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Development of Electromagnetic Shielding Knitted Fabrics and Conceptual Design Proposals for Ergonomic Maternity Clothing

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ABSTRACT

Current study focuses on developing conductive weft-knitted fabrics with electromagnetic shielding properties for potential use in ergonomic maternity clothing. Conductive core-spun yarns were produced by wrapping 40 µm stainless steel wires with cotton fibers via ring spinning and knitted into single jersey, rib (1×1), and interlock structures. The fabrics' electromagnetic shielding effectiveness (EMSE) and surface resistivity were tested across 0.1 to 3 GHz. Fabrics with higher conductive yarn content showed lower surface resistivity (down to 6.54 × 104 Ω) and higher EMSE, with the best-performing sample achieving 10.09 dB. Shielding effectiveness was strongest at lower frequencies, gradually decreasing as frequency increased. Interlock and rib structures outperformed single jersey due to their denser configurations. Building on these results, a conceptual collection of ergonomic maternity dresses was suggested, emphasizing protection, comfort, sustainability, and the needs of pregnant women.

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Electromagnetic shielding, Conductive yarn, Weft knitted fabrics, Core-spun yarn, Maternity wear design

1. INTRODUCTION

The habits of individuals have changed drastically in recent years because of rapid technological advancements worldwide. Electrical and electronic equipment have evolved into essential tools of daily life, and their utilization both at home and workplaces has grown tremendously. Cell phones, wireless internet networks, computers, radio and television transmitting devices, medical monitoring equipment, electric power lines, radars, base stations, and so on have all become vital in modern life. However, such electrical and electronic appliances release considerable quantities of electromagnetic waves into their surroundings (1–3). The growing prevalence of these devices on a daily basis boosts the level of electromagnetic pollution to which individuals are exposed. Electromagnetic (EM) radiation has become the fourth most critical source of pollution after noise, water and air pollution (4, 5).

EM waves are comprised of electric and magnetic fields and are defined by three fundamental parameters: wavelength, frequency, and energy. Wavelength is interpreted as the amount of space between two subsequent wave crests and is measured in meters. Frequency is the number of wave oscillations per second and is expressed in Hertz (Hz). Wavelength and frequency have opposite correlations, therefore as wavelength increases, frequency declines. Individual photons in the wave convey energy. The quantity of energy transported by an EM wave is proportional to its wavelength, hence, the shorter the wavelength, the greater the energy (3, 6).

In literature, several studies about the harmful impacts of EM radiation on the human body have been reported. Many researchers have investigated the effects of EM waves on human nerve cells, brain tissue, DNA, genes, reproductive system, immunity, and metabolism (7, 8). It has been specified that EM waves cause molecules in biological cells to vibrate, resulting in additional uncontrolled rise in temperature. Furthermore, DNA and RNA renewal of the cells is halted. Besides, it has been emphasized that EM waves might trigger abnormal chemical activity in the body

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to form cancer cells, increasing the risk of leukemia and other types of cancers. Moreover, EM waves have been shown to cause headaches, fatigue, dizziness, sleeplessness, and memory loss in people (9, 10). Some studies have also indicated that there may be a risk of miscarriage in pregnant women who are exposed to EM waves for a long time, and mental retardation and immune system weaknesses may occur in the baby (11, 12).

"Shielding" is considered the most effective strategy for mitigating the potential hazards associated with electromagnetic (EM) radiation. Electromagnetic shielding involves the attenuation of electromagnetic fields by employing conductive or magnetic materials as protective barriers (13). While metals are widely recognized for their excellent EM shielding capabilities, their practical application is often limited by high cost and considerable weight. Furthermore, challenges related to thermal expansion, oxidation, and corrosion further restrict their usage (14). Conversely, conductive textile fabrics offer a promising alternative due to their lightweight, flexibility, and cost-effectiveness, making them suitable for use in defense, electrical, and electronic industries. These textiles can achieve electromagnetic shielding functionality through the integration of metallic particles, metal fibers, carbon fibers, metal wires (such as stainless steel, aluminum, or copper), or conductive yarns into the fabric structure (3,15). In this regard, a substantial body of literature has explored the electromagnetic shielding effectiveness (EMSE) of various textile structures, including woven fabrics (16–20), woven fabric-reinforced composites (14), knitted fabric-reinforced composites (21), hybrid textile configurations combining woven and knitted fabrics (22, 23), and nonwoven materials (24–26).

Numerous studies in the literature have focused on the development of fabrics with electromagnetic (EM) shielding capabilities through the incorporation of conductive yarns. For example, Rajenkumar and Thilagavathi engineered core-spun yarns by enveloping silver-plated copper wires with cotton fibers using a ring spinning system. These yarns were subsequently used to fabricate knitted structures exhibiting EM shielding properties. In their study, cotton roving with a linear density of 226 tex (~Ne 2.6) was utilized to produce core yarns with a fineness of 38 tex (~Ne 15.5). The resulting knitted fabrics demonstrated shielding effectiveness exceeding 40 dB in the lower frequency spectrum (27). Similarly, Ortlek et al. employed a siro core spinning technique to produce core yarns, wherein stainless steel wire was wrapped with cotton to create yarns with a count of Ne 24 and a twist factor (αe) of 3.7. These yarns were used to manufacture various knitted fabric structures. Electromagnetic shielding effectiveness (EMSE) measurements conducted across the 30 MHz to 9.93 GHz frequency range indicated that the fabrics generally achieved shielding levels of 20 dB or higher, particularly within the 60 MHz to 1 GHz range (28). Despite these advancements, further research is necessary to address existing gaps in the literature, particularly regarding the development of highly conductive yarns and improved production efficiency through alternative spinning techniques or machine modifications.

Knitted fabrics are considered highly suitable for the development of electromagnetic (EM) radiation protective textiles due to their inherent versatility, flexibility, and breathability (29, 30). Kumar et al. fabricated plain knitted structures using 96 tex conductive yarn composed of six plies, each containing 29 silver-coated filaments. The resulting fabrics demonstrated outstanding electromagnetic shielding effectiveness (EMSE) at frequencies of 500 and 800 MHz (31). Commercially available EM shielding knitted materials, which are predominantly produced using metallic composite yarns, are also widely utilized. However, these products often compromise on comfort and aesthetic appeal due to the incorporation of coarse metallic wires or insufficient EM shielding performance caused by suboptimal loop configurations. As such, additional research is necessary to enhance EMSE through the use of finer metallic wires combined with optimized textile constructions and loop geometries (32).

To maintain the psychological and physiological well-being of pregnant women, it is essential to consider both the design and functional aspects of maternity clothing. In addressing the aesthetic preferences of women whose body shapes undergo significant changes during pregnancy, garments should incorporate elements such as visual appeal, alignment with current fashion trends, and artistic detailing. From an ergonomic perspective, maternity wear must be anatomically suitable, hygienic, and designed to allow unrestricted physical movement in daily activities (33). A critical consideration in the development of ergonomic maternity apparel is the continuous change in body measurements throughout pregnancy, particularly in the bust, waist, and hip regions. Consequently, maternity garments should be designed to adapt to these evolving body dimensions, ensuring comfort and practicality at every stage of pregnancy (34).

According to research conducted by Future Market Insights (FMI), the global maternity clothing market is currently valued at approximately $21.6 billion and is projected to reach $41.3 billion by 2031. This anticipated growth is largely attributed to the increasing participation of women in the workforce and the rising number of women who remain employed throughout their pregnancies (35). From a commercial perspective, maternity apparel offered in the textile and ready-to-wear sectors predominantly emphasizes attributes such as color, lining, style, and pricing. However, there is a notable deficiency in the incorporation of ergonomic design elements tailored to the specific anatomical needs of pregnant women (36, 37). Moreover, the fabrics commonly used in maternity garments tend to be conventional and lack functional properties; they are typically produced using traditional manufacturing methods rather than utilizing intelligent, technical, or protective textile technologies.

The primary motivation behind the current research is to develop novel conductive core-spun yarns to produce weft

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knitted garments with the properties of EM shielding. For this purpose, stainless steel wires were wrapped with short cotton fibers using a special technique in the ring spinning machine. Then, conductive single jersey, rib (1x1), and interlock fabric structures were yielded in the flatbed knitting machine, and EMSE properties of the fabrics were examined. Another goal of this research is to propose ergonomic maternity clothing designs including conductive single jersey, rib (1x1), and interlock fabrics within the concept of EM shielding by utilizing fashion design sketches and digital design programs.

2. MATERIAL AND METHOD

2.1 Preparation of conductive core-spun yarns

In the present study, 100% stainless-steel wire (Elektrisola, Germany) with a diameter of 40 µm was employed as the conductive core material. The conductive core-spun yarn, comprising stainless-steel (SS) wire and 100% cotton, was produced on a ring spinning machine (Suessen, Germany). The stainless-steel wire was precisely centered within the final core-spun yarn through the controlled feeding of elastane guides on the ring spinning machine.

During the production process, the stainless-steel (SS) wire was wrapped by carded cotton roving (Ne1). The cotton fibers were attenuated to the desired fineness in the drafting zone of the machine before undergoing the spinning process. The SS wire was then incorporated into the cotton fibers as they passed over the exit cylinder, allowing the wire to be placed directly into the cotton fibers without introducing tension or subjecting them to further drawing (*Figure 1*). Ultimately, two yarn counts (~Ne10 and ~Ne20) were produced at a specific twist level of αe: 4.8 and a spindle speed of 7000 t/m. The physical properties of the resulting conductive core-spun yarns, along with the accompanying 100% cotton yarns used in the knitting process, are presented in Table 1.

2.2 Production of conductive weft knitted fabrics

Various types of weft-knitted structures, including single jersey, rib (1x1), and interlock, were produced using conductive core-spun yarns and 100% cotton yarns on a 7G automatic flat knitting machine (CMS 420, Stoll). During the knitting process, three distinct course densities were selected for each fabric structure. Both the conductive core-spun and cotton yarns were fed through the same carrier on the machine. The structural characteristics of the resulting knitted fabrics are detailed in Table 2, Table 3, and Table 4, respectively.

Table 1. Physical characteristics of the prepared conductive core-spun yarns and 100% cotton yarns used in knitted fabrics.

Yarn types	Yarn count (Ne)			Tenacity (CN/tex)			Elongation (%)			Hairiness			Twist (T/m)		
		sd	CV%		sd	CV%		sd	CV%		sd	CV%		sd	CV%
Core-spun 1	20,15	0,12	0,59	7,99	0,84	6,16	3,32	0,74	11,34	15,93	3,81	23,95	867,5	31,86	3,67
100% cotton	**19,12**	**0,22**	**1,14**	**14,23**	**1,44**	**10,12**	**6,92**	**0,73**	**10,58**	**11,1**	**0,84**	**7,54**	**687,9**	**27,02**	**3,92**
Core-spun 2	9,56	0,05	0,53	14,68	1,08	6,56	6,89	0,45	4,26	9,22	0,8	8,64	590,7	31,47	5,32
100% cotton	**10,8**	**0,33**	**1,1**	**18,52**	**1,45**	**9,95**	**12,05**	**0,82**	**12,58**	**12,84**	**0,77**	**9,56**	**548**	**30,56**	**2,18**

Table 2. Structural properties of single jersey knitted fabrics.

Fabric Code	Core Spun Yarn	100% cotton yarn	Loop length (cm)	Courses (per cm)	Wales (per cm)	Amount of conductive yarn (cm/cm^2)	Fabric thickness (mm)	Fabric weight (g/m^2)
S-10-32	Ne10/1	Ne10/1	0,9	7	5	32	1,72	352
S-10-43	Ne10/1	Ne10/1	0,8	9	6	43	1,53	373
S-10-46	Ne10/1	Ne10/1	0,7	11	6	46	1,43	440
S-20-32	Ne20/1	3x(Ne20/1)	0,9	7	5	32	1,59	356
S-20-43	Ne20/1	3x(Ne20/1)	0,8	9	6	43	1,5	390
S-20-46	Ne20/1	3x(Ne20/1)	0,7	11	6	46	1,38	453

Table 3. Structural properties of rib (1x1) knitted fabrics.

Fabric Code	Core Spun Yarn	100% cotton yarn	Loop length (cm)	Courses (per cm)	Wales (per cm)	Amount of conductive yarn (cm/cm^2)	Fabric thickness (mm)	Fabric weight (g/m^2)
R-10-33	Ne10/1	Ne10/1	1,1	5	3	33	2,11	347
R-10-43	Ne10/1	Ne10/1	0,9	6	4	43	2,37	437
R-10-45	Ne10/1	Ne10/1	0,8	7	4	45	2,41	518
R-20-33	Ne20/1	3x(Ne20/1)	1,1	5	3	33	1,89	348
R-20-43	Ne20/1	3x(Ne20/1)	0,9	6	4	43	2,3	415
R-20-45	Ne20/1	3x(Ne20/1)	0,8	7	4	45	2,46	508

R-10-33= R: Rib (1x1) (knitting type), 10: Yarn count (Ne), 33: Amount of conductive yarn (cm/cm^2)

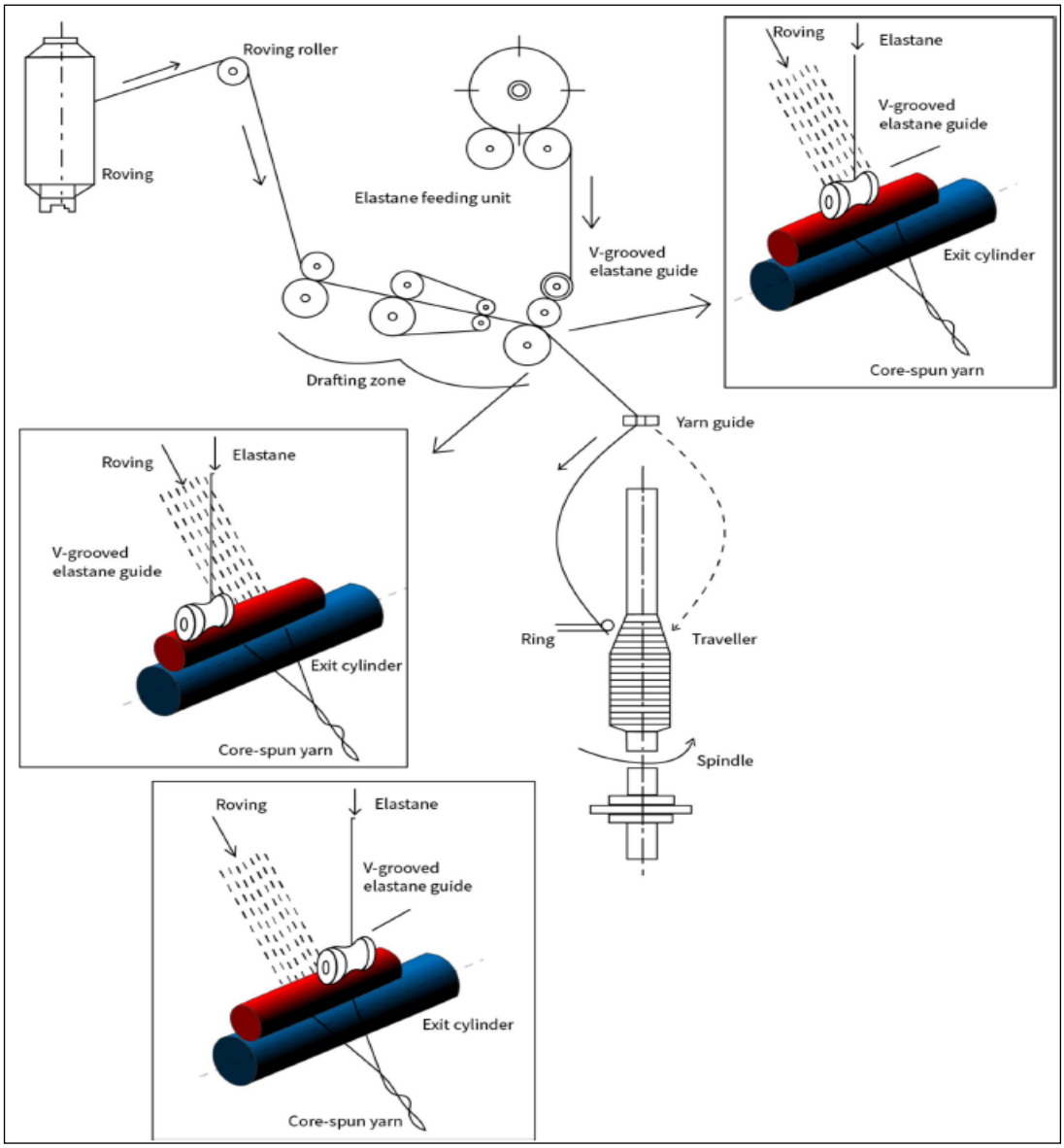


Figure 1. Schematic illustration of ring-spinning machine and conductive core-spun yarn production

Table 4. Structural properties of interlock knitted fabrics.

Fabric Code	Core Spun Yarn	100% cotton yarn	Loop length (cm)	Courses (per cm)	Wales (per cm)	Amount of conductive yarn (cm/cm^2)	Fabric thickness (mm)	Fabric weight (g/m^2)
I-10-36	Ne10/1	Ne10/1	0,9	5	4	36	2,65	578
I-10-48	Ne10/1	Ne10/1	0,8	6	5	48	3,15	666
I-10-49	Ne10/1	Ne10/1	0,7	7	5	49	3,07	722
I-20-36	Ne20/1	3x(Ne20/1)	0,9	5	4	36	3,12	581
I-20-48	Ne20/1	3x(Ne20/1)	0,8	6	5	48	3,14	664
I-20-49	Ne20/1	3x(Ne20/1)	0,7	7	5	49	3,08	693

I-10-36= I: Interlock (knitting type), 10: Yarn count (Ne), 36: Amount of conductive yarn (cm/cm^2)

2.3 Measurement of electromagnetic shielding effectiveness (EMSE)

The knitted fabrics were conditioned at a temperature of 20±2 ºC and relative humidity of 65±2% for 24 hours prior to the experiments. Electromagnetic shielding effectiveness (EMSE) of the specimens was measured in accordance with the ASTM D4935-10 standard using the coaxial transmission line technique, within the frequency range of 0.1 GHz to 3 GHz. A compact testing device (Electro-Metrics Inc., model EM-2107 A, USA) was employed to assess the EMSE of the knitted fabrics. The reflectivity, absorption, and transmissibility of the electromagnetic (EM) wave power through the textiles were evaluated using

a network analyzer (Rohde & Schwarz, ZVL/9 kHz-13.6 GHz), which was equipped with two coaxial connectors and two 10 dB attenuators for generating and receiving the EM signals (Figure 2-a).

To assess the EMSE of the knitted fabrics using the insertion-loss method, two specimens were required for each test: one serving as the reference and the other as the loaded sample (conductive knitted fabrics such as single jersey, rib (1x1), and interlock). The specimen dimensions were standardized at 133 mm, corresponding to the outer ring diameter (*Figure 2-b*). By comparing the incident and transmitted power, the difference in attenuation between the reference and the loaded specimen was used to determine the EMSE. The following equation (Equation 1) was used to calculate the EMSE, with the results expressed in decibels (dB), a unit indicating the power ratio used to specify shielding efficiency.

$$EMSE\ (dB) = P_out/P_in \quad (1)$$

where Pout is the output power (watts) and Pin is the input power (watts) in the reference sample. All measurements were performed in triplicate on different parts of the fabrics, and the average values were subsequently calculated.

The surface resistivities of the knitted fabrics were measured using the Keithley 6517A Electrometer/High Resistance Meter, following the ASTM D257-07 standard. The surface resistivity was determined by applying a voltage potential across the outer layer of the specimen, measuring the resulting current, and subsequently calculating the value using Equation 2.

$$ps = 53.4V / I\ ohm(\Omega) \quad (2)$$

where *ps* is the specimen's surface resistivity, V is the applied voltage, and I is the current measured by the equipment.

2.4 Designing Maternity Dresses

In the second phase of this study, a series of ergonomic, sustainable, and functional maternity clothing designs were developed with the idea of including the EM-shielding knitted fabrics produced in the initial phase. The target demographic for these designs included pregnant women between the ages of 17 and 45, specifically those in their 5th to 9th month of pregnancy. The designs were conceptualized as “casual”, everyday wear suitable for the spring and autumn seasons.

Hybrid designs were created by combining EM-shielding fabric structures (single jersey, rib (1x1), and interlock) with complementary fabrics including crinkle fabric, Lycra-combed cotton, raised camisole knits, and viscose based textiles. During the design development process, sketchbooks reflecting the intended theme and concept were prepared. The color palette was selected based on PANTONE 17-1230 Mocha Mousse, a tone recognized for its sophisticated, earthy elegance and its association with naturalness and comfort, as highlighted in the International Pantone® Fashion Color Trend Report for the year 2025 (38).

Subsequently, a comprehensive visual presentation of the designs was developed, including a two-dimensional storyboard (mood board), a material board, and an accessory board. Based on these resources, the initial hand-drawn sketches were transformed into detailed digital illustrations using Adobe Illustrator CC, combining traditional drawing techniques with modern digital design tools.

3. RESULTS AND DISCUSSION

The Electromagnetic Shielding Effectiveness (EMSE) of knitted fabrics—referring to their capacity for absorption and reflection—was evaluated across frequencies ranging from 0.1 GHz to 3 GHz. To enhance the correlation and comprehensiveness of the analysis, surface resistivity measurements were also conducted. The study further examined the influence of variables such as the proportion of conductive yarn, knitting pattern type, and yarn count on both the EMSE performance and surface resistivity characteristics of the fabrics.

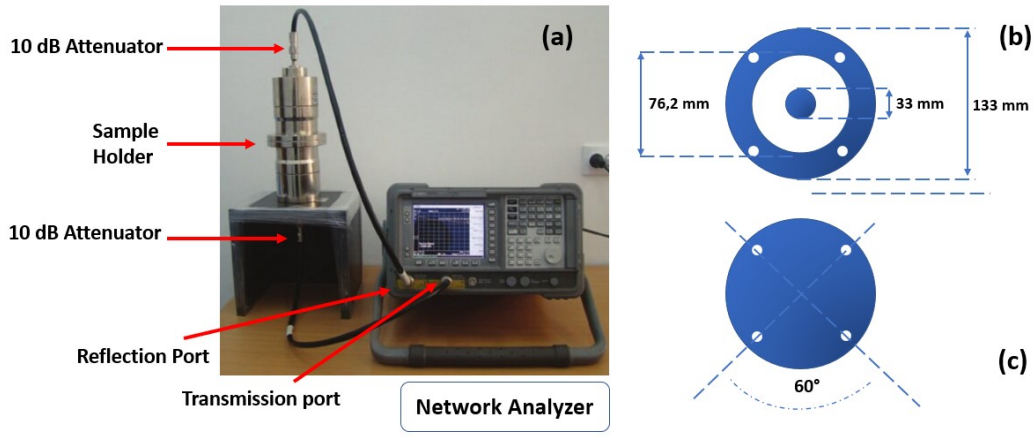


Figure 2. Image of EMSE testing equipment; (a) sample holder and network analyzer, (b) and (c) specimens for reference and load, respectively.

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3.1 The impact of conductive material amount on EMSE and surface resistivity

To evaluate the influence of conductive yarn content on the electromagnetic shielding effectiveness (EMSE) and surface resistivity of knitted fabrics, the knitting pattern and yarn count were held constant. Consequently, all fabric samples shared the same knitting structure and yarn specifications, allowing for a controlled comparison (Figure 3 a–f). It is well-established that surface resistivity and electrical conductivity exhibit an inverse relationship, whereby lower surface resistivity indicates higher conductivity. Additionally, the amount of conductive yarn per square inch varied depending on the total loop length within the knitted structures (39).

All surface resistivity and EMSE measurements were repeated at least three times under identical experimental conditions, and the results are presented as mean values to ensure the reliability and reproducibility of the data.

The corresponding graphs clearly demonstrate that the knitted fabrics coded S10-46, S20-46, R10-45, R20-45, I10-49, and I20-49 exhibited lower surface resistivity compared to other samples within their respective categories. This is attributed to a higher concentration of conductive materials per unit area. Regarding electromagnetic shielding effectiveness (EMSE), these same fabric samples outperformed their counterparts within the same groups, a result that can be associated with their enhanced electrical conductivity. The observed differences among fabric groups were found to be consistent across repeated measurements, indicating that the reported trends are not caused by random experimental variations.

Furthermore, all knitted samples displayed higher EMSE values within the 0.1–0.6 GHz frequency range, followed by a general decline in performance as frequency increased, despite some fluctuations. This trend can be partly explained by the fact that metallic conductive fibers are more effective at attenuating electromagnetic radiation at lower frequencies than at higher ones (15).

The process of shielding electromagnetic waves depends on two aspects: absorption and reflection (3). Accordingly, the absorption and reflection behaviors of the knitted fabrics are depicted in Figure 3 (a–f). Reflection and absorption levels tended downward with increasing frequency. Besides, absorption levels were perpetually greater than reflectance values in all groups between 0.1 GHz and 3 GHz, which is due to the intrinsic properties of the conductive material (21). Also, it was noticed for all samples that with the increment in frequency, the EMSE value declined, which is in parallel with previous studies in the literature where metal conductive wires have been reported to shield electromagnetic radiation more effectively at lower frequencies than at higher frequencies (15).

3.2 The impact of knitting type on EMSE and surface resistivity

Surface conductivity values and EMSE performances of single jersey, rib (1×1), and interlock knitted fabrics using core conductive yarns are presented in Figure 4 (a–f). All measurements were conducted at least three times under identical experimental conditions, and the reported values represent mean results to ensure data reliability and reproducibility.

When the graphics were examined in general, it was determined that single jersey knitted fabrics showed lower EMSE compared to other knitted structures, where the surface resistivity increased up to 1.5493E+8 ohm and the average EMSE value was calculated as 5.58 dB for S-10-32 (Figure 4a) within the 0.1–3 GHz frequency range. On the other hand, the highest EMSE values were obtained for interlock knitted fabrics; for example, the lowest surface resistivity value (6.5391E+4 ohm) was recorded for I-20-49, while the corresponding average EMSE value reached 10.09 dB within the same frequency range (Figure 4 f). The consistency of these results across repeated measurements confirms that the observed differences between knitting structures are statistically meaningful rather than originating from random experimental variations.

The superior EMSE performance of rib (1×1) and interlock knitted fabrics can be attributed to their production on double needle beds, which enables a greater amount of conductive material to be incorporated per unit area compared to single jersey fabrics produced on a single needle bed. Consequently, surface resistivity decreases as the overall amount and continuity of conductive material increase, leading to enhanced electromagnetic shielding performance. In addition, the thickness of fabrics knitted on double needle beds is greater than that of single-bed knitted fabrics, which may further contribute to improved EM wave attenuation.

Furthermore, the needle beds are positioned opposite each other during the production of interlock fabrics, while they are arranged crosswise in rib (1×1) structures. This configuration provides superior dimensional and form stability in interlock fabrics compared to rib (1×1) fabrics, resulting in more effective electromagnetic shielding. It was also observed that increasing loop density led to a systematic decrease in surface resistivity and a corresponding increase in EMSE values, a trend that was consistently reproduced across all repeated measurements.

3.3 The impact of yarn count on EMSE and surface resistivity

The influence of yarn counts on surface resistivity properties and EMSE performances (within the frequency range of 0.1–3 GHz) of knitted fabric samples is demonstrated in Figure 5 (a–i). All measurements were repeated at least three times under identical experimental conditions, and the results are presented as mean values to ensure the reliability and reproducibility of the data.

Overall, fabrics produced with coarse count yarns (Ne10) exhibited lower EMSE values compared to fabrics knitted with finer count yarns (Ne20). The lowest average EMSE

value was measured as 2.59 dB for the R-10-33 sample, whereas the highest average EMSE value of 10.09 dB was recorded for the I-20-49 sample within the 0.1–3 GHz frequency range (Figure 5b). The consistency of these differences across repeated measurements indicates that the observed trends are systematic and not attributable to random experimental variations.

Several factors may account for these findings. One possible explanation is that finer yarn counts with identical core fineness result in a higher effective proportion of conductive material, as fewer cotton fibers are wrapped around the stainless-steel core during the ring spinning process. In addition, the thinner cotton sheath surrounding the conductive core in finer yarns enhances the potential for interaction between conductive components within the knitted structure (40). Furthermore, fabrics produced from finer conductive yarns exhibit a higher compactness ratio, which reduces the gaps between adjacent conductive yarns and limits electromagnetic wave transmission, thereby improving electromagnetic shielding effectiveness (41).

Conversely, in yarns with higher linear density (coarser yarn counts), a greater amount of cotton fibers envelops the conductive core material, leading to increased electrical insulation. This additional insulation increases surface resistivity in both the conductive yarns and the resulting fabrics, ultimately reducing their electromagnetic shielding effectiveness. These relationships between yarn count, surface resistivity, and EMSE were consistently reproduced across all repeated measurements, confirming the robustness of the reported results.

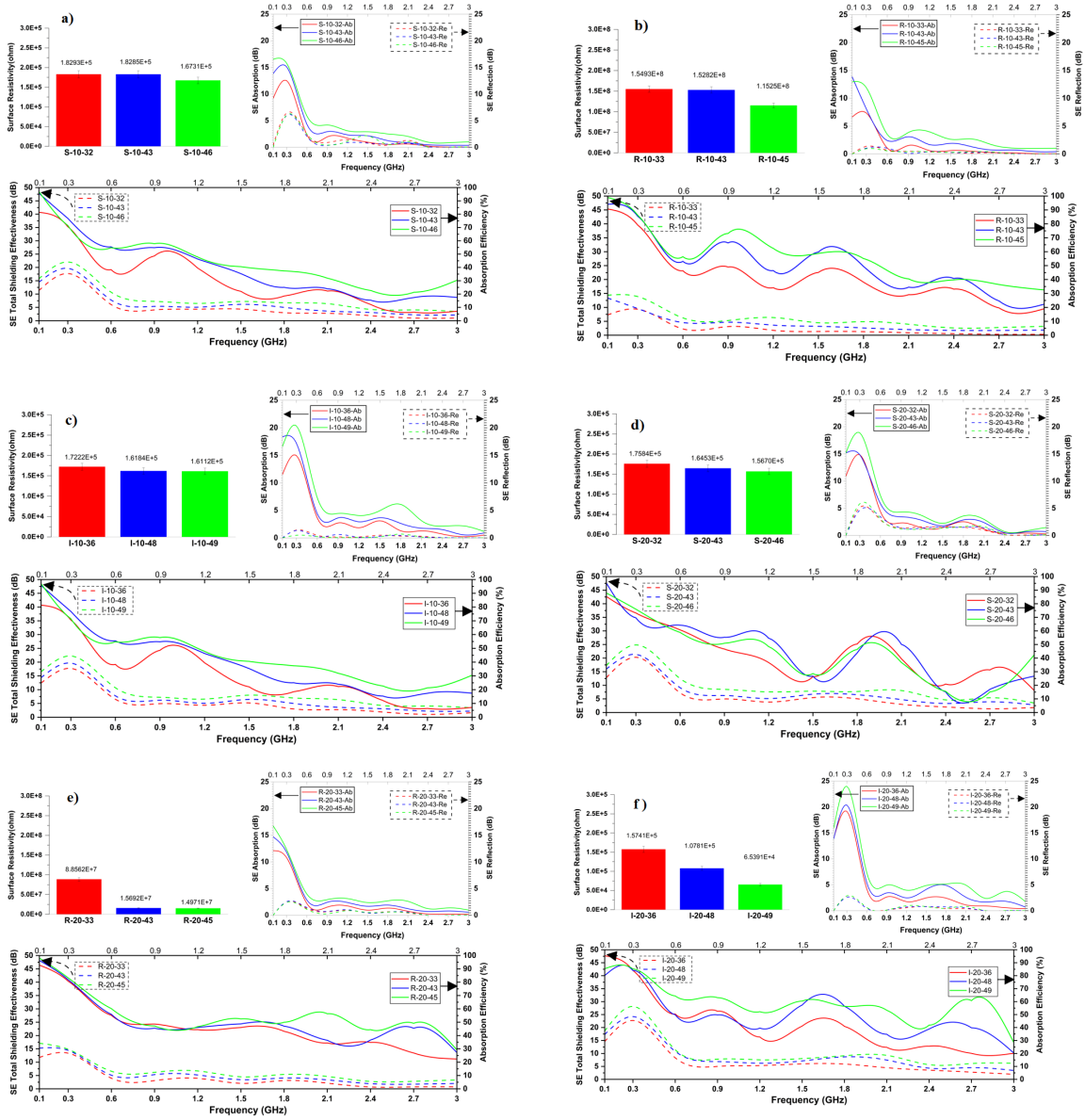


Figure 3. EMSE and surface resistivity of knitted fabrics (Analysis of the influence of conductive yarn content on EMSE and surface resistivity)

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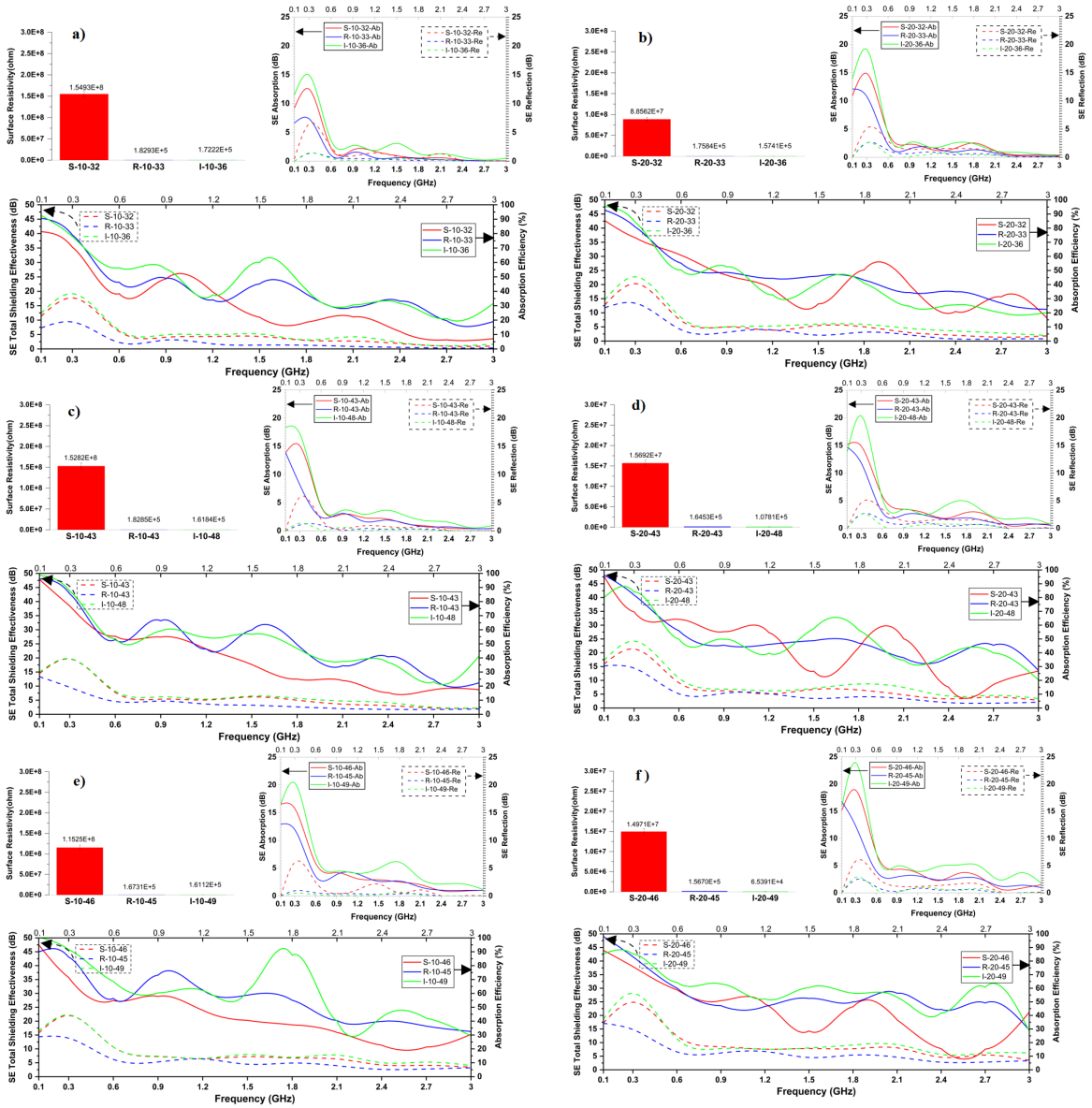


Figure 4. EMSE and surface resistivity of knitted fabrics (Analysis of the influence of knitting type on EMSE and surface resistivity)

From a practical perspective, EMSE values between 5 and 10 dB correspond to moderate attenuation levels suitable for daily wearable applications, whereas higher values indicate enhanced protection against electromagnetic exposure. The obtained EMSE levels demonstrate that the developed knitted fabrics can effectively reduce electromagnetic wave transmission while maintaining flexibility and comfort, which are essential for maternity wear applications.

3.4 Maternity Dresses Designs

Maternity garments are designed with a dual focus: ensuring functional and ergonomic support for the expectant mother while providing protective benefits for the developing fetus. In the design phase of this study, the conductive and protective knitted fabrics developed in the initial stage were strategically positioned to ensure comprehensive coverage of the abdominal and lower back regions of pregnant women. Recent studies have proposed various ergonomic maternity wear designs by utilizing advanced knitted structures produced with conductive core-spun yarns. It is well-established that pregnancy represents a unique physiological state characterized by significant alterations in normal human function (42). During this period, women may experience a weight gain of up to 25% of their pre-pregnancy weight, which averages approximately 12.5 kg and typically becomes more pronounced in the second half of pregnancy (43). Of this weight gain, around 4 to 4.5 kg of adipose tissue is typically deposited in the abdominal and hip regions (42, 44, 45).

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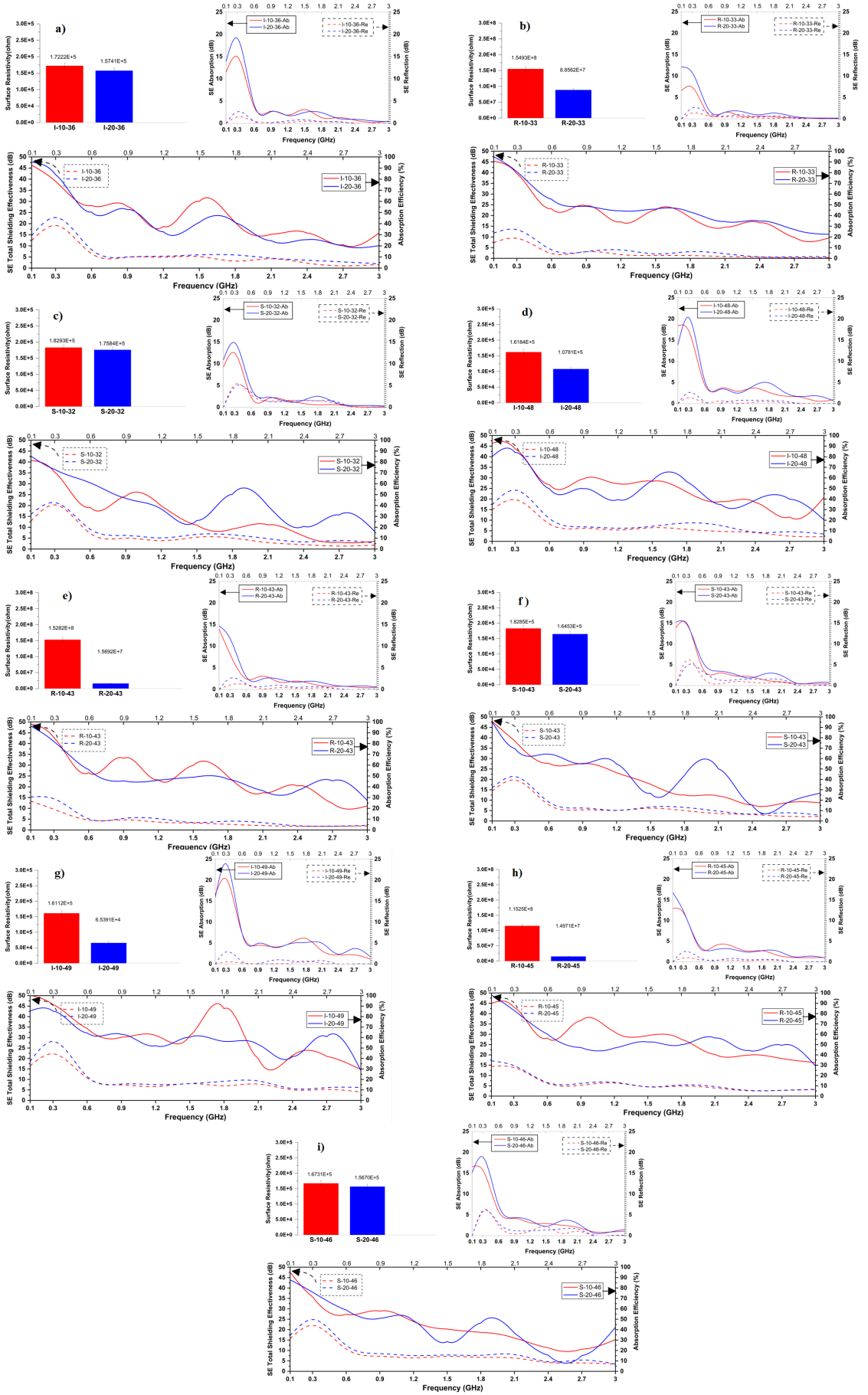


Figure 5. EMSE and surface resistivity of knitted fabrics (Analysis of the influence of yarn count on EMSE and surface resistivity)

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As body weight increases, notable biomechanical changes occur: the depth of the lumbar curve increases by approximately 0.5 cm, and the hip angle expands outward by about 2.8 cm by the 36th week of gestation (46). The growing fetus further alters the pregnant individual's posture, increasing the load on the abdominal muscles and spinal column. This shift leads to a posterior displacement of the head, which in turn negatively affects postural stability and balance (47, 48).

Due to the individual variations in abdominal size and overall body shape among women in the later stages of pregnancy—particularly by the eighth month—the fit and appearance of maternity garments can differ significantly from person to person (42). According to research, 26% of pregnant women report difficulty in finding garments they like, 23% are unable to find preferred styles, and 19% cannot find clothing that aligns both with their body shape and style preferences (49). A body shape analysis conducted on 109 pregnant women revealed that 14% had a V-shaped body, 23% had an X-shaped body, and 63% had an A-shaped body. Notable differences in breast, hip, and abdominal measurements were observed across these body types (42). These physical variations underscore the importance of prioritizing comfort, proper fit, and accurate sizing in the design and production of maternity wear within the ready-to-wear apparel industry.

The primary objective of the designs developed within the scope of this project is to safeguard fetal health during pregnancy by promoting the use of maternity garments constructed from protective weft-knitted fabrics with electromagnetic shielding properties. The design process focused on pregnant individuals between the 5th and 9th months of gestation, who were identified as the target demographic. Tailored for the Spring/Fall 2025–2026 fashion season, the garments are intended to appeal to women aged 17 to 45. The collection incorporates conductive single jersey, rib (1x1), interlock, and knit fabrics, along with complementary materials such as crinkle fabric, lycra combed cotton, brushed camisole fabrics, and viscose blends to ensure both functionality and aesthetic appeal. In the pattern design process of the garments, particular emphasis was placed on ergonomics, functional utility, fabric waste reduction, and the potential for continued use after pregnancy.

The designed collection includes a total of 9 pieces of clothing set consisting of 5 different models. This collection is structured as follows:

1. Tunic and mini skirt: 2 pieces
2. Sweatshirt and sports pants: 2 pieces
3. Blouse and underdress: 2 pieces
4. Tunic and pants: 2 pieces
5. Long dress (ankle length): 1 piece

These modular designs offer expectant mothers the flexibility to mix and match garments in various combinations, thereby enhancing both sustainability and functional value. The collection’s components are designed to be mutually compatible, enabling users to assemble diverse outfits that contribute to a versatile and visually appealing wardrobe which is consistent with an emerged style called “pregnant look” (50, 51). This design strategy not only promotes economic efficiency throughout the pregnancy period but also enhances the overall user experience by prioritizing adaptability and functionality.

3.4.1 Tunic and mini skirt: 2 pieces

In *Figure 6*, the design of maternity dress constitutes of tunic and mini skirt, and related garment patterns are illustrated. To mitigate the impact of physiological changes experienced during pregnancy on maternal comfort, a tunic has been designed using a Safari-colored (15-1116 TCX Pantone) bias-cut, double-sided elastic crinkle fabric. The inclusion of lycra in the fabric composition enhances flexibility and facilitates ease of movement. Furthermore, the flexible and fluid design helps to alleviate physical pressure on the pregnant body, thereby reducing potential adverse effects on breathing and blood circulation (52). Using a one-piece cutting technique without armhole seams, the tunic is designed to fall just below the hips, with a slightly extended back hem. The garment features a curved silhouette that contributes to its aesthetic appeal.

Functionality is further enhanced through the incorporation of a concealed zipper, which also provides compactness and fullness (53), along the front center neckline, extending to just below the bust. This design element maintains visual coherence while enabling ease of dressing and undressing, as well as supporting breastfeeding. With its relaxed and ergonomic fit, the tunic is suitable for continued use throughout the later stages of pregnancy and the postpartum period, effectively addressing diverse wardrobe needs.

The skirt components of the tunic were shaped manually, taking into account the fabric’s stretch characteristics and seamlessly integrated into the pattern design. The pattern itself was developed in accordance with zero-waste design principles, ensuring optimal material utilization and sustainability.

In consideration of the expanding abdominal region and heightened sensitivity experienced during pregnancy, a mini skirt has been developed to complement the tunic, with the aim of enhancing maternal and fetal comfort. The skirt is constructed from viscose knit fabric in the 16-1414 Chanterelle TCX Pantone color, selected for its softness and flexibility, which contribute to improved wearer comfort.

To reduce abdominal and waist pressure, provide optimal support, and protect against electromagnetic exposure, the front abdominal panel has been considered to be crafted from single jersey / rib (1x1) / interlock knit fabrics (S10-46, S20-46, R10-45, R20-45, I10-49, or I20-49) by using 17-1230 Mocha Mousse TCX Pantone color. This fabric serves a dual purpose: offering electromagnetic shielding while maintaining gentle contact with the abdominal area to ensure minimal pressure.

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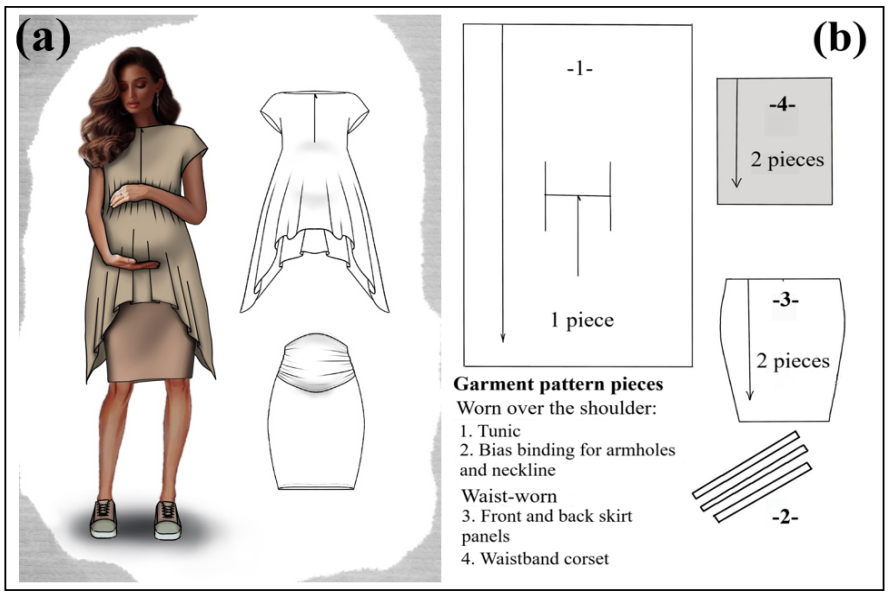


Figure 6. Design of maternity dress including tunic and mini skirt (a) and related garment patterns (b)

A concealed zipper is proposed along the left side seam to facilitate ease of dressing, while the addition of two hooks at the zipper's origin ensures it remains securely fastened during use. To prolong the garment's lifespan and reduce the frequency of washing, the lower panel—responsible for electromagnetic shielding—can be detached via a zipper mechanism. This modularity prevents fabric wear and tear due to repeated laundering.

Furthermore, the detachable front panel enables the skirt to be repurposed as a conventional mini skirt with the addition of a waist belt post-pregnancy. The modular design also allows for integration with other garments, such as trousers, shorts, or skirts through a zip-in system, reinforcing its multifunctionality and sustainable fashion attributes.

3.4.2 Sweatshirt and sports pants: 2 pieces

The design of maternity dress with sweatshirt and sports pants, and related garment patterns are depicted in *Figure 7*. The extent of abdominal expansion during pregnancy can vary significantly among individuals. While some women carry the fetus in the upper abdominal cavity, others experience more pronounced growth in the lower pelvic region. Additionally, an average increase of 5–8 cm (2–3 inches) in bust circumference is typically observed throughout pregnancy (54).

Taking these anatomical changes into account, a sweatshirt has been designed with a flexible and ergonomic structure that accommodates the volumetric growth occurring in the body during pregnancy. The side panels are intentionally constructed with slight draping to provide additional space and comfort for the expanding bust area. A cross-cut opening in the front chest area, reinforced by a concealed interior zipper, offers a discreet and functional breastfeeding solution.

The front panel of the sweatshirt incorporates an expandable structure to adapt to abdominal growth, while the back panel retains a more traditional, straight-cut sweatshirt form, contributing to a balanced overall silhouette. Aesthetic cohesion is achieved through the use of a coordinated color palette, employing three distinct Pantone tones: the central front panel and sleeves are made from 15-1116 TCX Safari-colored Lycra combed cotton fabric; the torso and abdominal area are constructed with 17-1230 Mocha Mousse TCX fabric; and the shoulder panels are crafted from 15-1317 TCX Sirocco-colored Lycra jersey, which has been chosen for its elasticity and breathability.

The raglan sleeve design eliminates shoulder seams, thereby enhancing comfort and allowing greater freedom of movement (55). The use of flexible fabric throughout the garment further contributes to its practicality for daily wear. Developed with sustainable fashion principles in mind, this sweatshirt features an adaptive design suitable for both pregnancy and the postpartum period.

One of the most critical determinants of user satisfaction in apparel is garment fit. Achieving optimal fit involves the application of advanced pattern-making techniques and the integration of appropriate size grading systems (54). In the context of maternity wear, fit must be evaluated not only from an aesthetic perspective but also as a functional component that accommodates the evolving physiology of pregnancy.

Within the scope of this study, a pair of trousers was designed using lycra-blended thick combed cotton fabric colored with 19-1216 Chocolate Martini TCX. This garment functions both as a standalone piece and as a complementary element within a modular wardrobe system. To provide targeted support to the abdominal region, conductive interlock fabric (I10-49 or I20-49) with 17-1230 Mocha Mousse TCX Pantone color has been incorporated into the waist and abdominal panels. This material, selected for its high elasticity and comfort, offers gentle support to the abdominal area while enhancing the wearer’s mobility.

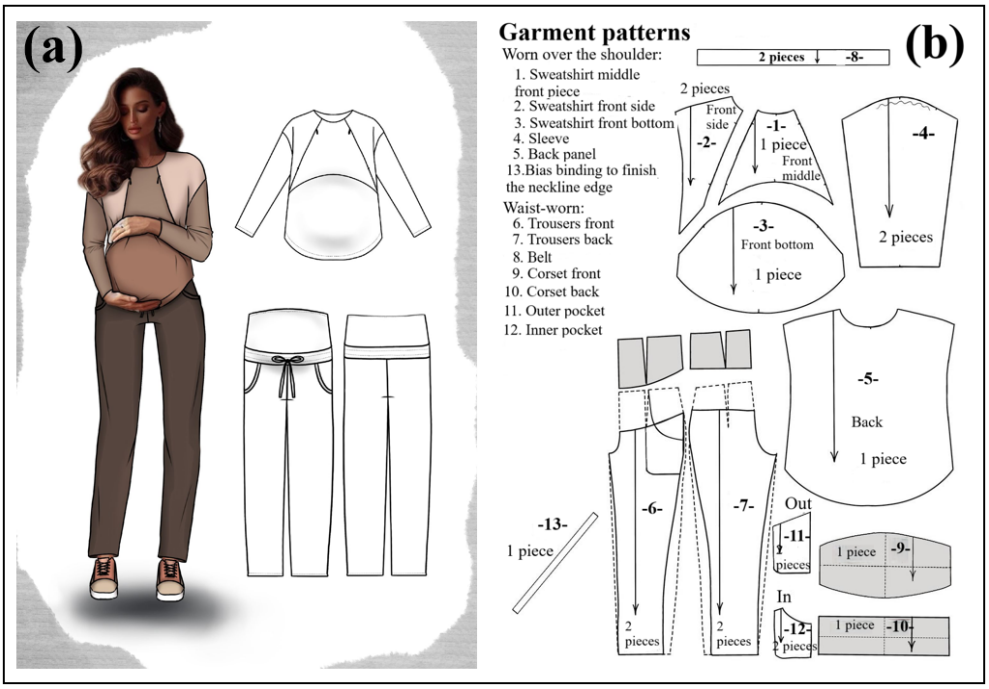


Figure 7. Design of maternity dress including sweatshirt and sports pants (a) and related garment patterns (b)

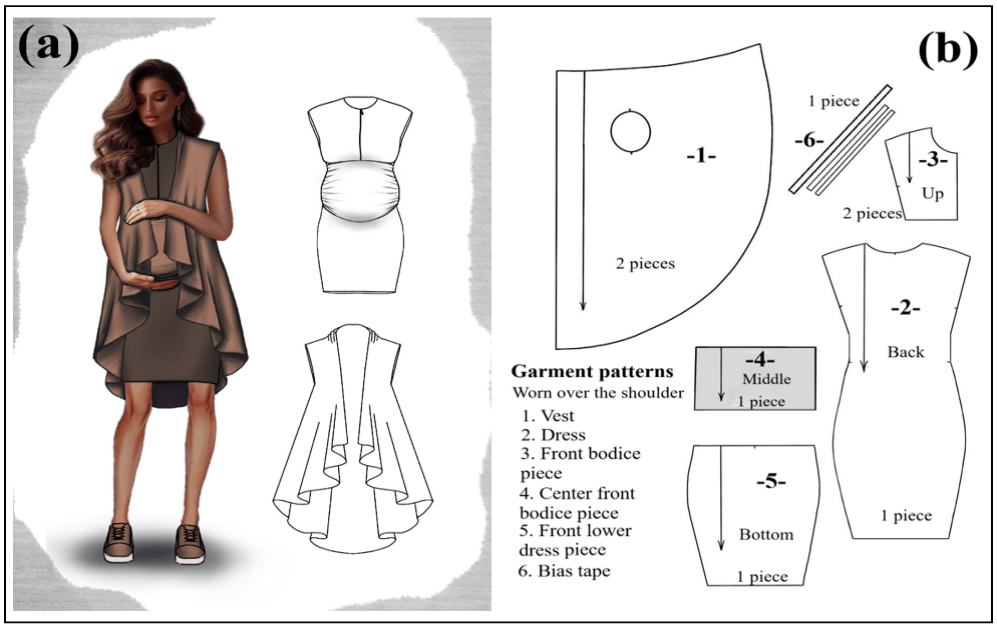


Figure 8. Design of maternity dress including blouse and underdress (a) and related garment patterns (b)

Additionally, the conductive interlock fabric serves a dual function by offering electromagnetic shielding, thereby contributing to maternal and fetal safety. The design includes detachable support panels at the front and back, connected via a concealed zipper mechanism along the abdominal section. This modular feature facilitates functional versatility and aligns with sustainable fashion principles by enabling postnatal transformation of the garment.

The ergonomic design ensures maximum adaptability to the anatomical changes that occur during pregnancy. A wide, flexible maternity waistband provides enhanced comfort and support, especially in the later stages of pregnancy. The band includes a lace detail, allowing for individualized adjustment and further improving user experience.

In terms of silhouette, the trousers feature a slightly loose, straight-leg cut that promotes ease of movement. The leg design, which tapers subtly toward the hem, offers a balance between style and practicality, making it suitable for daily wear. Additionally, the inclusion of deep, functional front pockets enhances the garment's utility for everyday use.

3.4.3 Blouse and underdress: 2 pieces

In *Figure 8*, blouse and underdress designs for maternity wear purposes, and related garment patterns are presented.

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The blouse featured in this design exemplifies an adaptive clothing model tailored to accommodate the anatomical and physiological transformations experienced during pregnancy, while also providing versatile functionality for the postpartum period. The design incorporates a flexible and fluid textile structure that responds effectively to changes in body proportions, thereby ensuring optimal ergonomic comfort and practicality. Constructed from crepe viscose fabric with lycra content, the blouse is presented in the Pantone 18-1421 TCX Baltic Amber shade. This material selection offers a suitable textile solution for both pregnancy and postpartum use due to its lightweight texture, high breathability, and tactile quality akin to natural fibers. The open-front design facilitates ergonomic ease during breastfeeding, while asymmetrical cuts and layered elements harness the draping characteristics of viscose to create a dynamic silhouette. Additionally, the lycra component enhances the fabric's elasticity, allowing it to move in harmony with the body and ensuring sustained comfort throughout and beyond pregnancy.

Specifically designed for maternity use, this undergarment dress distinguishes itself through a supportive structure that conforms to the anatomical changes of the pregnant body. Presented in the Pantone 17-1230 TCX "Mocha Mousse" shade, the garment is constructed from a combination of conductive single jersey, rib (1x1) or interlock fabrics (S10-46, S20-46, R10-45, R20-45, I10-49 or I20-49) chosen to deliver targeted support to the abdominal and waist regions. This fabric composition not only enhances comfort but also instills a sense of security and confidence in the expectant mother by accommodating bodily movements throughout pregnancy.

The dress features high-weight, thick combed cotton fabric with lycra content in the Pantone 19-1216 TCX "Chocolate Martini" color for all sections excluding the abdominal area. This selection allows for flexibility and unrestricted movement, gently contouring the body to create a comfortable and flattering silhouette. A concealed zipper extending to the waist at the center front enables ease of dressing and undressing, while also serving as an ergonomic solution that facilitates breastfeeding.

The design further incorporates a two-way hidden zipper beneath the bust and abdomen, introducing a modular element that allows the dress to be separated into two distinct pieces. In the postpartum period, this functionality enables the upper section to be repurposed as a crop top and the lower section as a mini skirt, promoting continued and versatile use.

Aligning with the principles of sustainable fashion, the garment's transformable nature supports long-term usability and environmental responsibility. By adapting to the evolving anatomical needs during and after pregnancy, this design offers a durable, multifunctional alternative that integrates comfort, practicality, and ergonomic features tailored for everyday wear and the breastfeeding process.

3.4.4 Tunic and pants: 2 pieces

In Figure 9, the maternity dress design including tunic and pants, and related garment pattern are shown. The anatomical changes that occur during pregnancy significantly heighten the demand among women for clothing preferences that prioritizes both comfort and functionality in daily wear. According to research, most pregnant women begin to require alternative wardrobe options by the fourth or fifth month of pregnancy, as their existing garments become increasingly restrictive (54). In response to these evolving needs, an ergonomic, functional, and aesthetically conscious tunic and trousers ensemble was developed to accommodate physical changes from the 21st week of pregnancy through the postpartum period.

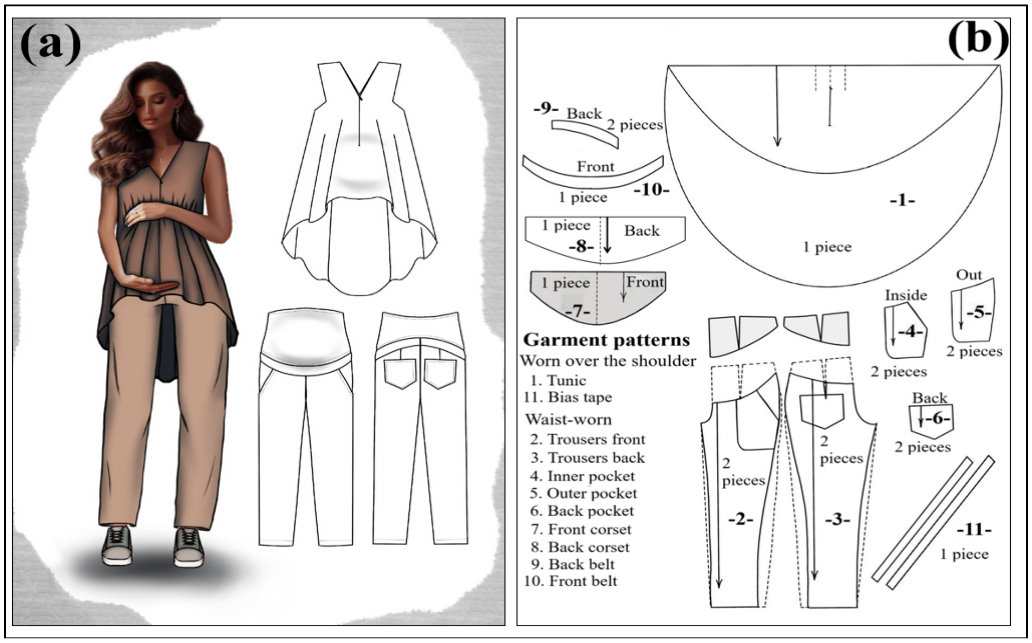


Figure 9. Design of maternity dress including tunic and pants (a) and related garment patterns (b)

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The tunic is constructed from lycra crepe viscose fabric, selected for its elasticity and soft drape, which collectively enhance mobility and wearing comfort. The design features the Pantone 18-1421 TCX “Baltic Amber” shade, a warm-toned hue that contributes to a feminine and modern visual appeal. A deep V-neckline serves to elongate the neck region and add an element of elegance, while wide shoulder straps offer structural support. The integration of a concealed zipper along the front neckline maintains the garment's aesthetic coherence while enabling discreet functionality for breastfeeding.

An A-line silhouette was employed to allow the tunic to adapt to the changing body proportions experienced during pregnancy. Additionally, pleats positioned on the front panel add volume and tactfully conceal abdominal expansion. The asymmetrical hem—shorter in the front and longer in the back—enhances the freedom of movement. This garment exemplifies a user-centered design approach, developed to fulfill the functional, aesthetic, and comfort-related expectations of women during pregnancy.

The trousers are constructed using raised camisole fabric in Pantone 13-1108 TCX “Cream Tan,” selected for its soft texture and flexible surface properties, which collectively contribute to a high level of user comfort. Designed in a regular fit with a straight-leg silhouette, the model embodies a timeless aesthetic that aligns with classic design principles. To accommodate the anatomical changes that occur during pregnancy, the front waist and abdominal area feature a supportive knitted panel made from conductive ribana fabric (R10-45 or R20-45) in Pantone 17-1230 TCX “Mocha Mousse”.

This specialized fabric panel offers gentle yet secure support by conforming to the body’s contours, delivering an ergonomic wearing experience that avoids applying pressure to the abdominal region. Additionally, the panel serves a protective EM shielding function for the baby due to its inherent conductive properties. A concealed zipper integrated into the left side seam facilitates ease of wear, while an additional hidden zipper at the lower end of the panel enables the section to be detached. This removable feature allows for reduced washing frequency compared to the main garment, thereby extending the material’s lifespan and aligning with sustainability-focused design practices.

The inclusion of classic back pocket detailing enhances the garment with both decorative and functional attributes, maintaining compatibility with traditional trouser aesthetics. Furthermore, the side seams, which follow a straight vertical line from waist to hem, help preserve visual body proportions and contribute to the garment’s clean, minimalist design language. Overall, this trouser model integrates ergonomic functionality, aesthetic versatility, and sustainable design considerations, making it a well-suited option for maternity wear collections focused on user-centered, long-lasting, and adaptable garments.

3.4.5 Long dress (ankle length): 1 piece

The long maternity dress design and related garment patterns are exhibited in Figure 10. This maternity clothing is designed for practical and comfortable use from the fifth month of pregnancy through to the final stages. Featuring a loose, flowing cut that begins just below the bust, the dress accommodates the progressive anatomical changes associated with pregnancy. Constructed from a lycra-blend combed fabric in the Pantone TCX 15-1317 "Sirocco" color, the design offers a high degree of comfort due to the material's flexibility and soft drape.

The zero-collar, buttonless, bridge-stitched one-piece dress merges comfort and elegance, with a form intentionally suited for the second and third trimesters. A double-breasted front cut is incorporated to accommodate chest expansion, enhancing both functionality and comfort. Internally, the abdominal section is reinforced using conductive single jersey / rib (1x1) / interlock fabrics (S10-46, S20-46, R10-45, R20-45, I10-49 or I20-49) in Pantone TCX 17-1230 "Mocha Mousse." These fabrics are integrated seamlessly along the front waist curve via a concealed zipper, offering discreet structural support to the abdomen and lower back without compromising aesthetic appeal.

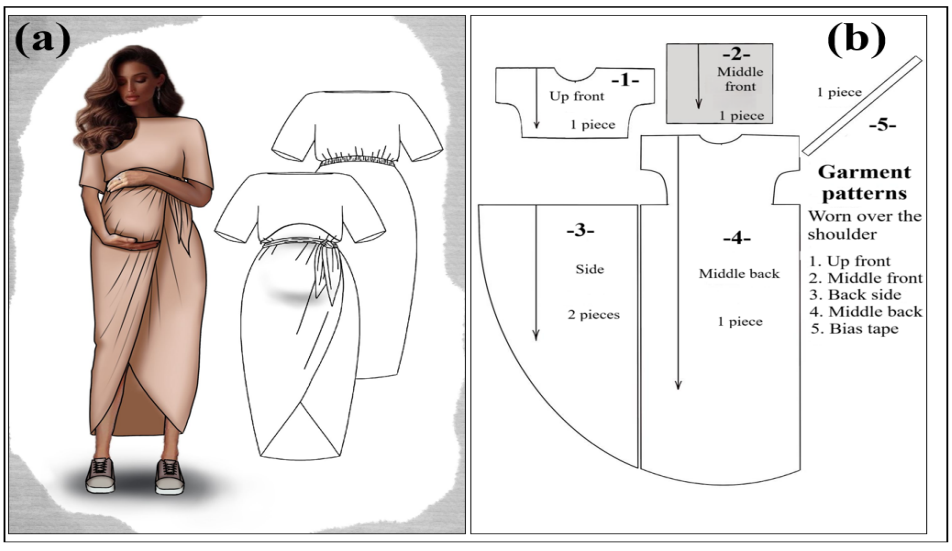


Figure 10. Design of maternity dress including long dress (a) and related garment patterns (b)

An adjustable bridge belt is integrated at the waist seam to enhance both form and function (56). This detail allows the garment to be loosened in response to abdominal growth, ensuring continued comfort while subtly shaping the silhouette. Designed to extend to the ankle, the dress provides necessary freedom of movement during the final months of pregnancy.

To maximize postnatal utility, the garment is constructed without armhole seams, allowing it to be paired with various lower-body garments such as leggings, shorts, or miniskirts during the postpartum recovery phase. Furthermore, the dress pattern is developed in alignment with zero-waste principles, reflecting an environmentally responsible approach to garment design. As a multifunctional maternity garment, this convertible one-piece dress exemplifies ergonomic, functional, and aesthetic principles, offering a versatile wardrobe solution that seamlessly transitions from pregnancy to the postpartum period.

4. CONCLUSION

In this study, conductive core-spun yarns were successfully developed using stainless steel wire and cotton fibers through a ring spinning method, and these yarns were used to fabricate various weft-knitted structures—including single jersey, rib (1×1), and interlock—for electromagnetic shielding applications. The experimental results demonstrated that fabric architecture, yarn count, and the amount of conductive material influence both the surface resistivity and electromagnetic shielding effectiveness (EMSE) of the knitted fabrics. Among the samples tested, interlock structures with finer yarn counts and higher conductive yarn densities exhibited the most promising performance, reaching an average EMSE of 10.09 dB and surface resistivity as low as 6.54×10^4 Ω within the 0.1–3 GHz frequency range.

Although the proposed ergonomic maternity clothing designs were not physically produced, the integration of the developed conductive fabrics into these garments presents a viable strategy for enhancing maternal and fetal protection against electromagnetic radiation. The suggested clothing concepts address not only functional and physiological needs during pregnancy but also ergonomic design, comfort, sustainability, and modularity.

Overall, this research provides a foundation for the future production of protective and user-centered maternity wear, highlighting the potential of textile-based electromagnetic shielding solutions in the field of functional fashion. Further work may focus on the prototype development of the proposed designs and the long-term performance evaluation of the fabrics under real-life usage conditions.

Although the present study provides valuable insights into the electromagnetic shielding behavior of conductive knitted fabrics, certain limitations should be acknowledged. The EMSE measurements were conducted within the frequency range of 0.1–3 GHz under laboratory conditions, and the effects of long-term wear, repeated laundering, and environmental exposure were not considered. Future studies may focus on durability performance and real-life usage conditions to further validate the applicability of these fabrics.

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