Abstract: People are no longer satisfied with only comfortable textile clothing with advanced technology and elevated standard of living and, thus, are gradually preferring functional textiles. In the meanwhile, the spread of medical knowledge has educated the public about the antimicrobial concept. In this study, composed of different twist coefficients and different numbers of plies, the zinc ion twisted yarns are made into knitted fabrics. Next, the knitted fabrics are examined for water vapor transmission rate and antimicrobial efficacy. The test results indicate that the water vapor transmission rate is 1013 g/m²/day for 2Zn-0C-K and 981 g/m²/day for 3Zn-0C-K. However, a rise in the twist coefficient adversely affects the water vapor transmission rate. The fabric 2Zn-3C-K exhibits the maximal air permeability of 265 cm³/cm²/s and 3Zn-3C-K 186 cm³/cm²/s. Regardless of whether it is at OD₆00, colony count observation, or antibacterial rate, 3Zn-5C-K exhibits the maximal antibacterial rate with the value being 0.45 at OD₆00 and the optimal antimicrobial efficacy being 85%. To sum up, based on the interest of the test results, production cost, and manufacturing process evaluation, 2Zn-5C-K is the optimal nonwoven fabric that achieved the maximal effects.

Keywords: zinc ion; twist coefficient; antimicrobial efficacy; antibacterial rate; Escherichia coli (E. coli); colony count

1. Introduction

With high social development and better living quality, people start to pay more attention to functional textile products more than simply comfortable textile ones, which makes the invention of functional products become a priority in the textile field. Public awareness of hygiene has increased, which in turn makes the antimicrobial concept widespread knowledge in today’s society [1–3]. When wearing textile garments, people metabolize and produce sebum cutaneum, sweat, and scales. These metabolites are nourishment for microorganisms that are the smallest creatures that cannot be observed by naked eyes. Microorganisms can be divided into bacteria, fungus, and virus, and the former can grow to a tremendous population almost everywhere. For instance, Escherichia coli (E. coli), one type of Gram-negative bacteria, can grow over the textiles and degenerate them in terms.
of discoloring, causing inferior quality, generating repulsive odors, and contaminating the environment. Worse, *E. coli* also survives in waters, soils, feces, and the human and animals’ digestive systems and skins and can inflict people with diarrhea [4–6].

Common antibacterial agents in the market involve inorganic, organic, and natural types. In the early stage, the majority of antibacterial agents are organic, because they have the optimal antibacterial performance. Nonetheless, the effect is not long lasting, and the stability is low otherwise, due to which organic antibacterial agents are gradually replaced by inorganic types [7–9]. Inorganic antibacterial agents are commonly used in disinfection, featuring long-lasting efficacy, high temperature resistance, and benefits to the environment and human health [10,11] and have been used in plastic, ceramics, and stainless steel in recent years. A recent study showed that most antimicrobial substrates used in the manufacturing process are mercury, silver, ZrO$_2$, zinc oxide, and chlorogenic acid (CGA). Among these antimicrobial agents, mercury is poisonous and, thus, banned, but silver antibacterial materials have a higher production cost. Chlorogenic acid (CGA) could be applied as a natural product to improve the antibacterial ability, but the using condition was highly restricted, and the transformation from ZrO$_2$ crystalline forms is a serious problem in the biomedical field. As a result, zinc oxide exhibits the most potential due to its intrinsic safety and stability with eco-friendly, ultraviolet resistant, and antimicrobial attributes [12,13]. Hence, zinc oxides have commonplace uses in sunblock, waste water, tectorial membranes of artificial teeth, and the textile field, becoming a critical material in developing green textiles [14–17].

The employment of twisting or wrapping may render functional yarns with a structural change, which may restrict the functions from effectuating. Some researchers studied the hygroscopicity of functional yarns as related to the conduction of twisting. They found that excessive twisting damaged the yarn structure and reduced the capillary effect [18,19]. Therefore, in this study, two or three plies of zinc ion yarns are made into twisted yarns via a rotor spin device, and in the meanwhile, the rotating speed difference (between the winding and take-up rates) is changed during the twisting process. Next, a fully computerized, high-efficiency, single-cylinder hosiery machine is used to fabricate functional antibacterial knitted fabrics, after which the mechanical properties, water vapor transmission rate, air permeability, antibacterial OD value, colony count, and antimicrobial efficacy of the knitted yarn are examined, thereby evaluating the optimal manufacturing parameters. These results are of great significance for the design of low-cost, eco-friendly, sustainable, and mass-produced products.

2. Materials and Methods

2.1. Materials

Zinc ion yarns (Tung Ho Textile Co., Ltd., Tainan, Taiwan) have a fineness of 30 tex and are used to form twelve types of functional twisted yarns. For the antibacterial assay, *Escherichia coli* (*E. coli*, ATCC25922) is purchased from the Bioresource Collection and Research Center, Taiwan.

2.2. Preparation for Microcapsules

Functional antibacterial yarns are produced with two or three plies of zinc ion yarns. The yarns are fed into a reverse splitup (Shang Yang Machinery Co., Ltd., Taichung, Taiwan) to form plied yarns that are then made into zinc ion twisted yarns using the twist machine. The winding and take-up rates are changed, and the resulting rotary speed differences help attain different twist coefficients. Twisted yarns can be divided into two groups, the 2Zn and 3Zn groups, which are denoted according to the constituent yarn counts and type (i.e., Zn yarns). Figure 1 shows the process rote of functional antibacterial nanometer zinc ion yarns. Meanwhile, the subtitle of denotations indicates that the sample are yarns (C) or knitted fabrics (K), while the affix digit means the twist coefficient. For example, 2ZN-3C means that 2 zinc ion yarns are made into twisted yarns with a twist coefficient of 3. Specification of twisted yarns in Table 1.
Table 1. Specification of twisted yarns.

| Zinc Ion Yarn (Counts) | Sample Code | Twist Coefficient | cN/Tex | Irregularity (CV%) | Hairiness (H) |
|------------------------|-------------|-------------------|--------|-------------------|---------------|
| 2Zn-0C                 |             | 0                 | 1.26 ± 0.09 | 7.33              | 365           |
| 2Zn-1C                 | 1           | 1.37 ± 0.09       | 6.71   | 158.4             |
| 2Zn-2C                 | 2           | 1.62 ± 0.09       | 5.61   | 65.6              |
| 2Zn-3C                 | 3           | 1.65 ± 0.07       | 4.42   | 20.2              |
| 2Zn-4C                 | 4           | 1.55 ± 0.05       | 3.39   | 17.6              |
| 2Zn-5C                 | 5           | 1.50 ± 0.12       | 8.14   | 6.8               |
| 3Zn-0C                 |             | 0                 | 1.31 ± 0.07 | 5.76              | 501.4         |
| 3Zn-1C                 | 1           | 1.49 ± 0.02       | 1.80   | 281.8             |
| 3Zn-2C                 | 2           | 1.64 ± 0.04       | 2.29   | 39.8              |
| 3Zn-3C                 | 3           | 1.67 ± 0.07       | 4.23   | 12                |
| 3Zn-4C                 | 4           | 1.64 ± 0.10       | 6.60   | 6.4               |
| 3Zn-5C                 | 5           | 1.62 ± 0.04       | 2.44   | 4.8               |

Functional antibacterial knitted fabrics are made as follows. Two or three plies of zinc ion yarns are twisted at a rotary rate of 0, 3000, 6000, 9000, 12,000, and 15,000 rpm with a corresponding twist coefficient of 0, 1, 2, 3, 4, and 5. Afterwards, a fully computerized, high-efficiency, single-cylinder hosiery machine (DK-B318, Da Kong Enterprise Co., Ltd., Changhua, Taiwan) is used to produce twelve kinds of knitted fabrics. Due to a greater variety in the sample range, the denotations listed in Table 2 will be used in subsequent discussions.

Table 2. Specifications of functional antibacterial knitted fabrics.

| Sample Code | Weight of Knitted Fabrics (g/m^2) | Thickness (mm) | Tensile Stress (N) | Tensile Stress along the Weft Direction (N) |
|-------------|----------------------------------|----------------|-------------------|--------------------------------------------|
| 2Zn-0C-K    | 241.93 ± 8.72                    | 0.52 ± 0.01    | 37.48 ± 8.24      | 41.71 ± 9.58                               |
| 2Zn-1C-K    | 257.88 ± 12.38                   | 0.50 ± 0.01    | 50.46 ± 10.22     | 45.03 ± 5.91                               |
| 2Zn-2C-K    | 272.08 ± 9.85                    | 0.50 ± 0.01    | 77.95 ± 12.28     | 51.72 ± 6.33                               |
| 2Zn-3C-K    | 286.15 ± 8.86                    | 0.50 ± 0.02    | 83.08 ± 9.15      | 53.13 ± 6.05                               |
| 2Zn-4C-K    | 300.96 ± 10.50                   | 0.53 ± 0.01    | 68.42 ± 10.33     | 54.76 ± 7.61                               |
| 2Zn-5C-K    | 319.29 ± 6.43                    | 0.54 ± 0.02    | 55.19 ± 21.28     | 48.32 ± 4.61                               |
| 3Zn-0C-K    | 320.91 ± 5.44                    | 0.73 ± 0.01    | 116.28 ± 13.69    | 79.79 ± 5.19                               |
| 3Zn-1C-K    | 332.79 ± 10.50                   | 0.69 ± 0.01    | 129.27 ± 14.33    | 82.81 ± 7.87                               |
| 3Zn-2C-K    | 343.46 ± 11.85                   | 0.70 ± 0.02    | 134.21 ± 15.56    | 90.07 ± 10.11                              |
| 3Zn-3C-K    | 352.15 ± 9.24                    | 0.70 ± 0.02    | 147.50 ± 18.12    | 97.07 ± 7.26                               |
| 3Zn-4C-K    | 366.74 ± 5.02                    | 0.75 ± 0.01    | 116.85 ± 13.71    | 88.29 ± 15.04                              |
| 3Zn-5C-K    | 374.82 ± 5.48                    | 0.74 ± 0.02    | 84.44 ± 7.74      | 81.2 ± 9.74                                |
2.3. Measurements

2.3.1. Mechanical Properties of Twisted Yarns

As specified in the ASTM D2256 test standard, an automatic yarn tester (FPA/M, Statimat-M, Textechno Ltd., Mönchengladbach, Germany) is employed to test the maximal tensile strength of twisted yarns at a tensile rate of 300 mm/min. The gauges are 250 mm apart. Twenty samples for each specification are tested for the average, recorded as Table 1.

2.3.2. Mechanical Properties of Knitted Fabrics

As specified in the ASTM D5034 test standard, the breaking tenacity of knitted fabrics is measured using a universal testing machine (HT-2402, Hung Ta Instrument Co., Ltd., Taichung, Taiwan) at a tensile rate of 300 mm/min. The gauges are 100 mm apart, and knitted fabrics have a size of 20 × 2.5 cm. Ten samples for each specification are tested for the average, recorded as Table 2.

2.3.3. Water Vapor Transmission Rate (WVTR) of Knitted Fabrics

As specified in the ASTM E96 test standard, the water vapor transmission rate of knitted fabrics is measured as follows. Samples are placed in a flask that is located in a test case at 25 °C and a relative humidity of between 30 and 35%. Next, a precision balance weighs the sample bottle, yielding the initial weight (W₀). The whole set is then mounted in the test case for the conduction of water vapor transmission rate for 24 h, after which samples are removed and weighed with a precision balance. The yielded weight is the weight after evaporation (Wₜ). Accordingly, the water vapor transmission rate is computed using the subsequent equation.

\[
\text{water vapor transmission rate} = \frac{(W₀ - Wₜ)}{(A \times t)} \times 100\% \tag{1}
\]

where W₀ is the initial weight (g) including the glass flask, water, and fabrics; Wₜ is the total weight (g) of the glass flask, water, and fabrics after a 24 h evaporation; A is the surface area of knitted fabrics; t is the water evaporation time (hour).

2.3.4. Air Permeability of Knitted Fabrics

As specified in ASTM D737 test standard, the air permeability of functional antibacterial knitted fabrics is measured using an air permeability tester (Textest FX3300, Zürich, Switzerland). Samples have a size of 25 × 25 cm, and twelve samples for each specification are used for the average.

2.3.5. Ultraviolet/Visible Spectrophotometer (UV-Vis) Antibacterial Efficacy (OD600) of Knitted Fabrics

With a concentration of 10⁵ CFU/mL, 1 mL of E. coli suspension is dripped over the functional antibacterial knitted fabrics for a 16 h co-culture in an incubator. Afterwards, 9 mL of nutrient solution is infused into the flask and shaken for five minutes. One milliliter of nutrient solution is then removed to be infused into a cuvette and, finally, scanned using an ultraviolet-visible spectrophotometer at frequency of 600 nm, and the values are recorded for the average [4,20].

2.3.6. Washing Test

As specified in GB20944-2008 test standard, functional antibacterial knitted fabrics were washed with 2% soapy water for 15 min and rinsed in clean water. The laundered cycles were 5 times. The washing resistance test was used to evaluate the antimicrobial efficiency of the knitted fabrics before and after washing [21].
2.3.7. Antimicrobial Assay of Knitted Fabrics

According to the AATCC100-2004 test standard, the test sample is placed in a sample bottle containing a volume of 25 mL. *E. coli* (1 mL, $10^5$ CFU/mL) is dripped over the functional antibacterial knitted fabrics and kept in an incubator for 16 h. Nine milliliters of (Lysogeny broth, LB) nutrient solution is then infused into the sample bottle that is then shaken for five minutes. One hundred microliters of (LB) nutrient solution is smeared evenly over the solid culture dish for overnight, and the sample condition is observed and photographed the next day. The control group uses knitted fabrics consisting of non-twisted yarns and is divided into 2Zn-0C-K and 3Zn-0C-K. The equation used to compute antibacterial rate is as follows [22,23].

\[
\text{Antibacterial rate} = \frac{(A - B)}{A} \times 100\% 
\]

where A and B is the colony count of the control and experimental groups, respectively.

2.3.8. Statistical Analysis

SPSS 17.0 was used for statistical analyses. Data are presented as the mean standard deviation (SD). Statistical analysis of all data was performed using one-way ANOVA, where $p$ values < 0.05 are considered statistically significant.

3. Results and Discussion

3.1. Surface Observation of Functional Antibacterial Yarns Based on the Twist Coefficient

Figure 2a demonstrates two plies of zinc ion yarns, while Figure 2b shows the control group that is non-twisted. Made with a twisting process and twist coefficients (1, 2, 3, 4, and 5) via a rotor spin device, the two- and three-plied twisted yarns are separately shown in Figures 2 and 3. It is observed that a rise in the rotary rate of the rotor spin device increases the number of coils of twisted yarns per unit length.

![Figure 2. Two-plied zinc yarns: (a) 2Zn-0C, (b) 2Zn-1C, (c) 2Zn-2C, (d) 2Zn-3C, (e) 2Zn-4C, and (f) 2Zn-5C.](image-url)
3.2. Effects of Twist Coefficient on Water Vapor Transmission Rate (WVTR) of Functional Antibacterial Knitted Fabrics

The water vapor transmission rate (WVTR) of functional antibacterial knitted fabrics depends on several factors, such as fiber type, twist coefficient of yarns, fabric structure, and fabric thickness [24,25]. In this study, the WVTR of antibacterial knitted fabrics is investigated as related to the twist coefficient. Previous study reported that the human body exhibited a WVTR of about 215–350 g/m²/day. If knitted fabrics showed a WVTR that was lower than that of the human body, condensation of moisture could happen, and the moisture will then be kept in the knitted fabrics [26,27]. As for the control groups that the constituent yarns are not twisted, the WVTR is 1013 g/m²/day for 2Zn groups and 981 g/m²/day for 3Zn groups. (**p < 0.01). Figure 4 shows the experimental group that the constituent yarns are twisted, the WVTR of knitted fabrics descends as a result of increasing the twist coefficient. Comparatively, non-twisted yarns comprise knitted fabrics with more voids due to a small twist degree, and moisture is prone to go in and out of the fabrics, which in turn causes the optimal water vapor transmission rate. By contrast, a rise in the twist coefficient makes yarn arrangement compact, which hampers the moisture from entering the knitted fabrics, resulting in a descending WVTR. According to previous literature, we could conclude that the permeability of both air and moisture is largely dependent on the porosity of fabrics [28,29]. In conclusion, all types of the proposed knitted fabrics attain the WVTR required by the use standard for the human skin, and they are free from condensation of water vapor in the interior [30].
Figure 4. Water vapor transmission rate of functional antibacterial knitted fabrics as related to twist coefficient. Note: data shown as mean standard deviation (SD) (n = 12). ** p < 0.01.

3.3. Effects of Twist Coefficient on Air Permeability of Functional Antibacterial Knitted Fabrics

The air permeability of knitted fabrics serves an important index for the comfort that the users feel. Figure 5 shows the air permeability of functional antibacterial knitted fabrics as related to the twist coefficient, which is 188–265 cm$^3$/cm$^2$/s for the 2Zn groups and 141–186 cm$^3$/cm$^2$/s for the 3Zn groups. Regardless of whether it is 2Zn groups or 3Zn groups, an increase in the twist coefficient of the constituent zinc ion twisted yarns has a positive influence on the air permeability of the resulting knitted fabrics. This result is ascribed to the enhanced cohesion that strengthens the entanglement level among yarns firmly, while improving the air permeability concurrently. In particular, the optimal air permeability is 265 cm$^3$/cm$^2$/s for 2Zn-3C-K and 186 cm$^3$/cm$^2$/s for 3Zn-3C-K. Because of a greater twist count, knitted fabrics have a higher density that decreases the porosity and then reduces the air permeability [31,32].

Figure 5. Air permeability of functional antibacterial knitted fabrics as related to the twist coefficient. Note: data shown as mean standard deviation (SD) (n = 12). ** p < 0.01.
3.4. Effects of Twist Coefficient on Antimicrobial Efficacy of Functional Antibacterial Knitted Fabrics Based on UV-Vis Analysis

Figure 6 shows that the OD ultraviolet/visible spectrophotometer (UV-Vis) value is 1.62 for 2Zn-0C-K but is 0.56 for 2Zn-5C-K, and likewise, the OD value is 1.5 and 0.45 for 3Zn-0C-K and 3Zn-5C-K, respectively. To sum up, regardless of whether the knitted fabrics are composed of two or three plies of twisted zinc ion yarns, the greater the twist coefficient, the lower the OD value, which means that the knitted fabrics demonstrate better antimicrobial efficacy. On the other hand, when bacteria grow in a nutrient solution, they consume glucose as energy, and their metabolites generate acids. Hence, a decrease in glucose quantity as well as a raise in the metabolic acid could be used as the reference for corresponding bacterial growth. This method is, however, vicarious and unable to obtain a total viable count, but only serves an antibacterial index.

![Graph showing antimicrobial efficacy of functional knitted fabrics before and after washing](image)

**Figure 6.** Antimicrobial efficacy of functional knitted fabrics before and after washing as related to the twist coefficient.

The OD value after washing of 2Zn-0C-K, 2Zn-5C-K, and 3Zn-0C-K is 1.68, 0.58, and 1.58, respectively (Figure 6). It is worth noting that the OD value of the 2Zn-5C-K sample before washing is lower than that of the fabric after washing. However, for the 3Zn-0C-K sample, the OD value has a slight decrease after five cycles of washing. In fact, there was no large difference for the antimicrobial efficacy on the above samples before and after five cycles of washing in the statistical analysis method. The samples before and after washing showed outstanding antimicrobial efficacy.

3.5. Effects of Twist Coefficient on Antibacterial Rate of Functional Antibacterial Knitted Fabrics

Figures 7 and 8 show the colony count of *E. coli* when two- and three-plied knitted fabrics are used. Figures 7a and 8a show the control groups that are knitted fabrics composed of two and three plies non-twisted zinc ion yarns, where the colony count is comparatively greater than the experimental group. In the meanwhile, a rise in the twist coefficient proportionally restrains the bacterial growth. This result is ascribed to a greater quantity of zinc ion yarns per unit area, suggesting that the antimicrobial effect is proportional to the twist coefficient.
Furthermore, a rise in the twist rate of functional antibacterial knitted fabrics, which are made of both nanometer zinc ion yarns that then become functional antibacterial knitted fabrics on the surface. Figure 7 shows the colony count of functional antibacterial knitted fabrics made of 2-plied twisted yarns: (a) 2Zn-0C-K, (b) 2Zn-1C-K, (c) 2Zn-2C-K, (d) 2Zn-3C-K, (e) 2Zn-4C-K, and (f) 2Zn-5C-K.

Figure 8 shows the colony count of functional antibacterial knitted fabrics made of 3-plied twisted yarns: (a) 3Zn-0C-K, (b) 3Zn-1C-K, (c) 3Zn-2C-K, (d) 3Zn-3C-K, (e) 3Zn-4C-K, and (f) 3Zn-5C-K.

Figure 9 shows the antibacterial rate of the control and experimental groups as related to the twist coefficient, and the antibacterial rate is computed using Equation (2). As for the knitted fabrics composed of two plies of zinc ion yarns, the antibacterial rate is only 15% for 2Zn-1C-K, but it spikes to 81% for 2Zn-5C-K. Similarly, as for the knitted fabrics composed of three plies of zinc ion yarns, the antibacterial rate is 32% for 3Zn-1C-K and 85% for 3Zn-5C-K. Namely, both a rise in zinc ion yarns and a rise in the twist coefficient have a positive influence on the antibacterial rate. Due to a greater total amount of nanometer zinc ion yarns per unit area, the resulting knitted fabrics demonstrate higher antibacterial performance.
Nanometer zinc ions are able to kill and reduce the harmful effects of *E. coli* because *E. coli* is one type of Gram-negative bacteria. Despite a complex cell wall, *E. coli* has a bacteria lipid bilayer as its outer membrane. The internal side of the lipid bilayer is composed of phospholipids that have a rather low strength. In addition, *E. coli* carries negative electricity because of the presence of ionizing -COOH over its surface. In this case, nanometer zinc oxides dissociate antibacterial ions (Zn$^{2+}$) that will be adsorbed by the surface of bacteria with the aim of the coulombic force, thereby impairing the cell wall of bacteria. Besides, zinc oxides also interfere with the synthesis of peptidoglycan, hampering cell walls from formation, while restraining the propagation and growth. Then, Zn$^{2+}$ can penetrate the cell walls, replacing the surface cations over cell membranes and interacting with sulfur- or nitrogen-containing functional groups from the interior of bacteria, such as protein and nucleic acid (i.e., -SH and -NH), thereby generating protein denaturation and immobilizing cell synthetase. In the meanwhile, the cell membranes are destroyed, which subsequently discharges cell contents, hampering synthesis and metabolism of metabolic enzymes, while restraining cells from propagating, growing, and developing normally [33–37].

4. Conclusions

Using a rotor spin device, this study successfully turns nanometer zinc ion filaments into nanometer zinc ion yarns that then become functional antibacterial knitted fabrics on a single-cylinder hosiery machine. According to the test results, regardless of whether the twisted yarns are composed of two or three plies of zinc ion yarns, the optimal twist coefficient is 3 (i.e., 2Zn-3C and 3Zn-3C), which substantiates that the tensile strength of twisted yarns is dependent on the twist coefficient. Moreover, the water vapor transmission rate of functional antibacterial knitted fabrics, which are made of both of two- and three-plyed zinc ion twisted yarns, has a descending trend as a result of the increasing twist coefficient. By contrast, 2Zn-3C-K and 3Zn-3C-K exhibit the maximal air permeability. Furthermore, a rise in the twist coefficient results in a lower colony count of bacteria, suggesting greater antimicrobial efficacy. In particular, 3Zn-5C-K outperforms the other groups in terms of antimicrobial efficacy, but 2Zn-5C-K already has antimicrobial efficacy as good as 81%. In sum, when production cost and time are considered, the optimal twisted yarns are consisted of two plies of 30 tex nanometer zinc ion yarns and twisted at a rotary rate of 15,000 rpm, which indicates that 2Zn-5C-K is the optimal functional antibacterial knitted fabric.
Author Contributions: In this study, the concepts and designs for the experiment, all required materials, as well as processing and assessment instrument were provided by J.-H.L. and C.-W.L. Data were analyzed, and the experimental results examined, by M.-E.L. and M.-C.L. The experiment was conducted, and the text composed, by M.-C.H. All authors have read and agreed to the published version of the manuscript.

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