. (2003). In addition, different pulses show different dielectric values with the increase of moisture content. However, the moisture dependency of dielectric properties has a complex relationship with the frequency of heating. Considering the same products, the dielectric properties of chickpea have been explored at different moisture levels and frequencies by Taheri et al. (2018). The study found that the dielectric constant increases with moisture content, while it decreases with the frequency. According to Guo et al. (2010), dielectric properties of chickpea, green pea, lentil, and soybean as measured at 20°C and 90°C and a frequency of 27 MHz also showed a sharp increase with moisture content. They also reported that at low moisture content (15%), the differences in loss factors among four legume types are minimal. However, at 20°C and higher moisture levels, soybean showed the highest loss factor, followed by lentil, green pea, and chickpea. Foods with low moisture mainly contain chemically bound water, leading to lower dielectric properties compared to foods with higher moisture content. Moreover, the presence of different sugar levels can influence the dielectric properties (Piyasena et al. 2003).

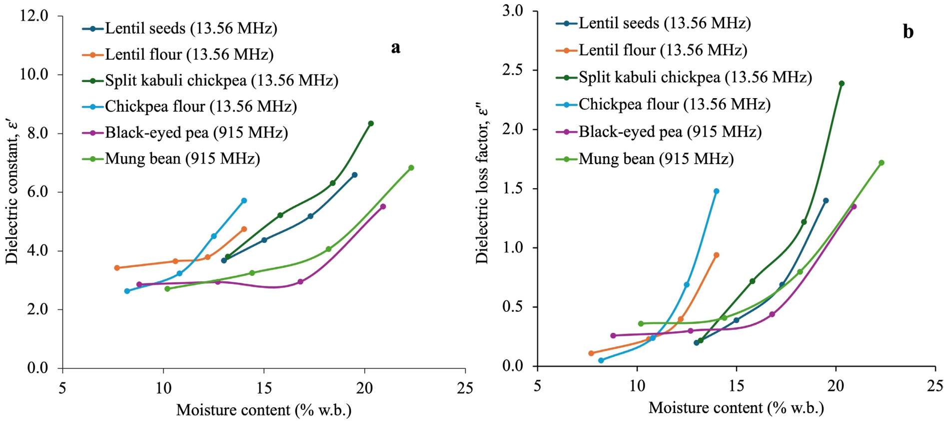

FIGURE 4 | Moisture dependence of the (a) dielectric constant and (b) dielectric loss factor of selected pulse grains and products (the figure was generated based on the data presented for lentil seeds, lentil flour, split Kabuli chickpea, and chickpea flour by A. Oke and Baik 2022, using CC BY license, and for black-eyed pea and mung bean by Jiao et al. 2011, with permission).

3.2 | Frequency

The dielectric characteristics of most materials show notable fluctuations with the frequency of the applied electric fields, except for a small number of very effective materials that absorb minimal energy from RF and MW fields. Polarization, which results in the alignment of particles with constant dipole moments when exposed to the applied electric field, is a significant element contributing to this frequency dependency. Taheri et al. (2018) reported the frequency-dependent dielectric properties of chickpea at different moisture levels and room temperature in the frequency range of 700–7000 MHz. Both ε' and ε'' decreased as frequency increased. For each moisture content, ε' showed a linear decline at higher frequencies. Additionally, the loss factor of chickpeas exhibited a negative linear correlation with frequencies above 3000 MHz across all moisture levels. However, from 700 MHz to approximately 2000 MHz, the loss factor increased before dropping again up to 7000 MHz. The decline in dielectric properties with increasing frequency has similarly been observed in lentil flour across a frequency range of 10–1800 MHz and temperatures between 20°C and 90°C, with a constant moisture content of 21.5% (Guo et al. 2010). The dielectric constant and loss factor of peanut kernels decrease quickly as frequency increased in the RF range (10–300 MHz) and more slowly in the MW range (300–4500 MHz) (S. Zhang et al. 2016). A similar decreasing trend has also been noticed for lentil seeds, chickpea flour, and chickpea grain over a frequency range of 5–30 MHz during RF heating for different moisture ranges and temperatures (A. Oke and Baik 2022). Ionic conductivity is the main cause of electric-field dispersion at low frequencies, while dipolar losses are the main cause at MW frequencies (Cloude 2009). Thus, it can be concluded that as frequency increases, the EM field alternates faster, leading to a drop in ε'. This occurs because fast alternation inhibits dipole reorientation, distorts ionic links, and impairs the interfacial polarization mechanism, resulting in decreased polarization (Zadeh et al. 2019).

3.3 | Temperature

Temperature plays a very critical role during dielectric heating of materials. Numerous factors, such as the presence of water and salt content in food, as well as the frequencies involved, influence how temperature affects the dielectric characteristics of foods (Tang 2005). As a result, depending on the substance, the temperature dependency of dielectric properties can be highly complicated and vary from increasing to decreasing (Sosa-Morales et al. 2010). At lower frequencies, the loss factor typically increases with rising temperature due to enhanced ionic conductance (Uan et al. 2004), while at high frequencies, it typically decreases because of free water dispersion (Y. Wang et al. 2003). Guo et al. (2008) conducted a study on the dielectric properties of chickpea flour, examining the effects of frequency, moisture, and temperature. The research utilized an open-ended coaxial-line probe with an impedance analyzer, covering frequency ranges from 10 to 1800 MHz, moisture levels from 7.9% to 20.9%, and temperatures from 20°C to 90°C. Based on their findings, the dielectric properties of chickpea flour increase with temperature across all moisture levels. At <40°C, the changes in dielectric properties are minimal. However, when the temperature exceeds 40°C, there is a significant increase in permittivity, especially at higher moisture levels. Lentil seeds had an ε' value of 3.82 at a frequency of 5 MHz, a temperature of 30°C, and a moisture content of 13.0%. However, with the increase in temperature to 90°C, the ε' values increased to 6.03 at the same frequency and moisture content (A. Oke and Baik 2022). In the case of ε'', the values also increased with the increase of temperature. The authors also reported similar trends for a few other products such as lentil flour, split Kabuli chickpea, and chickpea flour. The dielectric constant increases almost linearly with rising temperature, especially at higher frequencies and lower moisture contents (Nelson and Trabelsi 2012). Variations in temperature affect the moisture content and ionic conductivity of dielectric materials. The dielectric characteristics of water increase with temperature if it is in a bound state and decrease with temperature if it is in a free state inside the material (Bogale Teseme and

Weldemichael Weldeselassie 2020; Sipahioglu 2002). As a result, the proportion of bound water to free water in the materials determines how their dielectric characteristics change with temperature. Because different materials have varying ingredients and levels of moisture, their dielectric qualities fluctuate with temperature.

3.4 | Density

As the effect of dielectric heating relies on the quantity of material interacting with EM waves, the material density can influence its dielectric characteristics (Nelson and Trabelsi 2012). Variations in physical structure, the presence of air-vacuum space, moisture, and other components of the material are the factors affecting the density. Different processing methods of food materials often leads to physical and structural changes, which in turn modify their dielectric properties (Venkatesh and Raghavan 2004). To understand how density influences the dielectric properties of particulate matter, it is beneficial to examine the relationship between the dielectric properties of solid materials and mixtures of air and particles, such as powdered or coarse samples. Measuring the dielectric characteristics of chickpea seeds and flour, A. Oke and Baik (2022) found that split chickpea with a moisture content of 13.2% and particle density of 1.402 g/cm^3 had lower dielectric constants and loss factors than chickpea flour with almost similar moisture content but higher density (1.411 g/cm^3). Similarly, Guo et al. (2008) reported that both ε' and ε'' of chickpea flour increased with density. At a material density of 1.265 g/cm^3, they reported ε' and ε'' values of 2.51 and 0.15, respectively, at a constant frequency of 915 MHz. When the density increased to 1.321 g/cm^3, the ε' and ε'' values also increased to 3.33 and 0.54, respectively. Taheri et al. (2018) indicated a quadratic relationship between the dielectric properties and density of chickpea. Trabelsi et al. (1997) determined the relationship between dielectric properties and bulk densities (ρ) of particulate materials and reported a linear relationship between $^{\varepsilon'}/_{\rho}$ and $^{\varepsilon''}/_{\rho}$ at different temperatures and moisture. When measuring dielectric characteristics based on density, the existence of air gaps is important. Pulse seeds may have more air gaps between them when they are packed, which lowers the bulk density and the dielectric characteristics. In contrast, under identical processing conditions, flour tends to exhibit higher dielectric properties due to the lower air spaces between its particles. This information might be useful for the prediction of the density of pulses using their dielectric properties.

3.5 | pH

pH is an important parameter of food ingredients that affects their quality, functionality, and safety. The concentration of ions present in a pulse or pulse-based food matrix is influenced by the pH. The ion concentration, ion mobility, and solution structure have been reported to influence the dielectric characteristics (Tajparast and Glavinović 2018). A study on pH-dependent dielectric properties of soybean protein isolate showed that both acidic (pH: 4.5) and basic (pH: 10) states can significantly increase the ε' and ε'' values in comparison to a pH of 6.6 (Ahmed et al. 2008). In the case of β-lactoglobulin, a major whey protein of milk, changes in pH from neutral to either acidic or basic resulted in significant improvement of dielectric characteristics (Ahmed and Luciano 2009). The authors reported the ε' values as 35.3, 25.9, and 31.2, and the ε'' values as 4.8, 1.2, and 2.2, at different pH values of 4, 7, and 10, respectively, with a constant temperature of 70°C. In the food matrix, pH plays a key role in regulating intermolecular hydrophobic interactions and electrostatic repulsive forces, both of which affect the dielectric properties (Ahmed et al. 2008; Y. Sun et al. 2023). Additionally, fluctuations in the dipole moment and charge residues contribute to changes in dielectric parameters when the pH of a food sample is altered (Pitera et al. 2001). However, there are very few studies available about the effect of pH on the dielectric properties of pulse-based food ingredients. Thus, this information can provide insights into the processing of pulses at different pH using the EM spectrum.

4 | Penetration Depth of RF and MW Heating

The distance penetrated by a dielectric energy into a material before being absorbed and converted into heat is known as the penetration depth (P_d). Numerically, it is the depth within a material at which the energy is dropped to 36.8% of its value at the surface (J. Sun et al. 2016). It determines the heating uniformity, which facilitates effective designing of EM heating (D.U. Yu et al. 2015). The P_d is dependent on a number of factors such as moisture content of the materials being heated, temperature of

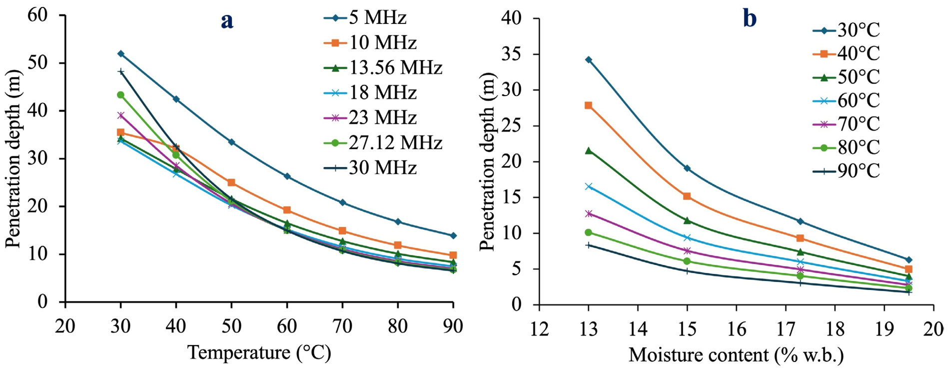

FIGURE 5 | Penetration depth of RF in lentil seed as a function of (a) temperature (°C) at 13% moisture and (b) moisture content (% wet weight basis [w.b.]) at a frequency of 13.56 MHz. The figure was generated based on the data presented by A. Oke and Baik (2022) using CC BY license.

the treatment (RF or MW), frequency of wave, and product characteristics. As shown in Figure 5, an increase in temperatures, frequency, and product moisture leads to a decrease in P_d values. The P_d thus has an inverse relationship with frequency, as well as effective dielectric properties (ε' and ε'') (J. Sun et al. 2016). At a lower frequency, a material has higher ability to convert the EM energy to heat with better penetration, and when the frequency increases, energy is mostly absorbed by the surface of the materials, resulting in lower penetration (Zhao et al. 2018). The frequency of the RF is much lower than that of the MW; thus, RF can be more suitable for industrial pulse processing with a higher bed thickness of the materials during heating. As shown in Table 4, heating of chickpea flour in MW spectrum resulted in a P_d of 0.37 cm at a frequency of 2450 MHz (Alifakı and Şakıyan 2017), whereas a substantially higher P_d of 26.98 m was reported for chickpea flour at a RF frequency of 13.56 MHz (A. Oke and Baik 2022). In the case of peanut, S. Zhang et al. (2016) obtained P_d as 524.85 and 26.97 cm for RF (27 MHz) and MW (915 MHz), respectively, indicating that RF results in better penetration into the materials than MW. As discussed previously, the dielectric parameters (ε' and ε'') increase with temperature and moisture, which in turn leads to a faster attenuation of the wave and reduction in the P_d. Thus, the selection of appropriate frequency, temperature, and product moisture is essential for processing of pulses in the EM spectrum.

5 | Nutrients and Antinutrients in Pulses

Pulses are widely consumed because of their high nutritional quality and bioavailability. Most of the major and minor nutrients necessary for human are available in pulses. Pulses can significantly enhance human health by offering various benefits, for instance, mitigating the probability of cancer, cardiovascular diseases, obesity, and diabetes. They provide an outstanding source of plant-based protein, minerals, fiber, and beneficial phytochemicals. Figure 6 represents the health benefits of pulses.

5.1 | Macronutritional and Micronutritional Characteristics

Pulses contain high amounts of proteins (~25% to 40%) with levels of the essential amino acid lysine, but lower levels of tryptophan and sulfur-containing amino acids such as cysteine and methionine (Dahl et al. 2012; Malcolmson and Han 2019). Moreover, pulses are good sources of polysaccharides, especially starch, and contain a low amount of fat. Various natural macromolecules and micromolecules in pulses make them promising foods and food products that can help protect human health from diseases such as cardiovascular diseases, cancer, obesity, and diabetes. Also, some of the plant secondary metabolite compounds present in pulses act as antioxidative, anti-inflammatory, and antiaging agents.

Table 2 lists the proximate composition and mineral profile of some common pulses based on the data reported by US Department of Agriculture (USDA). The estimated nutritional values of pulses are moisture ~10%, protein (21%–24%), carbohydrates (60%–63%), lipids (0.8%–2%), and ash (1%–4%). However, the composition of the pulses depends on the extent of drying as this process removes the moisture and the percentage of other components varies with the moisture level. In the case of faba beans as seen in Table 2, a comparatively lower amount of protein, fat, carbohydrate, and ash contents is observed as the moisture is relatively very high (72.60%). Being a good source of energy and fiber, 100 g of pulses can contribute to 10%–20% of the daily calorie requirement for humans and significantly contribute to the daily fiber requirements. Obesity affects one-third of adults, and the obesity prevalence among youngsters has increased from 5% to 17% in the last 30 years. Thus, high-fiber, low-calorie meals should be prioritized in order to enhance fiber consumption and reduce calorie intakes (Glickman et al. 2012).

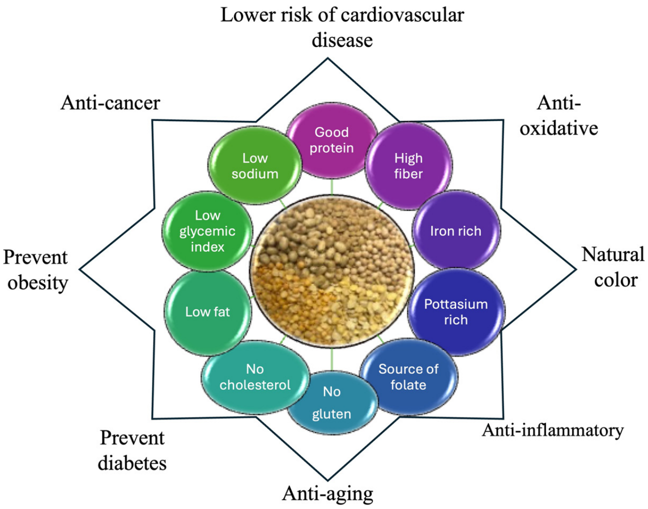

FIGURE 6 | Health benefits of pulses (adapted with modification from Acquah et al. 2021, using Creative Commons Attribution License [CC BY] and from Gurusamy et al. 2022, using CC BY-NC-ND license).

In undernourished regions of the world like Asia and Africa, adding lentils to daily diets can improve diet quality and help reduce micronutrient deficiencies, especially for women and children. Among all minerals, potassium is the dominant component in pulses with a quantity of 950–1420 mg/100 g (USDA 2024). Additionally, pulses contain a significant amount of magnesium and phosphorus. Iron and zinc are the important minerals required for the human body, and pulses contain around 5–8 and 2–4 mg of iron and zinc, respectively, per 100 g of serving (Langyan et al. 2022). Consuming 100–200 g of pulses like lentil, cowpea, and chickpea can fulfill daily mineral needs, while 100 g of most dietary pulses can meet daily iron requirements (Langyan et al. 2022). Furthermore, beans are rich in various forms of vitamin B, including folic acid and pantothenate. Chickpea and bean are also high in carotene and vitamin K (Gowda et al. 2015).

5.2 | Antinutritional Properties

Antinutrients are biomolecules that possess adverse nutritional or physiological properties and are present in varying amounts in different pulses and legumes. The impact of these compounds varies, predominantly based on their concentration, manifesting both beneficial and detrimental effects. Examples of antinutrients in pulses include saponin, lectins, tannins, phytates and oxalates, trypsin inhibitor (TI), amylase inhibitors, and phenols (Figure 7).

TABLE 2 | Macronutritional and micronutritional composition of different pulses (USDA 2024).

Components	Lentil	Chickpea	Blackeye pea	Cannellini bean	Faba bean	Pinto bean	Kidney bean	Mung bean
Proximates (g/100 g)								
Water	9.45	8.77	11.00	12.30	72.60	11.30	11.80	9.05
Protein	23.60	21.30	21.20	21.60	7.92	21.40	23.60	23.90
Fat	1.92	6.27	2.42	2.20	0.73	1.23	0.83	1.15
Carbohydrate	62.20	60.40	61.80	59.80	17.60	62.60	60.00	62.60
Ash	2.88	3.32	3.51	4.14	1.12	3.46	3.83	3.32
Energy (kcal)	360.00	383.00	354.00	345.00	88.00	347.00	333.00	347.00
Minerals (mg/100 g)								
Calcium	62.00	111.00	71.00	143.00	37.00	113.00	143.00	132.00
Iron	7.16	5.09	5.93	6.67	1.55	5.07	8.20	6.74
Magnesium	107.00	135.00	184.00	154.00	33.00	176.00	140.00	189.00
Phosphorus	374.00	353.00	428.00	412.00	129.00	411.00	407.00	367.00
Potassium	949.00	1070.00	1240.00	1420.00	332.00	1390.00	1410.00	1250.00
Sodium	< 2.50	9.00	3.00	< 2.50	25.00	12.00	24.00	15.00
Zinc	3.86	3.12	3.65	2.72	1.00	2.28	2.79	2.68
Copper	0.84	0.80	0.94	0.74	0.40	0.89	0.96	0.94
Manganese	1.57	3.58	1.29	1.78	0.661	1.15	1.02	1.04

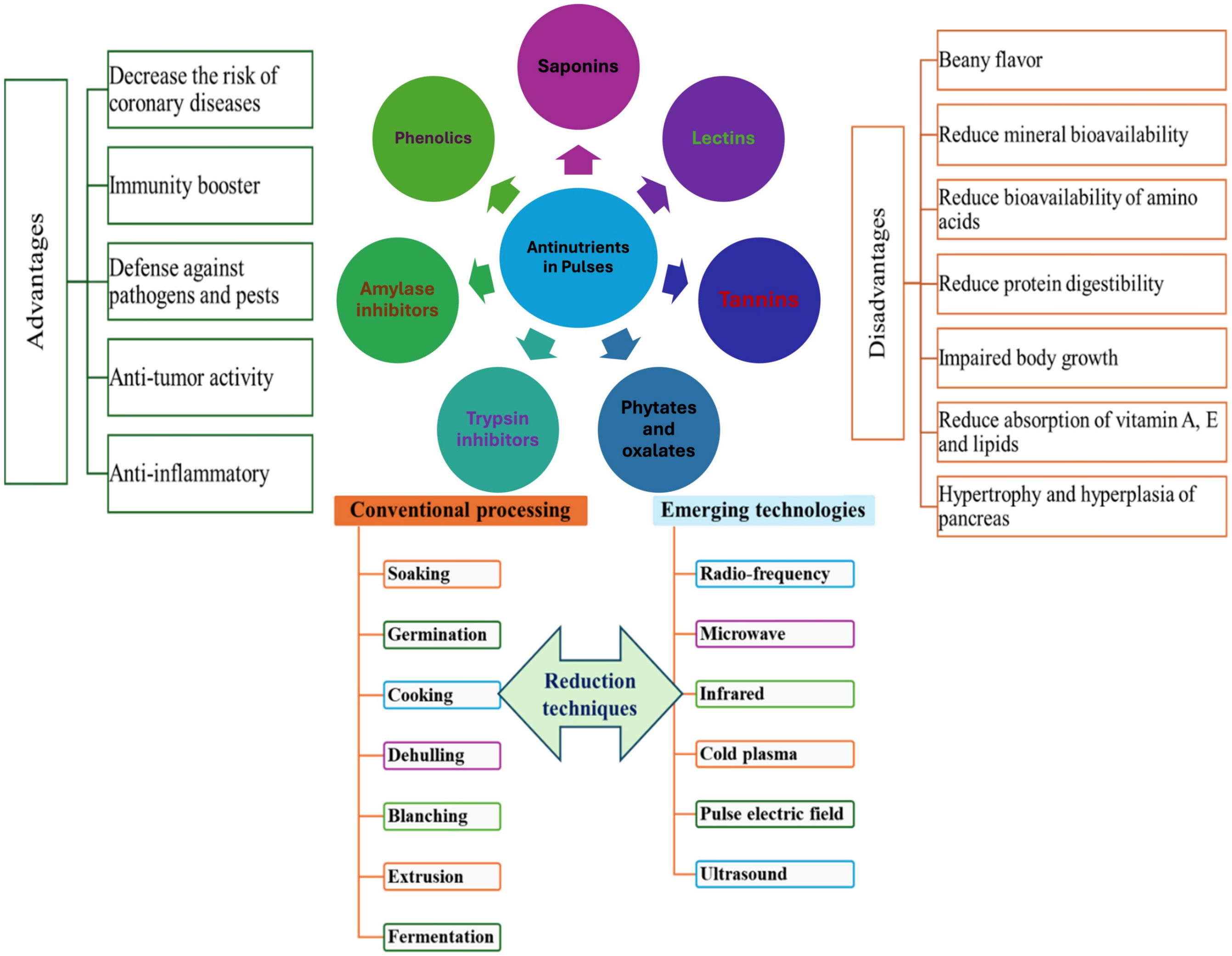

FIGURE 7 | Antinutritional factors in pulses, their benefits, and adverse effect as well as reduction process (adapted with modification from Purohit et al. 2023, using CC BY-NC-ND license, Salim et al. 2023, using Creative Commons Attribution License [CC BY], Samtiya et al. 2020, using Creative Commons Attribution 4.0 International, López-Moreno et al. 2022, using CC BY-NC-ND license).

The presence of antinutrients in cereals and legumes reduces the bioavailability of various beneficial components. This can lead to issues such as micronutrient malnutrition and mineral deficiencies (Samtiya et al. 2020). Moreover, they can hinder the metabolic system of the proteins, lipids, and vitamins by inhibiting the enzyme activity, thus contributing to impaired body growth. Deficiency in zinc minerals was reported in West Asian populations in the 1960s (Gibson 2012). Phytate is recognized as a significant factor contributing to this deficiency (Hassan et al. 2020). Similarly, dietary saponins negatively affect the growth and feed efficiency of chicks, along with hindering the absorption of vitamins A and E, as well as lipids (P. Singh et al. 2023). Additionally, a study reported that phytate adversely affected the metabolism of calcium, zinc, and phosphorus in humans (Schlemmer et al. 2009). Besides reducing the absorption of various minerals and nutrients, high levels of these antinutrients can lead to toxicity when present in the diet. Different factors like age, species, concentration, processing, and interactions with other nutrients all affect how harmful antinutrients are to nutrient metabolism (Salim et al. 2023). On the contrary, these compounds are also getting a lot of attention from researchers because of their incredible variety of biological functions that may be advantageous to humans (Pihlanto et al. 2017). According to Salim et al. (2023), antinutrients can benefit human health by exhibiting anticarcinogenic, anti-inflammatory, antioxidant, and anti-obesity effects as well as boosting up the defense mechanism against pests and pathogens. Despite their potential benefits, the harmful effects of antinutritional factors generally outweigh the advantages they may offer. This necessitates various actions to mitigate their presence and impact. It is likely that the concentration of these compounds is reduced during the most commonly practiced processing step, cooking, which is often applied to pulses before consumption. Moreover, there are several other conventional and modern processing operations that can potentially reduce the concentration of antinutrients. The conventional techniques include soaking, milling, roasting, cooking, germination and fermentation, blanching, and extrusion (Samtiya et al. 2020). Previous research on cooking, dehulling, boiling, and autoclaving of pulses have resulted in a significant reduction of the antinutrients including TI, tannins, and phytic acid (Hefnawy 2011; N. Wang et al. 2009). Most of these techniques remove the antinutrients by breaking down the structure, thermal degradation, and interaction with other components to form insoluble complex (Avanza et al. 2013; Suhag et al. 2021) or by dissolving them in water (Badifu 2001). However, long time exposure to different conventional processing methods like cooking, boiling, or autoclaving may result in alteration of the other nutritional qualities. With the progress of science and technology, several novel processing methods have been introduced, which can potentially contribute to the reduction of antinutrients as well as retain the necessary nutrients in pulses. Innovative nonthermal methods like irradiation, cold plasma, high pressure, ultrasound, pulsed light, and pulsed electric fields, along with EM heating techniques such as MWs, infrared, and RF, have potential for reducing antinutrients (D. Oke 2021; Sanaei Nasab et al. 2024).

6 | Effect of RF and MW Heating on Quality of Pulses

EM heating like MW and RF can affect the nutritional quality of the pulses or any products. They can speed up pulse cooking, maintain nutrients, and improve texture. While it enhances disinfection and uniform heating, it can change taste and moisture if not regulated properly. It also uses less energy and chemical preservatives, making it more ecologically friendly. Mechanism of MW and RF heating along with their effect on nutritional and antinutritional factors is outlined in this section.

6.1 | Mechanism of Dielectric Heating on Changes of Nutrients and Antinutrients

Dielectric heating accelerates the heating process and impacts the nutritional and antinutritional qualities of pulses and other dietary ingredients. The changes in these properties are primarily due to structural modifications, thermal degradation, and the formation of new compounds during EM heating (Suhag et al. 2021). MW or RF significantly impacts the secondary and tertiary structures of proteins by enabling polar groups to absorb energy, leading to free radical formation, aggregation, or unfolding of the sequences (Han et al. 2018). According to Gomaa et al. (2013) and Guan et al. (2011), dielectric heating usually disrupts noncovalent bonds, such as hydrogen bonds in protein molecules, leading to protein unfolding and structural modifications. In the case of fats and fatty acids, oxidation may take place due to MW or RF heating. Fats typically absorb EM waves due to the dipole moments of polar molecules present in fatty acids or triglycerides, leading to asymmetric vibrations to generate heat and can alter the fatty acid profile (Deng et al. 2022). Temperature, oxygen, and the amount of unsaturated fatty acid are the influencing factors for changes of fats and their quantity during dielectric heating (C. Zhang et al. 2022). Pulses are rich in carbohydrates, primarily present in the form of starch and contain polar hydroxyl groups (-OH) at different carbon numbers. Dielectric heating can change starch by creating free radicals at specific points (C1 and C6 positions) in the starch molecules. These changes can affect the structure of the starch, leading to modifications in its crystallinity, viscosity, and gelatinization (Deng et al. 2022). Micronutrients, such as vitamins and minerals, can be affected by MW or RF heating, primarily due to their heat sensitivity and water solubility. On the other hand, most of the antinutrients are heat sensitive, and volumetric heat generated by MW or RF can destroy their viability. The mechanism of thermal degradation of antinutrients includes the hydrolysis of peptide bonds, deamination (breakdown of covalent bonds), and the disruption or rearrangement of disulfide bonds (Irakli et al. 2020; Rahate et al. 2021). According to Deng et al. (2022), MW heating can partly remove phytic acid, oxalate, saponins, TIs, and tannin due to their heat-sensitive nature, whereas structural changes occur in oxalate, saponins, and TIs. The authors also mentioned that phytic acid and tannin produce insoluble complex due to dielectric heating. However, the extent of changes in nutrients and antinutrients may depend on various factors including the frequency, temperature, and exposure time of heating as well as the type of pulses.

6.2 | Effect on Macronutrients and Micronutrients

The effect of RF and MW on the nutritional quality of different pulses is shown in Table 3 and discussed here. As there is very little research available on nutritional quality of RF-treated pulses, the effect of MW on pulses nutritional quality is mostly presented in the table.

6.2.1 | Protein

Protein is the major component of pulses and accounts for around 25% of the dry mass. Typical cooking of pulses can reduce the protein content due to leaching of water-soluble protein in the cooking water (Habiba 2002). The amino acid profile and protein digestibility are the other determinants of protein quality. RF and/or MW heating has been attributed to changing the protein content, amino acid profile, and protein digestibility as seen in Table 3. Zhong et al. (2015) studied the effect of MW and RF heating along with high hydrostatic pressure treatment on the nutritional quality of black soybean, and they found that RF heating was more useful in retaining or improving protein quality. In terms of amino acids, they reported that both MW and RF heating decreased the amino acids, but the quantity lost during processing was lower for RF treatment (Zhong et al. 2015). They also mentioned that the high frequency of MW processing (2450 MHz) might be a reason behind the higher reduction in nutritional quality, maybe due to damage to cellular integrity causing changes in microstructure and subsequent loss of molecular constituents. The reduction in protein content can also be seen for other pulses (Table 3). Soaking of pulses during or before MW heating may accelerate the leaching of amino acids from the pulses and decreases the total protein content (Y. Xu et al. 2016). One important modification that takes place during thermal processing is protein denaturation. This process involves the unfolding of protein structures, which can modify the protein's functional characteristics and possibly even its nutritional value as well as quantity (Avanza et al. 2013). High temperatures in MWs can significantly alter the digestibility and nutritional value of protein-rich foods. This can lead to changes in their secondary and tertiary structure and the formation of hydrophobic proteins or cross-links and even trigger the Maillard reaction (Xiang et al. 2020).

TABLE 3 | Effect of microwave (MW) and radiofrequency (RF) heating on proximate composition of different pulses.

Product name	Heating method	Processing conditions	Components	Results	Reference
Black soybean	MW and RF	Two hundred fifty grams of black soybean was first soaked in deionization water (1:10 w/w) for 30 min. Heating for 30 min pouring the samples in a polypropylene container by a vacuum MW (2450 MHz and 1 kW) and RF (27 MHz and 6 kW)	Protein	Crude protein of RF heated seeds was similar ($p > 0.05$) to the control sample, whereas MW significantly ($p < 0.05$) reduced protein content, though the decrease was < 2.00%.	Zhong et al. (2015)
			Lipid	Raw seeds had around 20.23% (d.b.) lipid, which reduced significantly to 13% (d.b.) for MW and not significantly to 17.40% (d.b.) for RF treatment.	
			Starch	More than 20% starch decreased due to MW treatment but almost similar to the raw seeds for RF.	
			Ash	Around 7.50% ash lost due to RF where around 15% reduction for MW treatment	
			Amino acids	The total amino acid concentration of control/raw sample was 434 g/kg (db), and essential amino acids in raw seeds were 154 g/kg (db). Both MW and RF treatments reduced the amino acid contents. However, the reduction due to RF heating was less than MW or high hydrostatic pressure treatment. 3.26% vs. 5.76% reduction of the total amino acids, and 1.81% vs. 3.20% of the essential amino acids for RF vs. MW, respectively, from the raw seeds	
			Fatty acids	RF or MW processing had minor effect on the fatty acid profile. Total saturated fatty acids of raw-, RF-, and MW-treated samples were 15.83%, 15.80%, and 16.08%, respectively, whereas the monounsaturated and polyunsaturated fatty acids were 23.15%, 22.95%, and 22.96%, and 60.93%, 61.18%, and 60.72%, respectively.	

(Continues)

TABLE 3 | (Continued)

Product name	Heating method	Processing conditions	Components	Results	Reference
Pea	MW	MW (2450 MHz) cooking of pea seeds by soaking in water (1:2 ratio) for 4, 8, and 12 min, and then dried at 50°C for 12 h and ground into flour	Protein	Raw peas had protein content of 27.2%, which reduced to 26.3%, 26.2%, and 26.2% for 4, 8, and 12 min of MW treatment, respectively. These concentrations were higher than traditional cooking or even autoclaving at 121°C. Also, MW treatment resulted in better in vitro protein digestibility than raw samples.	Habiba (2002)
			Ash	MW resulted in lesser ash loss than traditional cooking.	

(Continues)

6.2.2 | Lipids

Pulses are moderate sources of fats or lipids. Beans, which are also classified under pulses, can contain a good amount of fats. EM heating has been attributed to both increases and decreases in fat content (Table 3) depending on the materials being processed and heating conditions. Lipid polymerization and thermal oxidative degradation can occur due to EM waves. However, the lipid oxidation caused by EM heating is comparatively lower than that caused by traditional cooking or heating techniques. This is because EM heating, in any case, speeds up denaturation and deactivation of enzymes such as lipase, lipoxygenase, peroxidase, and polyphenol oxidase (Y. Sun et al. 2023), leading to the stability of fatty acids. Unlike traditional methods, RF or MW heating has a lesser impact on oils. Although oils have a lower content of polar molecules, they primarily absorb EM waves due to the asymmetric vibrations of polar molecules (Deng et al. 2022). They also have very little effect on the chemical composition of fatty acids (Zhong et al. 2015). MW treatment can also deactivate lipoxygenase and eliminate hydrogen peroxide to minimize lipid oxidation (Akyol et al. 2006). It stimulates antioxidants such as tocopherol, phenolic compounds, and other chemicals in oil (L. Xu et al. 2022) and consequently produces more stable oil.

6.2.3 | Carbohydrates

RF or MW heating can increase the total carbohydrate content (Table 3). Carbohydrates in pulses are available in the form of complex starch. The structural stability of natural starch depends significantly on the presence of numerous intramolecular and intermolecular hydrogen bonds. EM heating impacts these bonds by altering the distribution and dynamics of water within the starch granules (Li et al. 2020). More details about the starch structure and the effect of MW heating have been discussed by Deng et al. (2022), in which it has been attributed that gelatinization, oxidation resistance, digestibility, and other properties of starch can be affected due to EM heating.

6.2.4 | Minerals and Vitamins

Minerals are important components for human health, and their quantity and quality are influenced by different food processing techniques. Minerals are extensively divided into major minerals (macrominerals) and trace minerals (microminerals). Major minerals include calcium (Ca), magnesium (Mg), potassium (K), sodium (Na), chloride (Cl), phosphorus (P), and sulfur (S); while trace minerals include iodine (I), zinc (Zn), selenium (Se), iron (Fe), manganese (Mn), copper (Cu), cobalt (Co), molybdenum (Mo), fluoride (F), chromium (Cr), and boron(B) (Gharibzahedi and Jafari 2017). All thermal processing methods, including household cooking and MW or RF heating, can affect the quantity or availability of the minerals. There are a few studies focusing on the minerals and vitamins profile as affected by MW and RF heating, instead of reporting on the mineral quantity in terms of ash content. Comparing the impact of different thermal processing on ash/mineral content, RF heating was more suitable for retaining higher mineral quantity in black soybean than MW

TABLE 3 | (Continued)

Product name	Heating method	Processing conditions	Components	Results	Reference
Kabuli chickpea	MW	Raw seeds were soaked in water (1:10 w/w) for 16 h at 22°C–24°C, and then, water was drained out, and seeds were rinsed. Then, MW cooking in a domestic MW for 15-min soaking water at 1:5 (w/w) ratio for the previously soaked samples and 1:10 (w/w) for nonsoaked sample	Protein	Nonsoaking MW cooking and soaking MW cooking significantly ($p < 0.05$) decreased amount of protein as found in the raw chickpea.	Y. Xu et al. (2016)
			Oil	Crude oil in the raw seeds was 4.73%, which increased to 4.87% due to 16-h soaking followed by MW cooking, and 6.19% due to nonsoaking and MW cooking.	
			Ash	Total ash or mineral contents decreased due to MW cooking. However, presoaking in water resulted higher loss.	
			Carbohydrate	Total carbohydrate content of the soaked and MW-cooked samples was significantly higher than raw and nonsoaked MW–processed chickpea seeds.	
			Amino acids	The raw sample contained 81.4 g of amino acids per 100 g of crude protein. Sulfur amino acids made up 3.24% and essential amino acids 39.7% of the total. All treatments significantly boosted total and essential amino acid levels. Soaking and microwave cooking notably increased most individual amino acids, except for cysteine, tryptophan, and arginine.	
			Minerals	Raw sample had total macroelement and microelement of 1.94 g/100 g and 143 ppm, respectively. MW processing either previously soaked or nonsoaked in water for 16 h resulted in significant decreasing of minerals compared to the raw. Soaking showed greater loss for microelements (Ca, Mg, K, P, and S) but almost similar loss for microelements (Cu, Fe, Mn, and Zn).	

(Continues)

TABLE 3 | (Continued)

Product name	Heating method	Processing conditions	Components	Results	Reference
Lentil	MW	Lentil seeds were soaked in distilled water (1:10, w/v) for 12 h at 25°C. After draining and rinsing three times, they were placed in tap water (1:10, w/v) and microwaved on high for 15 min until soft.	Protein	Raw lentil seeds had 26.6% protein, which is nonsignificantly reduced to 26.1%.	Hefnawy (2011)
			Ash	Compared to the raw seeds, around 5.88% reduction of ash content was noticed due to MW cooking. Traditional boiling and autoclaving also resulted in almost similar reduction of ash.	
			Fat	Total fat content of the raw seeds was 1.0%, which significantly reduced to 0.9%.	
			Crude fiber	A slight increase in crude fiber was found due to MW treatment.	
			Starch	Starch content increased from 42.0% in raw to 41.2% in MW-cooked sample.	
			Minerals	MW cooking resulted in losing all studied minerals such as Ca, K, Mg, Zn, P, Na, Fe, and Cu to some extent.	
			Amino acids	Microwave cooking slightly increased total essential amino acids but reduced some individual ones, such as tryptophan, and total aromatic and sulfur amino acids.	
Red gram	MW	Fifty grams of samples soaked in 475 mL of water for 40 min and then cooked in 24 min using high power in MW (2450 MHz, 1200 W)	Protein	Raw seeds had 22.2%, which significantly decreased to 21.5% due to MW cooking, but the protein content of MW was almost similar to that of pressure cooking.	Khatoon and Prakash (2006)
			Ash	MW cooking reduced the ash content significantly from 3.6% to 2.6%.	
			Fat	A slight increase in fat content	
			Fiber	Total dietary fiber, insoluble dietary fiber, and soluble dietary fiber of the raw seeds were 8.25%, 7.55%, and 0.24% (db), respectively. All of these parameters increased significantly due to MW cooking.	
			Vitamins and minerals	Vitamins (thiamin) and minerals (Fe, Ca, and P) content decreased significantly due to MW cooking except Fe.	

TABLE 4 | Effect of radiofrequency and microwave heating on antinutritional factors of pulses and their products.

Product name	Components	Amount before treatment	Heating method	Heating conditions	Results	Reference
Lentil flour	Trypsin inhibitor	51.8 (TIU/mg protein)	RF—27.12 MHz	3 kW, 115°C	↓40.54%	D. Oke (2021)
				7 kW, 75°C	↓14.09%	
				9 kW, 55°C	↓3.42%	
	Phytic acid	4.58 g/kg	RF—27.12 MHz	3 kW, 115°C	0.00%	
				7 kW, 75°C	↑8.30%	
				9 kW, 55°C	0.00%	
	Lipoxygenase	41.38×10^6 unit/g of total protein	RF—27.12 MHz	3 kW, 115°C	↓98.48%	
				7 kW, 75°C	↓46.13%	
				9 kW, 55°C	↑19.21%	
Chickpea flour	Trypsin inhibitory activity	133.59 (TIU/mg protein)	RF—27.12 MHz	3 kW, 115°C	↓29.29	
				7 kW, 75°C	↓68.43%	
				9 kW, 55°C	↓80.32%	
	Phytic acid	7.48 g/kg	RF—27.12 MHz	3 kW, 115°C	↓3.34%	
				7 kW, 75°C	↓9.89%	
				9 kW, 55°C	↓11.49%	
	Lipoxygenase	51.48×10^6 unit/g of total protein	RF—27.12 MHz	3 kW, 115°C	↓74.05%	
				7 kW, 75°C	↓99.17%	
				9 kW, 55°C	↓100.00%	
Black soybean	Saponins	62.13 g/kg	RF—27 MHz	6 kW, 30 min	↓> 22.00%	Zhong et al. (2015)
	Tannins	~7.00 g/kg			↓17.70%	
	Phytic acid	13.79 g/kg			↓27.60%	
	Trypsin inhibitor	37.15 g/kg			↓15.50%	
Soybean (Pannónia Kincse variety)	Trypsin inhibitor	9.4 ± 0.71 mg/g	RF—13.5 MHz	10 kW, 100°C	↓54.25	Takács et al. (2022)
				10 kW, 110°C	↓87.23	

(Continues)

TABLE 4 | (Continued)

Product name	Components	Amount before treatment	Heating method	Heating conditions	Results	Reference
Black soybean	Saponins	62.13 g/kg	MW—2450 MHz	1 kW, 30 min	↓> 22.00%	Zhong et al. (2015)
	Tannins	~7.00 g/kg			↓~17.00%	
	Phytic acid	13.79 g/kg			↓~20.00%	
	Trypsin inhibitor	37.15 g/kg			↓~10.00%	
Lentil	Trypsin inhibitor	2.83 ± 0.10	MW	Cooking with tap water (1:10 w/v) for 15 min	↓93.29%	Hefnawy (2011)
	Tannins	1.28 ± 0.05			↓34.38%	
	Phytic acid	4.11 ± 0.09			↓39.17%	
Chickpea flour	Tannins	0.83 ± 0.09 mg GAE/g	MW	Soaked in water (1:10 w/w) for 16-h cooking for 15 min	↓39.76%	Y. Xu et al. (2016)
	Phytate	6.60 ± 0.58 mg/g			↓25.30%	
Faba bean pesto sauce	Condensed tannins	5942 ± 39 mg catechin equivalents/kg	MW	11 kW, 110°C, 30s	↓20.40	Klug et al. (2018)
Yellow soybean	Tannins	9.91 ± 0.51 mg/g	MW—2.45 GHz	850 W, 3 min	↓15.14%	Yang et al. (2014)
	Phytic acid	11.8 ± 1.2 mg/g			↓18.72	
	Trypsin inhibitors	6.43 ± 0.10 TIU/g			↓97.96	
Black soybean	Tannins	11.34 ± 0.12 mg/g	MW—2.45 GHz	850 W, 3 min	↓1.34%	
	Phytic acid	16.70 ± 0.4 mg/g			↓14.61	
	Trypsin inhibitors	5.69 ± 0.15 TIU/g			↓76.91	
Velvet bean	Tannins	0.14 ± 0.01 g/100 g	MW—2450 MHz	900 W, 130°C, 12 min	↓43.00%	Kala and Mohan (2012)
	Phytic acid	483 ± 0.41 mg/100 g			↓36.00%	
	Hydrogen cyanide	0.16 ± 0.03 mg/100 g			↓100%	
	Total oxalate	0.12 ± 0.01 mg/100 g			↓100%	
	Phenol	3.68 ± 0.06 g/100 g			↑24%	
Pea	Phytic acid	11.9 mg/g	MW—2450 MHz	Cooking with two times of water for 4–12 min	↓0%–38.70%	Habiba (2002)
	Trypsin inhibitor	2.2 units/mg			↓100%	
	Tannins	2.06 mg/g			↓2.9%–25.7%	
	Lectins A	8 units			↓100%	
	Lectins B	8 units			↓100%	
	Lectins O	4 units			↓100%	

(Zhong et al. 2015), whereas MW was better than traditional cooking for peas (Habiba 2002). Moreover, soaking pulses in water prior to cooking can lead to more loss of water-soluble minerals (Y. Xu et al. 2016). Pulses and legumes are moderate sources of vitamins including vitamins C, E, and K (Prodanov et al. 2004). Like minerals, heating of pulses in the EM spectrum can result in quantitative loss of vitamins.

The changes in nutritional quality during MW or RF heating depend on several factors including the type and moisture content of the materials, and the duration and intensity of heat. Comparing between these two processes, RF might be more suitable than MW for the improvement or retention of macronutritional and micronutritional quality.

6.3 | Effect on Antinutrients

By reducing bioavailability and digestibility, antinutrients lead to lowering the nutritional value of foods in human body (Sinha and Khare 2017). Complete destruction or removal to a minimum level of the antinutrients is now a matter of concern. EM heating including MW, RF, and infrared can efficiently safely minimize antinutrient levels without the use of any chemical treatments. They also cause fewer nutritional losses and result in a final product of superior quality (Linsberger-Martin et al. 2013; Režek Jambrak et al. 2018). There are a few studies available on reduction of antinutrients using RF and MW. In this section, the effect of RF and MW on different antinutrients of pulses is discussed.

6.3.1 | TI

TIs are a class of protease inhibitors that impede the full absorption of nutrients in food. Naturally, TIs are polypeptides and based on the reactive site of TI, they are classified as the serine protease inhibitors (Das et al. 2022; Ram et al. 2020). Their presence in the human diet interferes with protein digestion and obstructs the metabolic utilization of amino acids and sulfur, potentially causing pancreatic hyperplasia (Adeyemo and Onilude 2013; Suhag et al. 2021). They inhibit the protease enzyme, resulting in diminished protein digestion in the small intestine and accelerating the removal of proteins from the body. As a result, sulfur-containing amino acids such as methionine and cysteine become less bioavailable in pulses (Nikmaram et al. 2017; Suhag et al. 2021). As seen in Table 4, most of the common pulses have a good amount of TI. EM heating can reduce the TI activity. D. Oke (2021) investigated the potential of RF (27.12 MHz) at three different powers (3, 7, and 9 kW) and temperatures (55°C, 75°C, and 115°C) on the reduction of the antinutrients in lentils. They reported that around 3%–40% and 29%–80% reduction of TI activity was possible for lentil and chickpea, respectively. The authors also observed that higher temperature of RF treatment can result in more reduction of TI activity from lentil. This correlation might be due to the denaturation of TI as they are small proteins. In the case of black soybeans and regular soybean, RF was able to deactivate around 15% (Zhong et al. 2015) and 55%–87% of TI, respectively. MW has also been identified to inactivate TI. Using MW, inactivation of more than 93% of TI in lentil seeds was reported (Hefnawy 2011), and a complete destruction of TI was reported for pea by Habiba (2002). A comparative analysis between MW and RF treatments revealed that RF was more potent in removing TI from black soybeans (Zhong et al. 2015).

6.3.2 | Phytic Acid

Phytic acid and its salts, known as phytates, are found in grains, legumes, nuts, and seeds. They bind with metal ions like iron, zinc, calcium, and magnesium, reducing their absorption and bioavailability. This chelating property, due to its six phosphate groups, makes phytic acid an antinutrient, potentially causing mineral deficiencies in humans and animals (Samtiya et al. 2020; Suhag et al. 2021). MW and RF have been successful in the reduction of phytates in different pulses as shown in Table 4. According to Zhong et al. (2015), MW was able to destroy 20% of phytic acid in black soybean, whereas RF destroyed around 28%. While RF reduced phytic acid in chickpea flours, in the case of lentils, D. Oke (2021) observed a slight increase in their levels at a heating temperature of 75°C. The author mentioned that the low moisture content of the raw seeds might obstruct the RF's ability to reduce phytic acid. On the contrary, all the research on MW resulted in the destruction of around 0%–40% of phytic acid based on the MW power, frequency, treatment time, product moisture, presoaking in water, etc. Thus, finding the optimum time, temperature, and cooking strategies is necessary for both RF and MW processing, focusing on individual pulse.

6.3.3 | Saponins

Saponins are nonvolatile, surface-active compounds mainly found in plants, often in pulses and legumes such as peanuts, soybeans, and chickpeas. They are structurally composed of either steroids or triterpenes with an attached sugar component (Moses et al. 2014; Samtiya et al. 2020). Saponins can adversely affect human health by reducing iron absorption, interfering with protein digestion by modifying protein structure, and causing significant hemolytic activity by interacting with cholesterol in red blood cell membranes (Fleck et al. 2019; Kaspchak et al. 2020; Suhag et al. 2021). From Table 4, it is evident that MW or RF potentially reduce the saponin content of different pulses. Only report on RF shows that the raw black soybean had 62.13 g/kg of saponin, of which around 22% could be reduced using 6 kW of 27-MHz RF treatment for 30 min. They also found almost the same amount of saponin reduction using 1 kW of 2450-MHz MW for 30 min. Very few studies are available on the MW or RF processing for the reduction of saponins from pulses; however, a study on MW treatment of horse chestnut resulted in a reduction of saponin content by 35.47% after 1 min, 57.64% after 1.5 min, 81.28% after 2 min, and 87.19% after 2.5 min (Rafiq et al. 2016). EM heating, either MW or RF, generally changes the structure of the pulses and other crops resulting in reduction of saponins (Badifu 2001). Based on this summary, MW and RF have potential for pulse processing, but comprehensive studies for determining optimum conditions are needed.

6.3.4 | Tannins

Tannins are water-soluble phenolic compounds classified as either hydrolyzable (like ellagitannins and gallotannins) or condensed (like proanthocyanidins) (de Camargo and da Silva Lima 2019). They hinder protein digestion by forming tannin–protein complexes through hydrogen bonding between the hydroxyl groups of tannins and the carbonyl groups of proteins, which can be either reversible or irreversible (Raes et al. 2014). They are mainly located in seed coats. Due to their water-soluble and heat-sensitive nature, they experience substantial reductions during heat processing methods (Sharma et al. 2018), such as MW and RF treatment. A comparative study on both MW and RF processing on black soybeans revealed that both of these EM heating methods had a similar effect on tannins reduction (~17%) (Zhong et al. 2015). Yang et al. (2014) reported that MW heating for 3 min at 850 W (2.45 GHz) removed more tannins from yellow soybean (15.14%) than black soybean (1.34%). Heating of faba bean pesto sauce using MW at 11 kW and 110°C for 30 s resulted in ~20% reduction of condensed tannins (Klug et al. 2018). MW cooking of lentils with tap water at a 1:10 w/v ratio for 15 min resulted in even higher reduction of around 35% tannins (Hefnawy 2011). However, soaking in water alone was not reported to be effective in significantly reducing tannin content from Kabuli chickpea (Y. Xu et al. 2016), though soaking before MW treatment enhanced the reduction of tannin content in velvet beans (Kala and Mohan 2012). In summary, RF and MW heating can reduce tannins, possibly by breaking down the tannin–protein complex and degrading the heat-sensitive–free tannins. Additionally, soaking before processing may help further reduce tannins through the process of leaching (Suhag et al. 2021).

6.3.5 | Others

There are a few other antinutrients such as lipoxygenase, oxalates, and lectins that can possibly be found in pulses. MW or RF may help in their reduction to a certain extent or even completely. D. Oke (2021) found that heating at 115°C using 3 kW of RF (27.12 MHz) can destroy ~99% of lipoxygenase in lentil flour, whereas comparatively lower temperature (55°C and 75°C) and higher power (7 and 9 kW) at the same RF frequency destroyed 99%–100% of lipoxygenase in chickpea flour. MW processing of velvet bean at 130°C and 900 W for 12 min reduced 100% of oxalate and hydrogen cyanide (Kala and Mohan 2012). A study on pea to remove lectins using MW heating resulted in complete destruction of lectins A, B, and O (Habiba 2002). These studies concluded that both RF and MW are very effective for the reduction of these minor antinutrients.

7 | Limitations of RF and MW Heating

Like most current technologies, both MW and RF heating presents some disadvantages that restrict their extensive use in the pulse processing sector. Nonuniform heating is one of the major limitations of MW and RF for bulk samples, resulting in hot and cold spots where the temperature is much higher or lower, respectively, compared to the average temperature (Altemimi et al. 2019; Suhag et al. 2021). This nonuniform heating can cause thermal damage to some parts of the products while other parts do not reach the expected temperature for desirable results. Additionally, penetration depth is another limitation of these heating methods. In the case of dense or bulk layer processing of pulses, MW or RF waves may have difficulty to reach the deep layers, leading to uneven heating Moreover, scaling up of RF and MW processes for commercial use is challenging due to difficulties in maintaining consistent heating and efficiency in larger volumes (Zeng et al. 2022). RF and MW heating is also subjected to high regulatory criteria to ensure safe and reliable processing. Operators need specific training to efficiently manage these systems. Industrial-scale equipment is often more expensive than conventional heating system equipment (Gao et al. 2023). As thermal processing techniques, both RF and MW have the potential to denature proteins and decrease their solubility and functionality, if not optimized properly.

8 | Knowledge Gaps

Both RF and MW have resulted in several beneficial outcomes in the pulse processing sector. As they play a potential role in the improvement of nutritional properties and reduction of antinutritional factors, researchers and processors are showing more interest in exploring these modern technologies in various ways. Following a thorough review of the available studies, we have listed the knowledge gaps in literature, and the potential future research outlook is listed below:

a. There is no research on the optimal processing parameters (frequency, power level, temperature, exposure period) for various pulses. Models that predict how various conditions influence different pulse varieties must be developed, emphasizing energy efficiency and uniformity while retaining nutritional quality and reduction of antinutrients.

b. Developing improved control systems, adaptive algorithms, and real-time monitoring approaches to improve heating uniformity and product quality.

c. Explore the advantages of combining MW and/or RF heating with other approaches to increase efficiency, reduce antinutritional components, and improve overall pulse quality.

d. Technoeconomic analyses are required to establish the cost-effectiveness and feasibility of using these technologies for industrial-scale pulse processing.

e. Life cycle assessment (LCA) studies should be conducted to evaluate the sustainability of these technologies, with the objective of developing energy-efficient and environmentally friendly pulse processing methods.

f. Sensory research might aid in the optimization of processing parameters to yield ingredients that are consistent with consumer tastes while still providing nutritional advantages.

9 | Conclusion

Pulses are a commonly cultivated and consumed food products owing to their unique nutritional value and availability. These protein-rich meals include some antinutritional compounds that reduce the bioavailability and effective use of nutrients in the human body. Limiting the scope of this review to RF and MW treatment of pulses, we outlined how these heating techniques function in food processing, as well as how processing factors affect heating efficiency in pulses. The use of these technologies has resulted in a significant reduction in antinutrients in various pulses. Combining with other procedures, such as soaking in water, may also be beneficial. Future research should also focus on process optimization, scaling up, environmental and technoeconomic evaluations, consumer acceptance, and so on. Further studies in this area will be useful for industries to set up MW- or RF-based processing facilities in future.

Author Contributions

Pabitra Chandra Das: conceptualization, writing – original draft, data curation, investigation, formal analysis. **Oon-Doo Baik:** writing – review and editing, supervision. **Lope G. Tabil:** writing – review and editing, supervision. **Nandhakishore Rajagopalan:** conceptualization, writing – review and editing, supervision.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

This article is not eligible for data sharing because it neither created nor examined any new data.

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