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Research Article

Bio-Shielding Potential of *Opuntia cochenillifera* on Uterine and Placental Integrity Under Electromagnetic Wave Exposure

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ABSTRACT

Continuous exposure to radiofrequency electromagnetic waves (EMW) emitted by mobile phones and Wi-Fi may disrupt reproductive tissues, particularly during pregnancy. This study investigated the bio-shielding potential of *Opuntia cochenillifera* applied externally as an abdominal belt to attenuate uterine and placental damage under EMW exposure. Pregnant Balb/C mice (n = 42) were allocated into six groups: healthy control (HCG), negative control exposed to EMW without protection (NCG), and four cactus-shielded groups (E1–E4; fresh cactus, dried cactus, gel extract, and powder extract). Animals were continuously exposed to EMW (900 MHz and 2.45 GHz; SAR 1.74 W kg^{-1}) during gestational days 1–19. Uterine and placental tissues were evaluated using histopathological scoring and morphometric measurements. Cactus materials were characterised using XRF and FTIR spectroscopy. The NCG group exhibited the most severe uterine and placental tissue injury, reflected by significantly higher endometrial, myometrial, and placental damage scores compared with HCG ($p < 0.001$). All cactus-shielded groups demonstrated significantly reduced uterine and placental damage scores and significantly improved labyrinth length compared with NCG ($p < 0.001$). No significant differences were observed among cactus preparations ($p > 0.05$). External bio-shielding using *O. cochenillifera*-based belts attenuated EMW-associated uterine and placental histopathological damage in pregnant mice. These findings supported cactus-derived materials as promising eco-friendly shielding candidates for reproductive health protection.

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INTRODUCTION

Wireless communication technologies have expanded rapidly over the past two decades, leading to a substantial increase in daily human exposure to radiofrequency electromagnetic fields (RF-EMF) (İkinci et al. 2019; Melnick et al. 2025). Mobile phones and Wi-Fi routers operate primarily within the 900 MHz and 2.45 GHz frequency ranges, which are major sources of continuous exposure in home and workplace environments (Melnick et al. 2025; Bertuccio et al. 2023).

International exposure guidelines and safety standards have historically focused on preventing tissue heating caused by RF-EMF (Lai & Levitt 2024; Melnick et al. 2025). However, in addition to thermal mechanisms, many experimental and mechanistic studies have proposed that RF-EMF may trigger biological responses through non-thermal pathways (Lai & Levitt 2024; Radil et al. 2024). Recent reviews have described these pathways as form of "cellular stress response", characterised by oxidative stress induction, mitochondrial dysfunction, altered calcium signalling, DNA damage, and modulation of inflammatory pathways (Salameh et al. 2023; Lai & Levitt 2024).

Pregnancy represents a highly sensitive physiological window for evaluating environmental stressors, given the strict cellular and vascular regulation required for successful reproduction and foetal development (Pacchierotti et al. 2021; Grzeszczak et al. 2023). The uterus plays a critical role in implantation, decidualisation, and maintenance of foetal growth, whereas the placenta functions as a transient organ responsible for gas exchange, nutrient transfer, endocrine signalling, and immunological regulation (Pacchierotti et al. 2021; Flores-Espinosa et al. 2023). Placental structure is composed of functionally distinct zones, including the decidua basalis and the labyrinth, where the labyrinth zone is essential for maternal–fetal exchange and microvascular organisation (Arumugasaamy et al. 2020; Pacchierotti et al. 2021; Elmore et al. 2022).

Concerns regarding RF-EMF exposure during pregnancy have led to systematic evaluations coordinated by the World Health Organization (WHO) framework (Melnick et al. 2025). One WHO-commissioned systematic review and meta-analysis in *Environment International* evaluated pregnancy and birth outcomes in experimental non-human mammals exposed to RF-EMF, highlighting the need for improved exposure characterisation and outcome consistency across studies (Cordelli et al. 2024; Bundesamt für Strahlenschutz (BfS) 2025). Similarly, ARPANSA published a systematic review and meta-analysis in 2023 summarising the evidence on RF-EMF exposure during pregnancy and adverse reproductive and developmental endpoints in experimental mammals (Australian Radiation Protection and Nuclear Safety Agency 2023).

These coordinated systematic reviews emphasised that although the evidence across studies remains heterogeneous, the reproductive and developmental domains warrant continued investigation due to biological plausibility and reported tissue-level alterations in some models (Pacchierotti et al. 2021; Australian Radiation Protection and Nuclear Safety Agency 2023). At the cellular and molecular levels, oxidative stress is frequently cited as the dominant mechanism by which RF-EMF influences tissue integrity (Lai & Levitt 2024). Lai and Levitt (2024) described that the cellular response to non-ionising electromagnetic fields resembles responses to other environmental stressors, involving oxidative damage to lipids, proteins, and DNA, and the activation of repair pathways (Lai & Levitt 2024; Meyer et al. 2024). Mitochondrial dysregulation and altered redox balance are repeatedly reported across RF-EMF experimental systems and are proposed as upstream factors contributing to inflammatory and apoptotic signalling cascades (Lai & Levitt 2024; Abtin et al. 2024; Hajinejad et al. 2024).

Given the ubiquitous presence of RF-EMF exposure, preventive strategies that reduce electromagnetic interactions with biologically sensitive tissues have gained attention (Melnick et al. 2025). Electromagnetic interference (EMI) shielding materials can reduce the penetration of electromagnetic waves primarily through reflection, absorption, and multiple reflection mechanisms (Joseph et al. 2025). However, conventional shielding materials, such as metals and carbon composites, have limitations, including rigidity, high cost, lack of biodegradability, and reduced suitability for wearable biological applications (Joseph et al. 2025; Yang et al. 2025). Consequently, research interest has shifted toward environmentally friendly and flexible shielding materials, including polymer-based and biomass-derived systems (Wang et al. 2023; Yang et al. 2025). Recent materials science reviews have highlighted polysaccharide-derived composites (e.g. cellulose, chitosan, and alginate) as promising candidates for eco-friendly EMI shielding owing to their biodegradability, biocompatibility, and capacity for structural engineering (Wan & Yang 2024; Tamuntuan et al. 2025).

In this context, plant-based biomaterials are attractive because they contain complex matrices of polysaccharides, mineral oxides, and functional organic groups that can contribute to electromagnetic attenuation through dielectric polarisation and absorption processes (Wan & Yang 2024; Tamuntuan et al. 2025). *Opuntia cochenillifera* (cactus) is widely distributed in tropical and subtropical regions and contains polysaccharide-rich mucilage, phenolic compounds, and mineral components that may influence its dielectric properties (Wan & Yang 2024; Tamuntuan et al. 2025). Although *Opuntia* species have been widely studied in nutritional and medicinal contexts, evidence supporting their use as a physical shielding interface against RF-EMF, particularly during pregnancy, is limited (Australian Radiation Protection and Nuclear Safety Agency 2023; Cordelli et al. 2023).

To date, most biological studies related to RF-EMF protection during pregnancy have focused on supplementation or biochemical interventions rather than wearable shielding approaches (Moghadasi et al. 2021; Zhou et al. 2023). Furthermore, few studies have investigated sustainable bio-based materials that can function as noninvasive shielding interfaces to protect uterine and placental tissues from chronic RF-EMF exposure (Joseph et al. 2025; Tamuntuan et al. 2025).

Therefore, the present study investigated the protective potential of *O. cochenillifera* preparations applied externally as abdominal belts (fresh cactus, dried cactus, gel extract, and powder extract) in pregnant Balb/C mice continuously exposed to RF-EMF (900 MHz and 2.45 GHz). Uterine and placental outcomes were evaluated using histopathological scoring and morphometric measurements to assess tissue integrity and placental zonation.

In addition, physicochemical characterisation using X-ray fluorescence (XRF) and Fourier-transform infrared (FTIR) spectroscopy was conducted to identify the mineral oxide profiles and functional group structures that may contribute to the shielding effectiveness.

MATERIALS AND METHODS

Animal Experimental

The experimental mice were obtained from the Faculty of Animal Science, Diponegoro University, and subsequently housed and acclimatized in the Animal Laboratory of the Faculty of Medicine, Diponegoro University, where all treatments and experimental procedures were conducted between June and December 2024. Forty-two Balb/C mice were acquired for experimental mating, ensuring a 3:1 female-to-male ratio. These rats weighed between 25 and 30 grams, irrespective of sex. Environmental parameters were regulated at 24 ± 2 °C, with humidity maintained at 50-60 % and alternate 12-hour light

and dark cycles. The animals had unimpeded access to water and food pellets.

Following seven days of isolation, the researchers cohabited 42 breeding mice during nocturnal hours. Morning inspections of vaginal plugs confirmed pregnancy, termed as gestational day 0 (GD 0), necessitating the removal of the men. Successful breeding was confirmed at G10 and G13, indicated by a 3–4 g rise in female body mass. Researchers have employed weight swings as indications of pregnancy, with increases suggesting successful gestation and abrupt decreases signaling prenatal problems or miscarriage (Neres et al. 2008).

The study divided 42 gestating subjects into six groups, accommodating them in 45 cm × 45 cm × 25 cm polypropylene containers. Absorbent wood chip bedding is renewed three times daily for enhanced living conditions.

Experimental Design and Treatment Description

The study included one healthy control group (HCG) that was not exposed to electromagnetic wave (EMW) radiation and five EMW-exposed groups: a negative control group (NCG) and four cactus-shielded groups (E1–E4). Pregnant Balb/C mice were randomly assigned into six groups: HCG, NCG (EMW exposure without shielding), and four treatment groups fitted with abdominal belts containing different *Opuntia cochenillifera* preparations: fresh cactus (E1), dried cactus (E2), gel extract (E3), and powder extract (E4).

All EMW-exposed groups (NCG and E1–E4) were subjected to continuous EMW radiation generated by a cellular phone operating at 900 MHz and a Wi-Fi source at 2.45 GHz, with a whole-body specific absorption rate (SAR) of 1.74 W kg^{-1}. Exposure was applied for 24 h day^{-1} from gestational day (GD) 1 to GD19. The NCG group received EMW exposure without any protective measures, while the E1–E4 groups received external shielding using cactus-filled abdominal belts designed to mitigate EMW-related effects.

For belt preparation, each abdominal belt was fabricated from a sterilised plastic pouch filled with the corresponding cactus material and molded to conform to the abdominal contour of the mice. Prior to belt placement, abdominal fur was removed to ensure direct skin contact. The belt was secured using waterproof adhesive plaster to maintain consistent positioning and continuous contact throughout EMW exposure. Belts were inspected daily and replaced every 24 hours to maintain hygiene and uniform exposure conditions. Importantly, cactus preparations were applied exclusively as an external, non-invasive physical shielding interface and were not administered orally or transdermally.

The belt contents were prepared as follows:

(i) E1 (Fresh Cactus Belt): freshly cut raw cactus was sliced into small fragments and placed into the belt pouch.

(ii) E2 (Dried Cactus Belt): cactus was sun-dried and processed into coarse powder before incorporation into the belt.

(iii) E3 (Cactus Extract Gel Belt): cactus extract was prepared by maceration using 70 % ethanol, formulated into a gel, and incorporated into the belt.

(iv) E4 (Cactus Extract Powder Belt): the gel extract prepared for E3 was dehydrated into a fine powder and used as the belt content.

Belt Composition and Application

Each therapeutic belt comprised a waterproof adhesive patch measuring 15 × 3 cm, including a 2 × 1 cm centre capsule constructed from a modified paper clip. The pill encompassed the cactus formulation pertinent to each treatment group. The cactus material was not administered transdermally nor orally, and there was no direct biochemical contact with cutaneous cells or systemic antioxidant mechanisms. The Cactus functioned as a physical interface engi-

neered to reflect or absorb incoming electromagnetic waves, providing a non-invasive protective mechanism. Ethical approval was secured from the Medical and Health Research Ethics Commission of Diponegoro University (No. 116/EC-H/KEPK/FK-UNDIP/IX/2023).

Sample collection

On gestational day 20, euthanasia was performed by intraperitoneal injection of ketamine. Following confirmation of death, pregnancy was terminated, and the placentas were carefully dissected from the Uterus. The tissues were then processed for histological examination and stained with Hematoxylin and Eosin (H&E).

Statistical analysis

A statistical study indicated that uterine and placenta tissue examinations exhibited non-normal distribution, as assessed by the Shapiro-Wilk test. Consequently, nonparametric testing was utilised. Group comparisons were conducted using the Kruskal-Wallis and Mann-Whitney U tests for post-hoc analysis. All data are presented as mean ± standard deviation (SD), with statistically significant differences indicated at $p < 0.05$. Analyses were conducted utilising SPSS version 26.0.

RESULT

Table 1 shows histopathological scores and thickness measurements of the endometrium (End), myometrium (Mio), decidua basalis (DB), and labyrinth zone in the placenta. Superscript letters indicate significant differences between groups ($p < 0.05$), with different letters representing statistically distinct values. Parameters with no letter variation indicated non-significant differences in the Kruskal–Wallis test. Different superscript letters within the same row indicated significant differences between groups at $p < 0.05$ (Mann–Whitney post-hoc test following Kruskal–Wallis).

Table 1. Uterine and placental histopathological scores and thickness (Mean ± SD) in Balb/C mice.

Group	End Score	Mio Score	End Thickness (cm)	Mio Thickness (cm)	Placenta DB Thickness (cm)	Placenta Labyrinth Thickness (cm)	DB Placenta Score	Labyrinth Placenta Score
HCG (Healthy Control)	0.40 ± 0.50^{a}	0.48 ± 0.51^{a}	1.52 ± 0.57^{a}	2.35 ± 0.40^{a}	0.95 ± 0.17^{a}	2.77 ± 0.27^{a}	0.36 ± 0.49^{a}	0.64 ± 0.49^{a}
NCG (Negative Control)	3.32 ± 0.63^{b}	1.72 ± 0.61^{b}	0.74 ± 0.13^{b}	2.00 ± 0.51^{a}	0.94 ± 0.17^{a}	2.35 ± 0.20^{a}	3.08 ± 0.64^{b}	1.72 ± 0.61^{b}
E1 (Fresh Cactus)	0.57 ± 0.51^{a}	0.68 ± 0.48^{a}	1.49 ± 0.59^{a}	2.25 ± 0.33^{a}	0.95 ± 0.17^{a}	2.74 ± 0.28^{a}	0.36 ± 0.49^{a}	0.48 ± 0.51^{a}
E2 (Dried Cactus)	0.56 ± 0.51^{a}	0.48 ± 0.51^{a}	1.35 ± 0.60^{a}	2.15 ± 0.24^{a}	0.94 ± 0.16^{a}	2.75 ± 0.26^{a}	0.60 ± 0.50^{a}	0.88 ± 0.33^{a}
E3 (Cactus Extract Gel)	0.67 ± 0.48^{a}	0.76 ± 0.44^{a}	1.33 ± 0.47^{a}	2.16 ± 0.28^{a}	0.95 ± 0.17^{a}	2.71 ± 0.29^{a}	0.44 ± 0.51^{a}	0.56 ± 0.51^{a}
E4 (Cactus Extract Powder)	0.68 ± 0.48^{a}	0.76 ± 0.44^{a}	1.21 ± 0.42^{a}	2.07 ± 0.29^{a}	0.93 ± 0.18^{a}	2.54 ± 0.30^{a}	0.48 ± 0.51^{a}	0.60 ± 0.50^{a}

Uterine Histopathological Scores

The NCG group exhibited the most severe uterine injury, indicated by the highest endometrial score (3.32 ± 0.63) and myometrial score (1.72 ± 0.61). In contrast, HCG showed minimal tissue alteration with significantly lower endometrial and myometrial scores (0.40 ± 0.50 and 0.48 ± 0.51, respectively). Pairwise comparisons confirmed significant differences between HCG and NCG across all parameters ($p < 0.001$).

All cactus-shielded groups demonstrated significantly lower uterine damage scores compared with NCG ($p < 0.001$). No significant differences were observed among cactus preparations (E1–E4) ($p > 0.05$).

Uterine Morphometry

Endometrial length was reduced in NCG (0.74 ± 0.13 cm) relative to HCG (1.52 ± 0.57 cm). Treatment groups showed improved endometrial length (1.21–1.49 cm). Post hoc testing showed that E2 and E3 had significantly longer endometrial length than NCG ($p = 0.019$ and $p = 0.028$), whereas E1 did not ($p = 0.149$) and E4 showed borderline significance ($p = 0.050$).

Myometrial length also decreased in NCG (2.00 ± 0.51 cm) compared with HCG (2.35 ± 0.40 cm), and increased again in cactus-treated groups; however, differences were not significant among treatment groups ($p > 0.05$).

Placental Morphometry and Damage Scores

Decidua basalis length remained stable across groups (approximately 0.94–0.95 cm) and did not show significant differences ($p > 0.05$). In contrast, labyrinth length decreased in NCG (2.35 ± 0.20 cm) compared with HCG (2.77 ± 0.27 cm), and was significantly restored in all cactus-shielded groups ($p < 0.001$), particularly in E1 and E2.

Placental damage scores were highest in NCG for both DB and labyrinth regions (3.08 ± 0.64 and 1.72 ± 0.61, respectively). All cactus-treated groups showed significantly reduced placental damage scores compared with NCG ($p < 0.001$), approaching HCG values. No significant differences were observed among E1–E4 groups ($p > 0.05$).

Mineral Composition and FTIR Spectral Analysis

X-ray fluorescence (XRF) analysis (Table 2) revealed distinct variations in mineral profiles among the raw Cactus, dried Cactus, cactus extract gel, and cactus extract powder preparations. Dried Cactus exhibited the highest calcium oxide (CaO) content (1.90 %), while cactus extract gel was notably enriched in potassium oxide (K_2O, 8.45 %) and chloride (Cl, 5.43 %). Magnesium oxide (MgO) was markedly higher in the cactus extract gel (1.49 %) compared to other forms. Trace elements such as Fe_2O_3, Ag_2O, and iodine were detected predominantly in the raw Cactus, whereas bromine (Br) appeared only in the cactus extract gel and powder.

Table 2. Mineral content of cactus preparations determined by XRF.

Mineral	Raw Cactus	Dried Cactus	Cactus Extract Gel	Cactus Extract Powder
CaO	0.288 %	1.90 %	0.05 %	0.12 %
MgO	0.0728 %	0.353 %	1.49 %	0.0953 %
K_2O	0.0553 %	1.37 %	8.45 %	0.764 %
Cl	0.0683 %	0.245 %	5.43 %	0.349 %
Trace elements	Fe_2O_3, Ag_2O, I, RuO_2, TeO_2, ZrO_2/ Nb_2O_5	Fe_2O_3, P_2O_5, SO_3, SrO	Br, P_2O_5, SO_3, Rb_2O	P_2O_5, SO_3, Br, Rb_2O

Fourier-transform infrared (FTIR) spectroscopy identified key functional groups in all preparations (Table 3). Raw cactus spectra indicated potent hydroxyl stretching (3305 cm^{-1}), carbonyl amide (1636 cm^{-1}), and ether/polysaccharide peaks, consistent with high water and carbohydrate content. Dried Cactus retained hydroxyl and aromatic ring signals with increased ester/protein-associated peaks. Cactus extract gel exhibited vigorous carbonyl stretching (1722 cm^{-1}), indicative of ester or carboxylic acids, alongside aromatic and amine groups. Cactus extract powder showed intense hydroxyl and phenolic signals, complex polysaccharide bands, and substituted aromatic ring patterns.

Collectively, these results indicated that drying enhances CaO and K_2O concentration. At the same time, extraction—particularly in gel form—leads to substantial enrichment of K_2O, Cl, and MgO, alongside pronounced functional groups related to aromatic compounds and polysaccharides. These compositional and structural differences might underlie variations in the biological activity observed across preparations.

DISCUSSION

The present study investigated the potential of different cactus-based formulations: raw, dried, gel extract, and powder extract in mitigating the detrimental effects of electromagnetic wave (EMW) exposure on uterine and placental structures in Balb/C mice. The focus was directed toward understanding how the physicochemical composition of cactus materials, characterized via X-ray fluorescence (XRF) and Fourier-transform infrared spectroscopy (FTIR), could contribute to electromagnetic interference (EMI) shielding, thereby preserving maternal reproductive tissues during pregnancy.

Impact of EMW on Uterine and Placental Tissue

Exposure to EMW, particularly in the 900 MHz to 2.45 GHz frequency range typical of modern wireless devices, has been linked to adverse reproductive outcomes in both experimental animals and epidemiological studies (Australian Radiation Protection and Nuclear Safety Agency 2023; Johnson et al. 2024). Recent WHO-coordinated systematic reviews emphasised that evidence on RF-EMF exposure during pregnancy in experimental mammals remains heterogeneous due to differences in exposure characterisation, endpoints, and study quality, yet tissue-level alterations have been reported in a subset of studies, supporting continued research on uteroplacental integrity (Cordelli et al. 2023; Pacchierotti et al. 2021). ARPANSA's systematic review and meta-analysis in experimental mammals similarly highlights the need for improved standardisation while acknowledging reported effects in some outcomes across studies (Australian Radiation Protection and Nuclear Safety Agency 2023).

Table 3. Prominent FTIR peaks and corresponding functional groups in cactus preparations.

Sample	Main Peaks (cm^{-1})	Key Functional Groups
Raw Cactus	3305 (O–H), 2110 (Alkyne/N=C=O), 1636 (C=O amide), 1018 (C–O–C)	Hydroxyl, amide, ether/polysaccharide, reactive triple bond
Dried Cactus	3265 & 2917 (O–H, C–H), 1606 (C=C aromatic), 1316 & 1033 (C–O/C–N ester)	Hydroxyl, aromatic ring, ester/protein
Cactus Extract Gel	3217 (O–H), 1722 (C=O ester), 1584 (C=C aromatic/N–H), 1047 (C–O)	Hydroxyl, ester/carboxylic acid, aromatic/amine, carbohydrate
Cactus Extract Powder	3324 (O–H), 1593 (C=C aromatic/amide), 1030–1068 (C–O), 749 & 670 (Aromatic sub.)	Hydroxyl, phenolic, polysaccharide, substituted aromatic rings

In our EMW-only control group (NCG), uterine and placental deterioration was evident through increased histopathological injury, including inflammation, cellular degeneration, and necrosis. In the EMW-exposed group, histological analysis revealed apoptotic features within endometrial surface epithelium, glandular cells, and stromal compartments, consistent with tissue stress responses reported in prior EMF exposure studies (Asghari et al. 2016; Lai & Levitt 2024). These findings are broadly consistent with experimental studies reporting uterine epithelial degeneration, inflammatory infiltration, and vascular congestion following radiofrequency exposure (Santini et al. 2018; Cordelli et al. 2023). Although our study design did not evaluate endocrine endpoints, previous tissue and organ culture studies have shown that electromagnetic exposure can alter reproductive hormone signaling, including modulation of oestradiol synthesis depending on frequency and exposure duration (Mansouri et al. 2020; Kim et al. 2021; Lai & Levitt 2024).

From a biological perspective, placental disruption is particularly important because impairment of placental barrier integrity may compromise oxygen and nutrient transfer and contribute to adverse fetal outcomes (Blake et al. 2020; Cordelli et al. 2023; Danielsson et al. 2023). Human observational evidence remains limited by exposure assessment and confounding, but ARPANSA's 2024 systematic review indicated continued scientific concern regarding potential associations between RF-EMF exposure and pregnancy outcomes (Australian Radiation Protection and Nuclear Safety Agency 2023). Therefore, evaluation of structural endpoints such as labyrinth and decidua basalis integrity provides mechanistically plausible insights into the uteroplacental effects of EMW exposure (Drews et al. 2020; Elmore et al. 2022; Ortega et al. 2022; Cordelli et al. 2023).

Potential Biological Mechanisms: Stress Response, Oxidative Balance, and Cellular Signaling

Electromagnetic waves can interact with biological systems through multiple mechanisms, and the resulting outcomes depend strongly on frequency, intensity, exposure duration, and tissue context (Pacchierotti et al. 2021; Cordelli et al. 2023). Mechanistic reviews propose that RF-EMF exposure may influence oxidative balance, mitochondrial function, calcium signaling, and inflammatory pathways, which together may manifest as a generalised "cellular stress response." (Pacchierotti et al. 2021; Cordelli et al. 2023). Lai and Levitt (2024) emphasised that cellular responses to non-ionizing EMFs resemble responses to other stressors and may include oxidative stress, macromolecular damage, and activation of repair pathways (Pacchierotti et al. 2021; Australian Radiation Protection and Nuclear Safety Agency 2023; Cordelli et al. 2023; Lai & Levitt 2024)

Although oxidative stress and inflammation are frequently proposed pathways in the literature, oxidative stress biomarkers (e.g., MDA, SOD, CAT) and inflammatory mediators (e.g., IL-6, TNF-α) were not measured in the current study. Therefore, mechanistic interpretation in this study should be considered hypothesis-based rather than definitive. Nonetheless, the observed preservation of uterine and placental histological integrity in cactus-treated groups is consistent with a protective tissue-level profile and supports future work to validate redox and inflammatory mechanisms using direct biomarkers.

Mineral Composition and Potential EMW Attenuation

X-ray fluorescence (XRF) analysis identified distinct mineral oxide profiles among the four cactus preparations, indicating compositional heterogeneity that may affect their electromagnetic response. Notably, the dried cactus material demonstrated relatively higher concentrations of CaO compared to the

raw cactus, whereas the gel extracts were enriched in K_2O and exhibited elevated chloride levels. Trace amounts of Fe_2O_3 were detected in both the raw and dried samples. The compositional variations in materials may significantly influence electromagnetic wave (EMW) interactions through various physical attenuation mechanisms, as extensively documented in the electromagnetic interference (EMI) and microwave absorption literature. Materials containing magnetic constituents, such as iron oxides (e.g., Fe_2O_3), primarily contribute to magnetic loss mechanisms, including natural resonance and domain wall motion (Huang et al. 2024). These mechanisms enhance the absorption of incident electromagnetic fields by converting magnetic field energy into heat or other forms of internal energy, a phenomenon frequently observed in recent studies on ferrite-based absorbers (Dai et al. 2024; Yusmadi et al. 2025)

In contrast, oxide components such as CaO, MgO, and K_2O predominantly influence the dielectric properties of the medium. These materials affect dielectric polarization and relaxation processes in alternating electromagnetic fields (Chen et al. 2010). Dielectric loss mechanisms arise from interfacial polarisation, dipolar orientation, and defect-induced polarisation, thereby facilitating the dissipation of the electric-field component of the EMW (Qin et al. 2022). This framework aligns with recent comprehensive reviews of microwave dielectric and absorbing materials, which acknowledge that dielectric losses, including polarization contributions, are crucial for EMW attenuation (Jin et al. 2024). The incorporation of chloride ions into hydrated or gel matrices significantly influences ionic conductivity and the dielectric environment. Ionic species present in hydrogels and related composites have been demonstrated to markedly enhance electromagnetic attenuation by increasing charge mobility and interfacial polarisation. This, in turn, facilitates absorption-dominated shielding behavior at gigahertz frequencies (Wang et al. 2025).

The mineral oxides and salts present in cactus matrices may collectively contribute to the attenuation of electromagnetic waves (EMW) through three primary mechanisms, which are comprehensively examined in the existing shielding literature:

1. Magnetic loss occurs due to magnetic components such as Fe_2O_3, which cause permeability and resonance effects (Yusmadi et al. 2025)
2. The phenomenon of dielectric loss, associated with the presence of CaO, MgO, K_2O, and ionic species, enhances polarization and conduction mechanisms (Jin et al. 2024)
3. Impedance mismatch and microstructural scattering, resulting from heterogeneities that enhance internal reflections and multiple scattering, contribute to overall energy dissipation (Jin et al. 2024).

These mechanisms are consistent with the prevailing understanding in the field of electromagnetic interference (EMI) shielding and absorber design, where achieving a balance between magnetic and dielectric responses is essential for effective attenuation across a wide frequency range.

Organic Functional Groups and Dielectric Interaction

Fourier Transform Infrared (FTIR) analysis provided complementary insight into the dominant organic functional groups present in the cactus preparations, which may influence dielectric interactions with electromagnetic waves (EMW). All cactus samples exhibited prominent O–H stretching bands, corresponding to hydroxyl-rich polysaccharides and other oxygen-containing moieties; these polar functional groups possess permanent dipoles that can respond to alternating electric fields, facilitating dipole rotation and dielectric relaxation processes that contribute to energy dissipation at microwave frequencies. In dielectric microwave absorbers, such polar groups and associated vibrational modes are known to influence complex permittivity and enhance

dielectric loss through dipolar polarization mechanisms (Joon An et al. 2010; Dallaev et al. 2024).

Cactus gel and powder extracts also showed absorption bands attributable to C=O stretching, consistent with the presence of ester and carboxylic acid functionalities. Such carbonyl groups exhibit relatively high electronegativity differences and contribute to molecular polarisability, which affects dielectric relaxation behavior as the material's dipoles attempt to reorient with the alternating field. These effects have been correlated with modifications in dielectric properties in polymer and composite systems, where shifts in FTIR peak positions reflect changes in polar group interactions that affect complex permittivity (Eleojo et al. 2018; Dallaev et al. 2024).

The C–O stretching region observed across preparations suggests the presence of polysaccharide networks capable of forming hydrogen-bonded domains (Gieroba et al. 2023). Hydrogen-bonded networks can create dielectric heterogeneity and promote interfacial polarization at multiple scales, which in turn increases dielectric loss through relaxation and scattering phenomena in bio-based composites (Joon An et al. 2010). Lastly, aromatic C=C signatures detected in dried cactus and gel extracts are indicative of phenolic structures (Zeghbib et al. 2022). Although π-electron resonance interactions can contribute to polarization under high-frequency electric fields, these effects are generally weaker compared to dipolar and ionic mechanisms in typical dielectric loss processes (Joon An et al. 2010)

Synergistic Protection of Uterus and Placenta

The combination of mineral-based and organic-based attenuation mechanisms likely explains protect uterine and placental profiles observed in cactus-treated groups. Mineral oxides act as inorganic shielding agents, providing stable dielectric and magnetic losses, while organic polar groups offer dynamic dipole-based dissipation. This dual-mode attenuation reduces the net EMW energy reaching reproductive tissues, thereby mitigating structural and functional disruption.

In biological terms, attenuated EMW exposure could translate into preserved vascular integrity in the placenta, maintained endometrial thickness, and reduced inflammatory responses in uterine stroma. Although the present study did not directly measure inflammatory or oxidative stress biomarkers, histological assessments supported the protective narrative.

The differences among cactus preparations may also be explained through compositional factors: Dried cactus: high in CaO and MgO, good dielectric loss potential, Cactus gel extract: extremely high K_2O and Cl, enhancing scattering and impedance mismatch, Powder extract: balanced mineral and organic content, potentially offering intermediate but stable shielding, Raw Cactus: lower overall oxide content but retains complete hydration, possibly enhancing dielectric heating and scattering via water dipoles.

Implications and Future Directions

These findings open the door for bio-based EMI shielding materials derived from agricultural products such as Cactus. The ability to attenuate gigahertz-range EMW through a combination of mineral and organic mechanisms presents a sustainable alternative to synthetic shielding composites, which often involve costly or toxic components. Additionally, the application in maternal health contexts is particularly relevant, as pregnant individuals represent a sensitive population for EMW exposure risk.

Future work should focus on: Quantitative shielding measurements assessing specific reflection loss and absorption coefficients of cactus materials across relevant frequency bands, Long-term reproductive studies verifying whether the observed uterine and placental protection translates into im-

proved pregnancy outcomes, Material optimisation exploring cactus-mineral composites, possibly fortified with additional ferrite or conductive phases for enhanced shielding.

CONCLUSION

The present study demonstrates that continuous exposure to electromagnetic waves (EMWs) during pregnancy induces detrimental effects on maternal uterine integrity and is associated with placental structural disruption, which may contribute to impaired fetal development. Importantly, external shielding using cactus (*Opuntia spp.*) preparations applied via abdominal belt significantly attenuated uterine and placental histopathological damage compared with unprotected EMW exposure. Among the tested preparations, cactus powder showed the most consistent protective profile, suggesting that powder-based cactus materials may represent a promising natural, eco-friendly candidate for bio-shielding applications during gestation.

Although oxidative stress biomarkers were not directly measured in this study, the improved uterine and placental histological integrity observed in cactus-treated groups may involve oxidative stress–related pathways. Therefore, future studies should incorporate biochemical oxidative stress and inflammatory markers (e.g., MDA, SOD, CAT) to confirm the underlying mechanisms and to evaluate the translational potential of cactus-derived shielding materials in broader clinical settings.

LIMITATIONS AND FUTURE DIRECTIONS

This study primarily evaluated biological outcomes (uterine and placental histopathology and morphometry) and physicochemical characterisation (XRF and FTIR) of *Opuntia cochenillifera* preparations. A limitation of this work is the absence of direct, quantitative measurements of electromagnetic shielding effectiveness (e.g., reflection loss, transmission loss, absorption coefficient) at 900 MHz and 2.45 GHz. Future studies should incorporate vector network analyzer (VNA)-based measurements and standardised test fixtures to quantify shielding performance across relevant frequency bands.

In addition, the present study assessed reproductive tissue outcomes at a single time point (GD20) and did not evaluate long-term pregnancy outcomes such as fetal weight, live birth rate, neonatal survival, or postnatal developmental milestones. Longitudinal studies are warranted to determine whether histological protection translates into improved functional and developmental outcomes.

Although the discussion proposes potential attenuation mechanisms (dielectric loss, interfacial polarisation, scattering, and reflection), direct mechanistic validation was not performed. Future work combining computational electromagnetic modelling, advanced dielectric characterisation, and material microstructure analysis (e.g., SEM, impedance spectroscopy) will help elucidate the specific shielding mechanisms. Furthermore, oxidative stress and inflammatory biomarkers (e.g., MDA, SOD, CAT, ROS, IL-6, TNF-α) should be included to confirm biological pathways underlying EMW-induced tissue injury and cactus-mediated protection. Finally, material optimisation was not systematically explored in the current study. Future investigations may evaluate different cactus species, extraction methods, particle sizes, and composite formulations (e.g., incorporation of conductive or ferrite phases) to enhance shielding effectiveness and durability for wearable applications.

AUTHOR CONTRIBUTIONS

D.A. coordinated the study, contributed to the experiment's design, managed the preparation of cactus samples, and supervised animal trials. She handled

the overall project flow and served as the corresponding author. Desy also organised the research logistics and drafted the initial manuscript. N.S. performed animal dissection and histological processing of the uterus and placenta. H.S. was responsible for setting up the electromagnetic wave (EMW) exposure system and determining technical specifications related to the exposure parameters. He also conducted and interpreted the FTIR and XRF analyses of cactus extracts. S. assisted in histological interpretation, biological mechanism discussion, and manuscript refinement. All authors reviewed and approved the final version of the manuscript and were collectively responsible for the accuracy and integrity of the work.

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DISCLOSURE STATEMENT

The authors (s) declare there are no potential conflicts of interest.

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