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Development of multifunctional textile surface with electromagnetic shielding effectiveness, water and oil repellency and flame retardancy features

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ABSTRACT

The usage of textile surfaces is increasing across various sectors such as clothing, home textiles, health, and technical applications. Textile surfaces are expected to exhibit specific functional properties depending on their intended use, including antibacterial qualities, water and oil repellency, flame retardancy, and easy cleaning. Moreover, with the advancement of technology and communication, the use of intense electromagnetic waves in living environments is on the rise. Electromagnetic waves are now crucial in communication, robotics, autonomous systems, data transfer, and numerous other fields. Prolonged exposure to these waves has been linked to various health issues. Consequently, contemporary textile surfaces are expected to incorporate multifunctional features to mitigate these potential negative effects. This study produced multifunctional fabrics with electromagnetic shielding, water/oil repellency, and flame retardancy. Conductive yarn with 60-micron steel wire provided electromagnetic shielding. Fabrics with varying densities were woven using conductive yarns, treated with water/oil repellent and flame retardant chemicals. EMSE values were measured from 15 MHz to 3000 MHz per ASTM D4935. Fabrics underwent testing for water/oil repellency (AATCC 193, 118) and flame retardancy (BS 5852), alongside physical property evaluations.

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KEYWORDS

Electromagnetic shielding effectiveness (EMSE), Conductive yarns, Water and oil repellent fabrics, Easy clean feature, Flame retardant fabrics

1. INTRODUCTION

With the rapid development of technology, technical textile applications in the industry have gained speed [1] and these advancements have expanded their use into various fields [2]. There are many studies focus on designing textile products that shield against electromagnetic waves. In our article, we also conducted studies on water and oil repellency, as well as flame retardancy features, which are increasingly demanded by users in recent years.

Electromagnetic shielding is the primary method used to absorb and reflect electromagnetic waves emitted from electrical and electronic devices [3]. The shielding properties vary and they depend on the conductivity of shielding material [4]. Textile materials, as known, are typically non-conductive and therefore cannot effectively shield against electromagnetic waves [5]. One of the most common methods to achieve this is by incorporating metal materials into textile products using conductive yarn [6]. Textile material which contains conductive yarn shields the electromagnetic waves through either reflection or absorption [7]. If electromagnetic waves are not effectively isolated, they will interact with each other and cause technical problems. Moreover, people who are frequently exposed to electromagnetic waves will cause health problems [8]. Electromagnetic radiation emitted by electrical and electronic devices affects everyone, potentially leading to long-term health issues such as headaches, dizziness, and cancer [9]. Although the use of metal in the fabric structure has disadvantages in terms of weight and corrosion however these materials have the ability to absorb and reflect electromagnetic waves [10]. In recent years, fabrics with conductive materials have gained attention for electromagnetic shielding [11]. This is attributed to their flexibility and lightness [12].

In addition to electromagnetic shielding feature studied, water and oil repellency as well as flame retardancy

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properties were incorporated into the fabrics. Fluorocarbon chemical was used impart water and oil repellency to the fabrics. Additionally, halogen based chemical was used to make fabric flame retardant, utilizing a back coating technique for application. By using halogen based chemicals on the fabric reduces of carbon monoxide formation, and promotions of char formation. They are also relatively nontoxic when compared with many other flame retardants [13]. The halogen compounds depend on the ease of liberation of the halogen. Carbon/halogen ratio and carbon/halogen bond energy is related to the amount of halogen release the burning. In general, aliphatic or alicyclic ones are more effective than aromatic halogen compounds, because of the lower carbon–halogen bond energies, and so comparatively easily halogen-release [14]. In textile sector, flame retardant chemicals are applied at various rates to all types of raw materials and successful results are achieved [15].

Moreover, fluorocarbon has been used in the textile finishing process to make the fabric water and oil repellent [16]. Fluorocarbon is widely recognized as the most effective chemical for enhancing the water and oil repellency of textile products [17]. Fluorine has got a unique characteristic of lowering down surface energy and making fabric both water and oil repellent [18]. Reduction in surface energy is evidenced by the contact angle on the fabric surface [19]. The water contact angle (WCA) determines the hydrophilic property of a product. If water contact angle at the interface becomes lower than 90°, the surface becomes hydrophilic. On the other hand, if water contact angle is higher than 90°, the surface becomes hydrophobic. However, surface will be super hydrophobic characteristics, if it is greater than 150° [20].

Applying fluorocarbon and halogen-based chemicals to make fabrics water repellent and flame retardant is done with careful consideration. However, there is limited literature available on achieving both water/oil repellency and flame retardancy simultaneously. Achieving these dual properties involves a two-step process. Initially, applying a flame retardant chemical using the back coating technique can compromise the structure of the water/oil repellent chemical, necessitating the application of water/oil repellent chemicals first. This sequential approach can have a counterproductive effect on the application of flame retardant chemicals due to the repellent nature of both types. The study aims to determine the optimal ratios of these chemicals for fabric treatment and set a benchmark for future fabric development in this area.

There has been increasing attention towards multifunctional textiles that integrate electromagnetic shielding, water and oil repellency, and flame retardancy properties. However, few studies have explored the simultaneous enhancement of these three functionalities in textile products. Our research addresses this gap by systematically investigating the optimal integration of water/oil repellent and flame retardant chemicals alongside conductive yarns for achieving high Electromagnetic Shielding Effectiveness (EMSE). This approach not only aims to meet the stringent technical requirements of modern applications but also ensures that the physical properties of the fabrics conform to international standards. Core conductive yarn and these chemicals in the study were preferred because of easy to applicate and its price/performance ratio.

With developing technology, end users want to see many different applications on a single fabric at the same time. The fabrics produced in the study are among the features most requested by customers in recent years. There are many studies regarding shielding properties of conductive fabrics, however there is no research on water/oil repellency and flame retardancy feature with EMSE on the textile products together. While these features are being developed together, it is aimed that the physical properties of the fabrics are at international standards also.

In this study, two fabric groups were produced. The first group was intended to be multifunctional, incorporating the three features mentioned earlier. In the first group, conductive yarns were used only in the weft direction in order to provide electromagnetic shielding feature. However, when the results examined EMSE deemed insufficient. It is known in the literature that when the conductive content increases, EMSE value increases. However, it was observed that altering the direction of conductive yarn usage resulted in some fabrics achieving higher EMSE values than fabrics with higher overall conductive content. This result was obtained as additional information regarding the situation generally known in the literature. Moreover, some samples from the second group exhibited desired EMSE values at higher frequencies such as frequency bands used for mobile communications and Wi-Fi bands [21].

2. MATERIAL AND METHOD

In the experimental study, two groups of woven fabrics with different densities were produced using conductive yarns containing stainless steel wire. In addition to the conductive yarn, chenille yarns and textured yarns were also used in the study. While the aim of the fabrics in the first group is to have multifunctional features, the second group of fabrics aims to achieve higher EMSE values. In the first group of fabrics, the necessary chemicals were added to the woven fabric using conductive yarns only in the weft direction, achieving the targeted multifunctional feature. In contrast, this group focuses on achieving higher EMSE (Electromagnetic Shielding Effectiveness) values. To reach this goal, conductive yarns are utilized in both the weft and warp directions, enhancing the fabric's electromagnetic shielding capabilities. Overall, while the first group emphasizes multifunctionality, the second prioritizes improved electromagnetic performance. After the fabric production process, tests were conducted according to the international standards mentioned below.

2.1. Material

In this study, 43 tex cotton core yarn containing 60 micron stainless steel (SS) wire was used as a conductive yarn in both the first and second groups to create fabric with EMSE features. In order to produce conductive yarn, stainless steel wires were placed in the center of the yarns and processed on a ring spinning machine by wrapping cotton fiber around them. The main properties of this conductive yarn are presented in Table 1.

Furthermore, the production conditions of the conductive yarn, are provided in Table 2 for a comprehensive understanding of the manufacturing process

In the first group fabrics produced for this study, polyester chenille yarn of 125 tex (Nm 8) was used in the weft, and polyester filament yarn of 17.7 tex (177 dtex) was used in the warp direction. In the second group, polyester chenille yarn of 250 tex (Nm 4) was used in the weft, and polyester filament yarn of 50 tex (500 dtex) was used in the warp direction.

The sample fabrics of first group underwent finishing processes to impart flame retardancy and water/oil repellency. For oil and water repellency, REPELLAN RPC-6 fluorocarbon chemical from Pulcra Chemicals Company (Germany) was applied, while ORGAFLAME KT-EC halogen-based chemical from Organik Kimya (Turkey) was used for flame retardancy.

2.2 Method

2.2.1 Weaving of Fabric Samples

In this study, a weaving technique was used to produce fabric samples. Two groups of fabrics were produced to obtain the desired results with plain type weave. The first group of fabrics consists of six different samples. Conductive yarns were used only in the weft direction, while chenille and polyester textured yarns were used to create the fabric surface. The fabrics were produced using Stäubli jacquard and Dornier weaving machines, operating at a speed of 400 RPM. The main properties of this group are provided in Table 3.

Table 1. Main properties of conductive yarn

Count		Strength		Breaking Elongation		Twist	
tex	%CV	cN/tex	%CV	%	%CV	TPM	%CV
43	3.28	13.57	17.53	8.94	16.53	922	5.19

Table 2. Production conditions of conductive yarn

Wire type	Wire thickness (Micron)	Yarn count (tex)	Twist coefficient (αe)	Spindle speed (RPM)	Yarn Type
Stainless steel	60 Micron	43	4.8	7000	Carded

Table 3. The main properties of the first group weaved fabrics

Fabric Code	Weft Yarn Type 1	Weft Yarn Type 2	Warp Yarn Type	Weft Density (Thread/cm)	Warp Density (Thread/cm)	Fabric weight (g/m^2)	Composition	Conductive Yarn Weight in g/m^2	Weft Plan
A	Conductive Yarn (43 tex)	Polyester Chenille Yarn (125 tex)	Polyester Yarn (17.7 tex)	15	66	280	86.4% PES 9.5% CO 4.1% SS	11,48	1-2
B	Conductive Yarn (43 tex)	Polyester Chenille Yarn (125 tex)	Polyester Yarn (17.7 tex)	17	66	300	85.7% PES 10% CO 4.3% SS	12,9	1-2
C	Conductive Yarn (43 tex)	Polyester Chenille Yarn (125 tex)	Polyester Yarn (17.7 tex)	19	66	320	85% PES 10.5% CO 4.5% SS	14,4	1-2
D	Polyester Yarn (61 tex)	Polyester Chenille Yarn (125 tex)	Polyester Yarn (17.7 tex)	15	66	300	100% PES	0	1-2
E	Polyester Yarn (61 tex)	Polyester Chenille Yarn (125 tex)	Polyester Yarn (17.7 tex)	17	66	320	100% PES	0	1-2
F	Polyester Yarn (61 tex)	Polyester Chenille Yarn (125 tex)	Polyester Yarn (17.7 tex)	19	66	340	100% PES	0	1-2

The desired multifunctionality was achieved in the first group of fabrics. However, to obtain higher EMSE values, the second group of fabrics was produced. One of the objectives here is to understand the effect of the orientation of conductive yarns on EMSE values. In the second group of fabrics, conductive yarns were used not only in the weft direction but also in both the weft and warp directions. Stäubli jacquard and Dornier weaving machine were used to produce 6 different samples. Stäubli jacquard and Dornier weaving machines were used to produce six different samples in the second group. The RPM of the weaving machines was 400. To incorporate conductive yarn in the warp direction, the warp density was planned to be lower than that of the first group. The main properties of second group fabrics are given in Table 4.

2.2.2 Finishing Process

After weaving six different fabrics in the first group, as shown in Table 3, fluorocarbon and FR chemicals were added for water/oil repellency and flame retardancy features. The fluorocarbon chemicals (REPELLAN RPC-6) were applied to the fabric on the stenter machine before it entered the drying units. This chemical serves as a permanent finishing agent for water and oil repellency. It is especially recommended for synthetic fibers and can also be used on cellulosic, wool, and silk fibers. The quantity of fluorocarbon used in the process was 30 g/L. The fabric samples were then dried at 150 °C in the drying units of the stenter machine. Monforts stenter machine with eight drying units was used for this process.

After applying the fluorocarbon chemical, a halogen-based flame retardant chemical (ORGALAFLAME KT-EC) were added to the backside of the fabric using the back coating technique before the fabric samples entered the drying units. This marks the second step in the finishing process, where additional treatments are applied to enhance the fabric's properties. FR chemical is a flame retarding compound applicable for coating processes of especially synthetic fibres, performing excellent flame retarding capability. Quantity of FR chemical on the process was 800 g/l. This amount was determined to be the optimum ratio following the fluorocarbon application, ensuring the best balance between effectiveness and fabric performance. Following the weaving and finishing processes, all of the fabric samples were prepared for testing procedures. Since the amount of chemicals applied to the first group of fabrics was sufficient for the desired test results, these chemicals were not applied to the second group of fabrics. Because the primary aim of producing the second group of fabrics is to enhance EMSE results, the focus is on improving electromagnetic shielding effectiveness to meet specific performance standards.

The details of the finishing process for the first group of fabrics are shown in Table 5. Each fabric is assigned a unique code reflecting its finishing treatments, with the fluorocarbon process indicated by "3" and the FR process denoted by "8." This coding system allows for easy identification and comparison of the various finishing methods applied.

Table 4. The main properties of the second group weaved fabrics

Fabric Code	Weft Yarn Type 1	Weft Yarn Type 2	Warp Yarn Type 1	Warp Yarn Type 2	Weft Density (Thread /cm)	Warp Density (Thread/cm)	Fabric weight (g/m^2)	Composition	Conductive Yarn Weight in g/m^2	Weft Plan / Warp Plan
G	Conductive Yarn (43 tex)	PES Chenille Yarn (250 tex)	Polyester Yarn (50 tex)	-	15	21	263	%66.4 PES %23.5 CO %10.1 SS	26.3	1-1-1-2 / 1
H	Conductive Yarn (43 tex)	Polyester Chenille Yarn (250 tex)	Polyester Yarn (50 tex)	-	17	21	279	%65.2 PES %24.3 CO %10.5 SS	28.9	1-1-1-2 / 1
I	Conductive Yarn (43 tex)	Polyester Chenille Yarn (250 tex)	Polyester Yarn (50 tex)	-	19	21	299	%64.3 PES %25.0 CO %10.7 SS	31.7	1-1-1-2 / 1
J	Conductive Yarn (43 tex)	Polyester Chenille Yarn (250 tex)	Polyester Yarn (50 tex)	Conductive Yarn (43 tex)	15	21	260	%63.7 PES %25.4 CO %10.9 SS	28.6	1-1-1-2 / 1-1-1-1-1-1-2
K	Conductive Yarn (43 tex)	Polyester Chenille Yarn (250 tex)	Polyester Yarn (50 tex)	Conductive Yarn (43 tex)	17	21	276	%62.8 PES %26.0 CO %11.2 SS	31.4	1-1-1-2 / 1-1-1-1-1-1-2
L	Conductive Yarn (43 tex)	Polyester Chenille Yarn (250 tex)	Polyester Yarn (50 tex)	Conductive Yarn (43 tex)	19	21	296	%62.0 PES %26.6 CO %11.4 SS	34.0	1-1-1-2 / 1-1-1-1-1-1-2

Table 5. Six different fabrics with chemical concentrations in the first group

Fabric Code	Finishing Process	Finished Fabric Weight (g/m2)
A-3-8	30 g/l Fluorocarbon + 800 g/l FR chemical	335
B-3-8	30 g/l Fluorocarbon + 800 g/l FR chemical	355
C-3-8	30 g/l Fluorocarbon + 800 g/l FR chemical	375
D-3-8	30 g/l Fluorocarbon + 800 g/l FR chemical	355
E-3-8	30 g/l Fluorocarbon + 800 g/l FR chemical	375
F-3-8	30 g/l Fluorocarbon + 800 g/l FR chemical	395

2.3 Test Procedures

In our study, we not only evaluated the EMSE properties but also examined the physical characteristics of the fabrics, along with their water and oil repellent as well as flame retardant properties, which contribute to their multifunctional capabilities. The procedures for conducting these tests are detailed below.

2.3.1 Electromagnetic Shielding Effectiveness Measurement

The shielding effectiveness (SE) of woven fabrics made from conductive yarn was measured in accordance with ASTM D 4935 standards. The SE was assessed over a frequency range of 15 MHz to 3000 MHz using a Network Analyser and the EM2107A as a sample holder. The SE is calculated using Formula 1.

$$\text{Electromagnetic shielding effectiveness (EMSE)} = 10 \log (P_1/P_2) \quad (1)$$

Where P1 (watts) is received power with the fabric present and P2 (watts) is received power without the fabric present. In order to determine SE, first of all the received power is measured by using reference specimen with a diameter with a diameter of 133 mm of the outer ring in the text fixture. Then the load sample is fastened and another received power measurement is taken shown at Figure 1 [22].

The total shielding effectiveness is equal to sum of the absorbsion loss (A) and the reflection loss (R) and correction factor to account for multiple reflections (B) in the shield. This equality is shown in Formula 2 [23].

$$SE_{sheet} = A_{sheet} + R_{sheet} + B_{sheet} \quad (2)$$

According to FTTS-FA-0003 standard desired EMSE value differs according to the place of use. For general use, electromagnetic shielding effectiveness range is shown in Table 6 [24]

2.3.2 Evaluation of Physical Properties

In the study, the physical properties of the first group of fabrics, determined based on their intended usage areas, were tested according to ISO standards. The tests were conducted using the James Heal Titan Strength Test Machine and the James Heal Martindale Abrasion and Pilling Test Machine. The physical tests performed in the study and their corresponding methods are presented in Table 7.

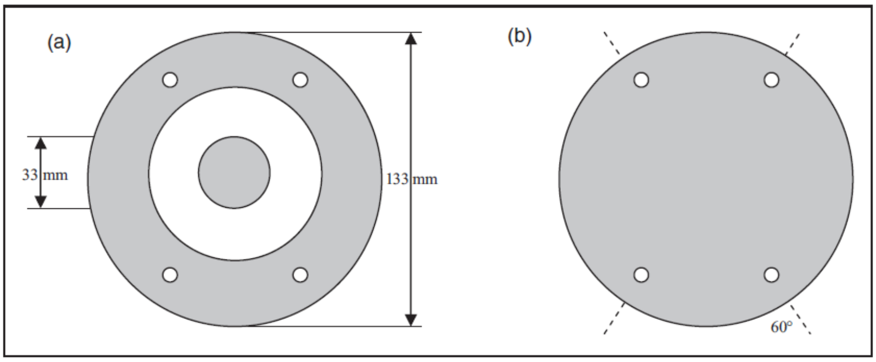

Figure 1. Specimen dimension for reference (left) and load test (right)

Table 6. Electromagnetic shielding effectiveness range for general usage at FTTS-FA-003

Grading	5 / Excellent	4 / Very Good	3 / Good	2 / Moderate	1 / Fair
Amount of EMSE	EMSE>99.9%	99.9%≥EMSE 99.0%	99.0%≥EMSE>90%	90%≥EMSE>80%	80%≥EMSE>70%
SE	SE>30 dB	30 dB≥SE>20 dB	20 dB≥SE>10 dB	10 dB≥SE>7 dB	7 dB≥SE>5 dB

Table 7. Physical tests methods on the study

Property	Test Method	Units
Tensile Strength	ISO 13934-1	N
Abrasion Resistance	ISO 13947-2	Rubs (x1000)
Pilling Resistance	ISO 12945-2	Scale grade 1 to 5

- **Determination of tensile strength**

The tensile strength of fabrics samples was determined according to ISO 13934-1. Strength tester machine was used to perform this test. According to this standard; the elongation of the maximum force of fabric shall be between 8% and 75%, rate of extension should be 100 mm/min [25].

- **Determination of abrasion resistance**

The abrasion resistance of fabrics samples was determined according to ISO 12947-2. The tests were completed when pile loss occur on the fabric. Martindale abrasion and pilling tester was used to perform this test [26]

- **Determination of pilling resistance**

The pilling resistance of the fabric samples was determined according to ISO 12945-2. A Martindale abrasion and pilling tester was used to conduct the test. After 2000 rubs, a viewing cabinet was employed to evaluate the test results. Following this, each fabric specimen was graded according to the grading scheme. [27].

2.3.3 Determination of water/oil repellency

AATCC 193 and AATCC 118 are among the most commonly used tests in the industry to determine water and oil repellency. AATCC 193, known as the test method for aqueous liquid repellency, assesses water/alcohol solution resistance. This method can be used to evaluate the effectiveness of a protective finish that imparts a low-energy surface on various types of fabrics. A water/alcohol solution is prepared for this standard, and fabrics are tested with this solution for different surface tensions. The standard test liquids are listed in Table 8.

The AATCC 193 test is conducted using the liquids listed in Table 8. Additionally, Figure 2 illustrates the water and oil repellent structures with varying contact angles, highlighting their effectiveness in repelling liquids. This visual representation emphasizes the relationship between the contact angle and the fabric's repellency properties.

Table 8. Standard test liquids according to AATC 193 test standard [28]

AATCC Aqueous Solution Repellency Grade Number	Composition	Surface Tension *N
0	None (fails more than 98% water)	
1	98:2/Water : isopropyl alcohol (vol:vol)	59.0
2	95:5/Water : isopropyl alcohol (vol:vol)	50.0
3	90:10/Water : isopropyl alcohol (vol:vol)	42.0
4	80:20/Water : isopropyl alcohol (vol:vol)	33.0
5	70:30/Water : isopropyl alcohol (vol:vol)	27.5
6	60:40/Water : isopropyl alcohol (vol:vol)	25.4
7	50:50/Water : isopropyl alcohol (vol:vol)	24.5
8	40:60/Water : isopropyl alcohol (vol:vol)	24.0

*N= dynes/cm at 25°C

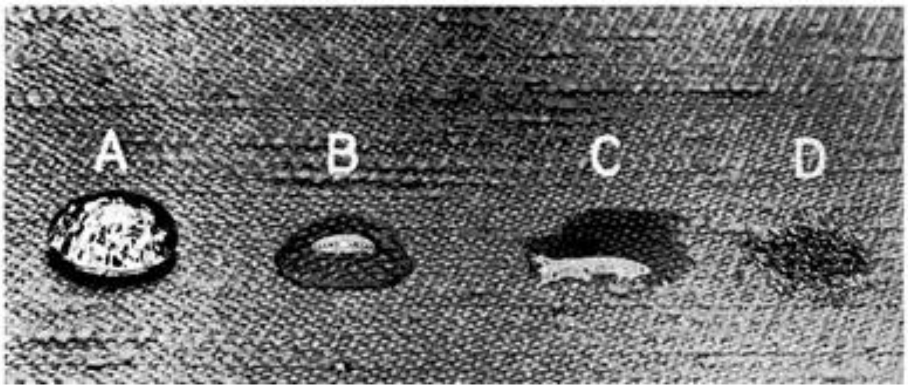

Figure 2. Grading example of repellency [28]
(A=Passes; Clear well-rounded drop, B=Borderline pass; rounding drop with partial darkening, C=Fails; wicking apparent and/or complete wetting, D = Fails; complete wetting)

The liquids shown in Table 8 are applied to the fabric using dropping bottles in a specified order, and the water repellent performance of the fabric is determined based on the images in Figure 2. Furthermore, AATCC 118, known as the test method for oil repellency (hydrocarbon test), is used to assess the oil repellency characteristics of fabrics. This test method detects the presence of a fluorocarbon finish or other compounds that can impart a low-energy surface by evaluating the fabric's resistance to wetting with a selected series of liquid hydrocarbons of varying surface tensions. The test liquids for this method are prepared and numbered according to Table 9. Figure 2 is also utilized in AATCC 118 to determine whether the test has passed.

Table 9. Standard test liquids according to AATCC 118 [29]

AATCC Oil Repellency Test Number	Composition
0	None (Fails Liquid paraffin)
1	Liquid paraffin
2	65:35 Liquid paraffin: n-hexadecane by volume
3	n-hexadecane
4	n-tetradecane
5	n-dodecane
6	n-decane
7	n-octane
8	n-heptane

2.3.4 Determination of flame retardancy

Flame retardancy of the fabrics was evaluated according to the BS 5258 Part 1 Source 1 test standard. The BS 5852 standard, known as the method for assessing the ignitability of materials by smouldering and flaming ignition sources, was also employed in this evaluation. The flowmeter must be calibrated to supply butane gas flow rates as specified in Table 10. According to Source 1, the flexible tubing connecting the output of the flowmeter to the burner tube should have a length between 2.5 m and 3.0 m, with an internal diameter of (7.0 ± 1.0) mm.

Table 10. Parameters of gas ignition Source 1 according to BS 5852 [30]

Parameter	Value for Ignition source 1
Gas flow rate	(45 ± 2) ml/min at 25 °C (44 ± 2) ml/min at 20 °C
Gas burn time	(20 ± 1) s
A) Under these conditions the flame height for source 1 is approximately 35 mm, measured from the top of the burner tube when held vertically upwards and when the flames are burning freely in air.	

3. Results and Discussions

In this section, we assess the findings related to the first and second groups of fabrics developed for this study, along with crucial discussions. The analysis emphasizes the performance attributes and properties of the fabrics, comparing the two groups to underscore their individual strengths and weaknesses. The insights derived from these evaluations enhance our understanding of the materials and their potential uses across different industries. The evaluation of the first group of fabrics encompassed EMSE, water and oil repellency, flame retardancy, and various physical properties, all assessed in relation to their intended production purposes. In contrast, the analysis of the second group of fabrics was concentrated exclusively on the EMSE values. This distinction highlights the specific objectives associated with each group, allowing for a more targeted examination of their respective attributes.

3.1 EMSE Test Results of the First Group Fabrics

The electromagnetic shielding effectiveness (EMSE) results for the first group of fabrics are presented in Figure 3. This figure highlights the performance of each fabric in attenuating electromagnetic interference, offering insights into their suitability for applications requiring electromagnetic protection.

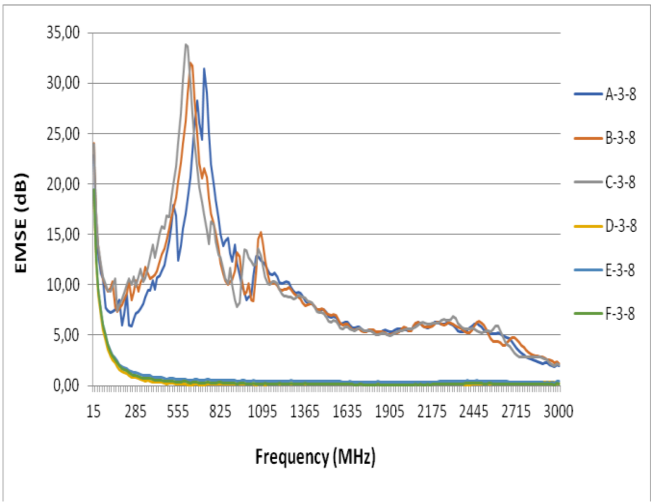

Figure 3. EMSE results of first group fabrics

Figure 3 shows the EMSE results for the first group of fabrics made from polyester yarns, both with and without conductive yarn, as mentioned in the study. It was observed that there is no electromagnetic shielding effectiveness (EMSE) in the D-3-8, E-3-8, and F-3-8 fabrics between 300 MHz and 3000 MHz due to the absence of conductive yarn. This finding indicates that textile products lacking conductive components are unable to provide effective shielding against electromagnetic interference. Consequently, it highlights the importance of incorporating conductive materials in fabric designs intended for applications requiring electromagnetic protection. On the other hand, fabrics that contain conductive yarn demonstrate significant electromagnetic shielding effectiveness (EMSE). The presence of conductive yarns enhances the fabric's ability to attenuate electromagnetic interference, making these materials suitable for applications where protection from such interference is critical. This highlights the importance of incorporating conductive elements into fabric designs to achieve the desired shielding performance. C-3-8 exhibits the highest electromagnetic shielding effectiveness (EMSE) result in the study, achieving 33.85 dB at the 600 MHz frequency level. Additionally, C-3-8 demonstrates the highest average EMSE value across the frequency range of 15 MHz to 3000 MHz. This superior performance can be attributed to the fact that C-3-8 contains the highest concentration of conductive material within the first group of fabrics. The enhanced presence of conductive fibers significantly contributes to its ability to attenuate electromagnetic interference, underscoring its suitability for applications that require effective shielding. Additionally, B-3-8 demonstrates higher average EMSE values compared to A-3-8 across the frequency range of 15 MHz to 3000 MHz. This observation highlights a clear trend: conductive content increase in the first group of fabrics, the EMSE values also rise correspondingly. This relationship underscores the critical role incorporation of conductive materials in enhancing the fabrics' ability to provide effective electromagnetic shielding.

Reflection and absorption results are also crucial for determining shielding effectiveness. The reflection and absorption results of the first group of fabrics are presented in Figure 4. According to this figure, fabrics that do not contain conductive yarn exhibit reflection and absorption properties below 12%. This indicates that these fabrics lack electromagnetic shielding effectiveness (EMSE) and are unable to effectively reflect or absorb electromagnetic waves.

In contrast, fabrics containing conductive yarn demonstrate significant reflection and absorption characteristics. As shown in Figure 4, as the frequency increases, the reflection values decrease while the absorption values increase. Notably, C-3-8 has the highest average reflection value, suggesting that the reflective properties of the conductive content, particularly steel metal are more pronounced. This emphasizes that a higher amount of conductive material positively influences the reflection properties of the fabrics.

3.2 Physical, Repellency and Retardancy Test Results of the First Group Fabrics

In addition to assessing the electromagnetic shielding features, a comprehensive evaluation of the fabrics' physical characteristics, flame retardancy, and water repellency was conducted in accordance with international standards. This multifaceted analysis provides a deeper understanding of the materials' performance and suitability for various applications. The detailed findings are presented in Table 11, highlighting the strengths of each fabric tested.

Upon evaluating the pilling values, it is evident that all the fabrics exhibit outstanding performance in terms of pilling resistance. This exceptional quality can be attributed to the inherent properties of polyester chenille fabrics, which are known for their high resistance to pilling. Notably, the specific type of fine yarns used in the fabric samples does not impact the pilling resistance results. Due to the structure of the fabric, the chenille yarns are directly exposed to pilling during the test, rather than the fine yarns. This finding reinforces the reliability of these fabrics in applications where aesthetic appearance and fabric integrity are essential.

The results of the tensile strength test results were analysed using one-way analysis of variance (ANOVA), as presented in Table 13. When the weft density increases, tensile strength results improve in the weft direction; however, increasing weft density does not affect the tensile strength test results in the warp direction. Additionally, when comparing fabrics with and without conductive yarn at the same weft density, it is observed that fabrics containing polyester yarn exhibit higher tensile strength in the weft direction. This is because polyester yarn is stronger than conductive yarn. On the other hand, it should be noted that the tensile strength test results for the samples using conductive yarns were also satisfactory.

3.2.1 Physical Test Results for First Group of Fabrics

According to Table 11, it has been determined that the primary factor influencing the abrasion resistance test results in the first group of fabrics is pile losing. Consequently, fabrics with higher pile density, meaning those with greater weft density, demonstrate superior abrasion resistance. Additionally, when a one-way analysis of variance (ANOVA) is applied to the results, it is revealed that increasing the weft density in the fabrics is statistically significant. This is illustrated in Table 12. Moreover, it has been observed that the presence of conductive yarn in the fabric structure does not affect the abrasion results, as the main reason for the test conclusion is the loss of pile in the chenille yarns.

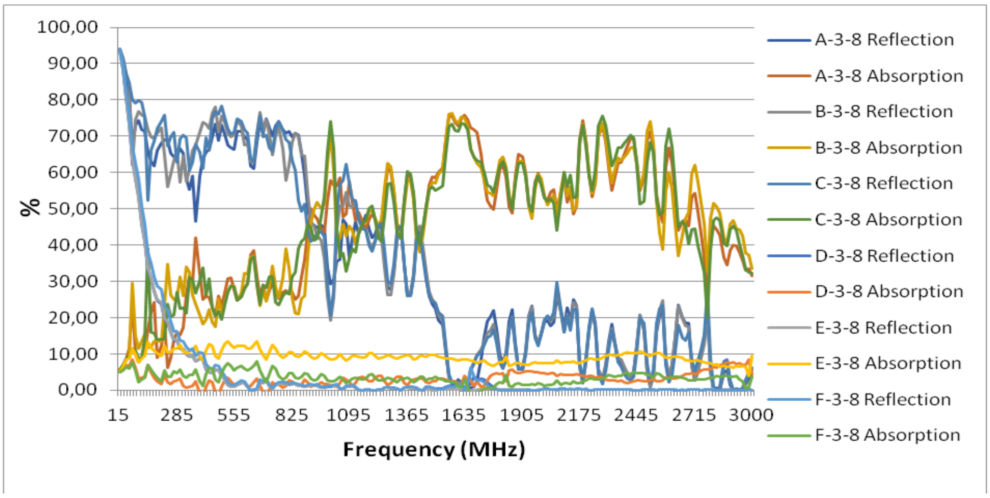

Figure 4. Reflection and absorption results of first fabrics

3.2.2 Water Resistance Test Results for First Group of Fabrics

The amount of fluorocarbon used in the samples for this study was carefully calibrated to align with the amount of flame retardant (FR) applied. This precise formulation ensured that all fabrics achieved optimal water and oil repellent properties. According to Table 11, the performance metrics across all samples were found to be exceptional, demonstrating remarkable resistance to both water and oil. This combination of fluorocarbon and FR not only enhances the functional attributes of the fabrics but also broadens their applicability.

Table 11. Physical properties, oil and water repellency and FR results of the fabric samples

Fabric Code	Fabric Weight	Abrasion Resistance	Pilling	Tensile Strength		FR test	WR Test	OR Test
	EN 12127 (g/m²)	ISO 12947-2 (rubs)	ISO 12945-2 (grade)	ISO 13934-1		BS 5852 Part 1 Source 1	AATCC 193 (grade)	AATCC 118 (grade)
				Warp (N)	Weft (N)			
A-3-8	335	16.000	5	1792	512	PASS	8	5
B-3-8	355	18.000	5	1832	626	PASS	8	5
C-3-8	375	20.000	5	1824	922	PASS	8	5
D-3-8	355	16.000	5	1805	830	PASS	8	5
E-3-8	375	18.000	5	1826	1106	PASS	8	5
F-3-8	395	20.000	5	1830	1267	PASS	8	5

Table 12. Effect of Weft Density on Abrasion Resistance Values

Parameter	F	Sig.(p)
The impact of weft density on abrasion resistance testing	18	0.00*

*Statistically significant according to α=0.05

Table 13. The Effect of Weft Density and Yarn Type on Tensile Strength

Parameter	F	Sig.(p)
The Effect of Weft Density on Warp Direction Tensile Strength Test Results	1	0.46
The Effect of Weft Density on Weft Direction Tensile Strength Test Results	24.3	0.00*
The Effect of Replacing Conductive Yarn with Polyester Yarn on Weft Direction Tensile Strength Test Results	290.58	0.00*

*Statistically significant according to α=0.05

3.2.3 FR Test Results for First Group of Fabrics

As mentioned above, the amount of flame retardant (FR) chemical applied to the fabric was meticulously designed to be compatible with the fluorocarbon treatment, ensuring the validity of the test results across all samples. The test results presented in Table 11 clearly demonstrate that all samples achieved successful outcomes in the FR test, attributable to the carefully determined quantities of each chemical. This strategic approach not only validates the effectiveness of the treatments but also underscores the fabrics' enhanced safety and performance characteristics in various applications.

3.3 EMSE Test Results of the Second Group Fabrics

The multifunctionality feature targeted in this study was successfully achieved, as evidenced by the test results of the first group of fabrics. Furthermore, the second group of fabrics was specifically designed to expand upon our findings and to attain even higher electromagnetic shielding effectiveness (EMSE) values. This innovative design not only yielded superior results but also challenged existing knowledge in the literature. Notably, it demonstrated that higher EMSE values can be achieved using less conductive material, indicating that efficient material design can enhance performance without the need for increased conductive content. This breakthrough insight paves the way for the development of more sustainable and cost-effective textile solutions in the field of electromagnetic shielding.

The second group of fabrics was specifically designed to achieve higher electromagnetic shielding effectiveness (EMSE) results at frequencies ranging from 850 MHz to 2400 MHz, surpassing the performance of the first group. To accomplish this, conductive yarns were strategically incorporated not only in the weft direction but also in the warp direction, enhancing the fabrics' overall shielding capabilities. This dual incorporation of conductive yarn significantly improves the fabrics' ability to attenuate electromagnetic interference. The EMSE results for the second group of fabrics are illustrated in Figure 5, showcasing their superior performance and potential for various applications requiring robust electromagnetic protection.

Figure 5 illustrates that samples containing conductive yarn in both the weft and warp directions exhibit similar EMSE results to those that have conductive yarn only in the weft direction within the frequency range of 15 MHz to 850 MHz. However, the samples with conductive yarn solely in the weft direction show insufficient EMSE results in the frequency range of 850 MHz to 2400 MHz, indicating a decline in performance at higher frequencies. Additionally, it is evident that the EMSE results for the first and second group fabrics, which both contain conductive yarn only in the weft direction, are comparable. This finding suggests that while the incorporation of conductive yarn enhances performance, the orientation of the yarn plays a critical role in the fabrics' effectiveness across different frequency ranges. Moreover, the samples that incorporate conductive yarn in both the weft and warp directions demonstrate the desired electromagnetic shielding effectiveness (EMSE) results. According to the FTTS-FA-003 standard, the EMSE results for fabrics “J,” “K,” and “L” are classified as “Good.” This classification indicates that these fabrics meet the necessary criteria for effective electromagnetic shielding, making them suitable for applications requiring reliable protection against electromagnetic interference.

It is well established in the literature that increasing the conductive content typically enhances EMSE results. However, this is not always the case. For instance, fabric "I" contains more conductive yarn than fabric "J," yet "J" exhibits better EMSE results. This discrepancy can be attributed to the structure of electromagnetic waves, which consist of an electric field and a magnetic field that are perpendicular to each other. Consequently, having more conductive content in a single direction within the fabric has a lesser impact than having conductive content oriented perpendicularly. Since the yarns in the weft and warp directions are perpendicular to each other, it can be explained that a fabric with lower conductive content may achieve a higher EMSE value than a fabric with higher conductive content that is only oriented in the weft direction.

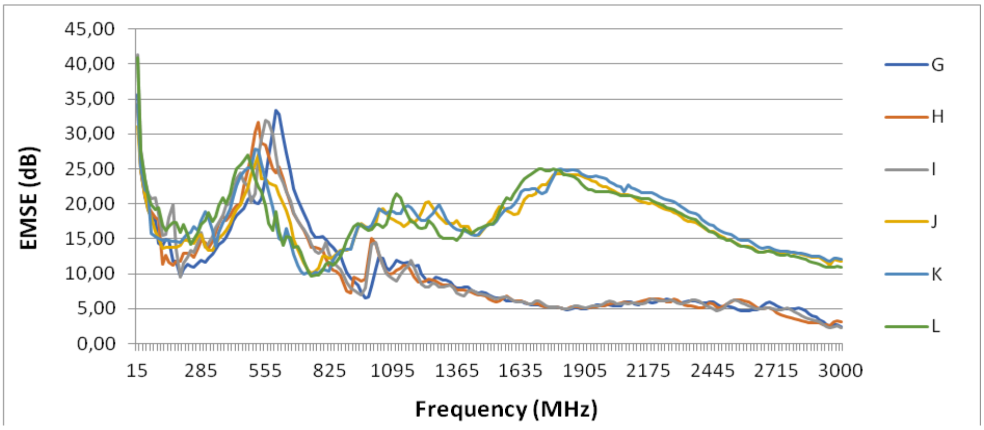

Figure 5. EMSE results of second group fabrics

In addition to EMSE results, reflection and absorption characteristics are equally important for evaluating fabric performance. The reflection and absorption results of the second group of fabrics are illustrated in Figure 6. This figure provides a detailed analysis of how effectively these fabrics can reflect and absorb electromagnetic waves, offering valuable insights into their overall shielding capabilities.

Figure 6 clearly illustrates that the reflection and absorption properties of fabrics incorporating conductive yarn in both the weft and warp directions are significantly higher than those of fabrics using conductive yarn solely in the weft direction. This enhanced performance can be attributed to the strategic placement of the conductive yarns within the fabric, which allows for more effective interaction with electromagnetic waves.

Furthermore, the data reveals a consistent trend across all fabrics in the second group: as the frequency increases, the reflection values decrease while the absorption values increase. This behaviour indicates that at higher frequencies, the fabrics are better able to absorb electromagnetic energy, which is crucial for applications that require effective shielding against interference. This relationship between frequency, reflection, and absorption underscores the importance of fabric design in optimizing performance for various electromagnetic applications.

4. CONCLUSION

In this study two group of fabric were produced. The aim of producing first group of fabrics was to create a multifunctional textile surface with electromagnetic shielding effectiveness, water and oil repellency, and flame retardancy features combined. As a result of the study, fabrics with all three features were successfully produced in the first group. On the other hand the aim of production the second group fabric was to get higher electromagnetic shielding effectiveness test results. Following the production all fabric groups, international tests were performed according to ISO, BS and AATCC standards. Upon examining the test results, the following conclusions can be drawn:

- One of the key results of this study is to establish the optimal ratios for water/oil repellency and flame retardancy in fabric treatment, thereby setting a benchmark for future advancements in fabric development in this field.
- The study revealed that changing the orientation of conductive yarn led certain fabrics to achieve higher EMSE values despite having lower overall conductive content, providing new insights beyond existing literature. In second group fabrics, some samples using conductive yarns in both weft and warp directions showed higher EMSE performance despite having lower total conductive content compared to samples with conductive content only in the weft direction. This phenomenon is related to the perpendicular orientation of electric and magnetic fields that create electromagnetic waves.
- In the first group of fabrics, an increase in conductive content on the fabric surface led to higher EMSE values. Additionally, between the frequency ranges of 850 MHz and 3000 MHz, increasing the frequency resulted in decreased EMSE values.
- It was observed that as the frequency increases, reflection values decrease while absorption values increase for fabrics containing conductive content in both the first and second groups.
- Fabrics without conductive content in their structure do not exhibit EMSE values.
- Between the frequencies of 850 MHz and 2400 MHz, while there was a decrease in EMSE values in fabrics using conductive yarn only in the weft direction, while samples using conductive yarn in both weft and warp directions get sufficient results.

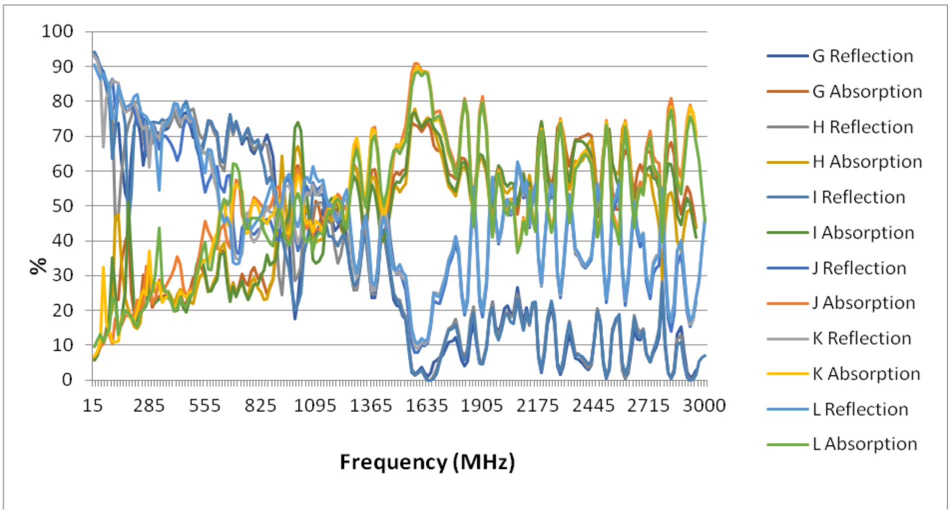

Figure 6. Reflection and absorption results of second group fabrics

- All fabric samples in the first group, which include fluorocarbon and halogen-based flame retardant chemicals, passed water/oil repellency and FR tests. This indicates that using 30 g/l of fluorocarbon and 800 g/l of FR chemicals is sufficient for all fabric samples.

- Since the end point of the abrasion test is realised by pile loss before two threads broken, it has been observed that the abrasion value increases as the weft density increases. Whether the fabric contains conductive yarn or not does not directly affect the results of the abrasion test due to the priority of pile loss.

- The all fabric samples of the first group fabrics have passed the pilling tests. This is because chenille yarns are resistant to the pilling and conductive yarns did not affect the pilling results.

- While increasing the weft density has a positive effect on tensile strength test results in the weft direction, but does not significantly affect results in warp direction. Due to the positive effect of polyester yarn, fabrics without conductive yarn have higher tensile strength test results in the weft direction than fabrics containing conductive yarn with the same weft density.

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