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Optimization of Finishing Process and Energy Savings in Denim Textile Facility

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Abstract

Denim is widely accepted among exported textile products due to its aesthetics, appearance, and fashion. Practitioners employed several physical or chemical treatments to improve denim qualities in denim finishing operations. So, several treatment processes, including enzymatic, bleaching, singeing, heat set, and ozone finish, are used, which made this processing more energy consumption and time-consuming. Therefore, it is significant to investigate how changing the chemicals and raw ingredients could improve the finishing process, which is environmentally and economically beneficial for sustainable production practices in the denim finishing process. This study's research design comprises an experimental investigation in a denim plant in Bangladesh. Two different fabrics were chosen to analyze, determining the potential savings of finishing on the denim fabrics' performance characteristics. By deducting singeing and heat-set processes, the researchers ran an experimental process by maintaining the same length of fabric. Then, the impacts of finishing process optimization on the mechanical, thermal, and comfort parameters of drape, stiffness, and tear strength were examined. The study's findings demonstrated that this experiment increased productivity and reduced the finishing unit's energy consumption without compromising the denim fabrics' quality. This study significantly impacts environmental sustainability by preserving limited energy resources and manufacturing denim finishing processes.

Keywords

Finishing Process, Energy Savings, Denim Fabrics, Potential Savings, Process

Optimization, Cotton-Elastane Fabric

1. Introduction

According to World Trade Organization, Bangladesh ranked among the world's top four largest textile and clothing exporters from 2015 to 2021 [1]. No other textile fabric has received such wide acceptance as denim among exported textile products. It has been used extensively by people of all ages, classes, and genders. Denim is a robust and long-lasting cotton fabric made with a 2/1 or 3/1 twill weave construction, in which the weft yarns are white, and the warp yarns are dyed with a blue pigment derived from indigo. Denim creates various clothing items for kids, adults, and women of all ages, including jeans, jackets, shirts, and skirts, because these denim clothes combine many qualities that customers find highly desirable, such as comfort, long-lasting, adaptability, inexpensive, and always in style [2] [3] [4].

Physical or chemical treatments are utilized in textile finishing operations, primarily to improve the texture and look of materials. This modernization of clothing increases market sales. Various frequently used treatment processes, including enzymatic, bleaching, acid, silicone, singeing, heat set, and ozone finish, are included in the finishing process for denim fabric.

Therefore, evaluating how these processes affect denim materials' performance and thermal comfort is essential, as comfort is one of the clothing's fundamental necessities for the end-users [5] [6] [7]. Further chemical processing steps, such as de-sizing, overdyeing, coating, retro dyeing, pigment dyeing, reverse dyeing, non-uniform dyeing, or multicolored dyeing, may be added on top of these process stages and depending on the desired outcome. These chemical finishing processes are used to alter or enhance a fabric's appearance, hand feel, and distinctive practical qualities, such as water- and oil-repellency, wrinkle resistance, and flame resistance, as well as to make the fabric easier to stitch [8].

Among all treatment processes, singeing is a process that uses a gas flame to burn off the fluff or tiny hairs on the surface of denim fabric. This process burns away surface material that makes the fabric look fuzzy, resulting in a cleaner and smoother appearance of denim fabrics. In addition, this process enhances the color and increases the fabric's wettability [8]. On the other hand, heat-setting is the most important since it gives the product the desired characteristics to make it suitable for further processing and use by the consumer [9]. Karmakar explained heat-setting as a heat treatment by which shape retention, crease resistance, resilience, and elasticity are imparted to the fibers. It also changes strength, stretchability, softness, dyeability, and sometimes on the material's color [10]. According to Gacén *et al.*, heat-setting improves the properties of the textile substrate (improves shrinkage resistance, removes any creases, guarantees level dyeing, and improves the fabric handle) [9].

As in most manufacturing facilities, a sustainable production method in textile mills can assist lower resource consumption, waste creation, and related expenses [11]. Implementing sustainable manufacturing in the textile industry will benefit the economy in two ways: it will lower production costs and eliminate the need for pricey end-of-pipe pollution control systems. At the same time, it will reduce the effects on the neighboring neighborhood and lessen the harmful effects on the health and environment of the plant's employees. One study demonstrated that it is possible to obtain energy savings between 15% and 79% as outstanding examples of success using sustainable production practices (European Commission, 2003) [12]. Also, according to several studies and national policy/strategy documents, the textile industry should implement sustainable production methods, as it is one of the critical sectors in economic and environmental indicators [13] [14] [15]. For instance—according to Wang *et al.* (2017) and Costa *et al.* (2018), the manufacturing industry constitutes 34% - 54% of the total energy consumption in industrialized countries [16] [17]. Khude stated that energy is one of the most significant process inputs and cost factors in producing textiles [18]. Electricity and thermal energy are the two main types of energy that are typically employed. Almost all steps in the manufacture of textiles include using electricity to run electric motors, lighting, compressors, pumps, weaving, and spinning machines.

On the other hand, natural gas (particularly in stenters) or steam produced by fossil fuels directly satisfies the thermal energy requirement in textile production operations. In one study, Chequer *et al.* [19] showed that the primary thermal energy-consuming processes in the textile business include drying, stenting, dyeing, burning (singeing), thermo-fixing, washing, and bleaching. Also, the finishing unit's devices, like sanforizing and calendaring, utilize heat energy. In textile facilities, energy consumption varies according to the type of fiber, machine characteristics, process structure, and length.

Several studies have investigated the effects of finishing conditions on fabric performance, electricity, and gas consumption [20] [21] [22]. For example, Honisch *et al.* [23] concluded that using a detergent with activated oxygen bleach or lengthening the wash cycle can compensate for the loss of hygienic effectiveness brought on by temperature lowering. Again, Fijan *et al.* [24] optimized a process to save energy by transforming from thermal to chemo-thermal action while ensuring disinfection. Finally, Han *et al.* [25] determined the best fuel usage and process effectiveness process techniques. The mechanical action of the agitation in the machine and the chemical action of detergents were examined; however, the authors did not consider the energy use and environmental harm associated with chemical manufacturing.

As enzymes are readily biodegradable, there are many potential uses and applications for their use in textile processing, which will have an incredible environmental impact [26]. For the bio preparation, biopolishing, and softening of cellulosic fibers, cellulase is the most well-known and valuable enzyme employed in wet processing. Biopolishing is an appearance-improving process that eliminates microfibrils and superficial fibrils. This process results are a softer, cooler feel, more vibrant color brightness, and increased resistance to pilling [27]. The same cellulase action is used in this biological process to break down the surface of the cellulosic materials. Although it can be done at any point during wet processing, it is most practical to do it after bleaching [28]. Additionally, because this process is ongoing and maintains the fabric's quality through numerous washing items, the finished goods are more appealing to customers and command higher pricing [29] [30] [31] [32] [33].

The researchers frequently used treatment processes, including enzymatic, bleaching, singeing, heat set, and ozone finish, which made this denim manufacturing process power, energy, and time-consuming. Therefore, searching for a sustainable production method in textile mills is imperative, which can assist lower resource consumption, waste creation, and related expenses. The purpose of this research was to investigate how changing the chemicals and raw ingredients could improve the finishing process of denim fabrics. Specifically, the aim is to analyze the treatment conditions for using biopolishing enzymes and evaluate the changes in properties like weight, strength, abrasion resistance, and pilling resistance of the treated fabrics. Prior works provide evidence that it is viable to reduce process costs by improving workflows and processes. Although many factors influence process costs, this study concentrates on the two most important ones: optimizing processes caused by changing raw materials and chemical use. This research also aimed to optimize a sustainable finishing process that can reduce energy consumption without additional chemicals.

2. Materials and Methods

2.1. Samples

In this research, two types of denim greige fabric were used, shown in **Figure 1** and **Figure 2**. After manufacturing, denim fabrics are often subjected to finishing processes to obtain a wide variety of aesthetic and tactile effects.

The research has been carried out using stretch denim fabrics with a composition of around 78% Cotton, 2% Elastane, and 3/1 Z twill weave. Fabric width is 78 inches, produced on PICANOL OMNI PLUS 800-air jet weaving machines. Structural characteristics of greige denim fabric are displayed in **Table 1**.

Figure 1. Fabric Sample E0001.

2.2. Experimental Area

The researchers completed this investigation in a renowned denim plant in Bangladesh. There are several departments, from raw materials to final inspection, such as materials testing, yarn processing, fabric manufacturing, fabric finishing, fabric dyeing, fabric washing, fabric testing, and fabric inspection. This study was based on the denim fabric finishing section among these departments, which aims to reduce denim fabric process costs by altering materials and minimizing process routes (**Figure 3**). Although various factors are involved in reducing process costs, this study was limited to process optimization of singeing and heat-setting.

Figure 2. Fabric Sample E0002.

Table 1. Greige fabric specifications.

Fabric Specification						
Fabric Name	**Construction**	**Composition**	**Weight (oz/yd²)**	**Weight (GSM)**	**Weave**	**Weaving Machine**
E0001	10 OE + 12 OE × 150L40D/71 × 57	Elastane 1.80%, Polyester 20.70%, Cotton 77.50%	8.25	280	3/1 RHT	Picanol Omniplus 800
E0002	10RSL + 10R × 16L40D/60 × 48	1% elastane, 9% Rayan, 22% polyester, 68% cotton	9.25	314	3/1 RHT	Picanol Omniplus 800

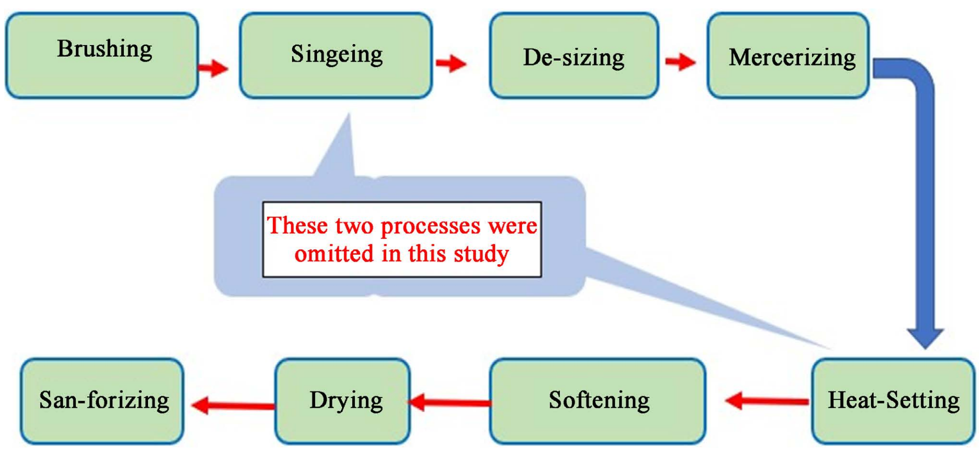

Figure 3. Process flow chart of denim fabric finishing.

2.3. Experimental Details

The primary function of the singeing machine is to remove hairiness from the fabric surface using a flame burner. It is possible to rule out this process using a biopolishing enzyme used as a de-sizing agent, replacing a de-size chemical during de-sizing and before the mercerizing process. The process aims to eliminate protruding micro hairs of cotton by an interaction of cellulase. Biopolishing (**Figure 4**) involves the use of cellulase enzymes to hydrolyze cellulosic micro-fibrils (hairs or fuzz) bulging out of the yarn surface, as these yarns are vulnerable to enzymatic attack [34].

As mentioned earlier, heat-setting imparts the fibers with shape retention, crease resistance, resilience, and elasticity. Additionally, it alters the material's tensile strength, stretchability, softness, dyeability, and occasionally its color. All these changes relate to the structural and chemical modifications occurring in the fiber. Denim woven fabrics from unset yams may be expected to shrink by approximately 5% in warp and weft during the scouring process. Their residual potential shrinkage ranges from 4.5% to about 11% over the temperature range of 150˚C to 220˚C. Fabrics made from staple fibers shrink less than filament-made fabrics, and stability adequate for apparel fabrics is conferred by setting at 170˚C to 180˚C. Polyester fabrics are effectively dimensionally stable if set at 30˚C to 40˚C higher than the temperature the fiber is exposed to during subsequent processes [35]. It is possible to deduce this process by altering raw materials. Previously, 2.8 drafts of spandex yarn were used for constructing this fabric (shown in **Table 1**), where a heat setting was required to achieve fabric stability. In this study, 2.0-draft spandex yarn is used to bypass this process, potentially saving a lot of time and money. The final time savings and cost calculations are shown in the results section.

2.4. Experimental Data

Two different fabric constructions were considered for 10000 meters for this experimental work. Firstly, the researchers ran these fabrics with regular processes and calculated the processing time, shown in **Table 2**. Secondly, they ran an

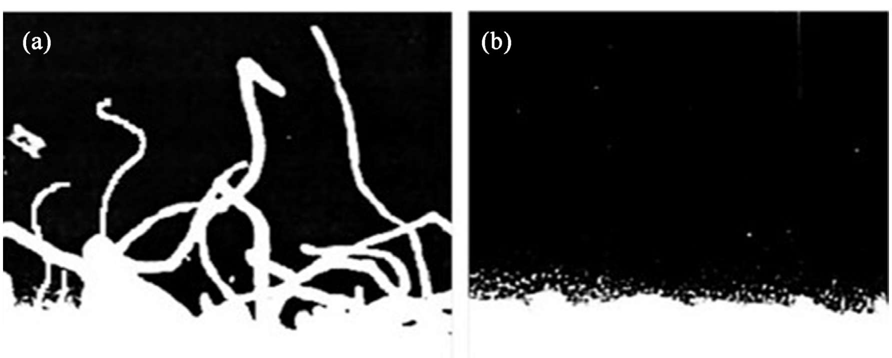

Figure 4. Cotton fabric surface before (a) and after (b) biopolishing treatment using cellulase enzyme.

Table 2. Regular process time for specific fabrics.

Fabric Name	Fabric Length (m)	Singeing Process Time (Hours)[1]	Heat-Setting Process Time (Hours)[2]	Total Process Time (Hours)
E0001	10000	4.15	4.75	9
E0002	10000	4.15	4.75	9
				Total—18 hours

[1]Singeing machine speed: 30 - 40 mpm; [2]Heat setting machine speed: 30 - 35 mpm.

experimental process with the same length of the fabric where singeing and heat-set processes were deducted. Finally, they completed this stage by using a biopolishing enzyme instead of a singeing process, and in the initial stage of fabric manufacturing, they also replaced weft yarn to avoid the heat set process. Due to this development, the researchers could omit these two processes and save a lot of time and cost, which is calculated in the next steps. After completing this stage, these researchers tested the fabrics of two routes and achieved the experimental result.

2.5. Test and Analysis

Denim fabric samples were conditioned under the standard atmospheric conditions of 20˚C ± 2˚C temperature and 65% ± 2% relative humidity for 24 hours. For the statistical analyses, researchers used IBM SPSS 23 statistic program. Researchers conducted a series of mechanical tests to evaluate the fabric's performance. For example, they used James Heal Tensile Tester according to TS EN ISO 13937-2 to perform tear strength tests of all the fabrics in warp and weft courses. Also, they used the SDL-Atlas fabric drape tester according to the test standard BS 5058 to conduct drape tests. Again, stiffness tests were applied on the SDL-Atlas stiffness tester, and standard ASTM D4032 was used to test fabrics' circular bending stiffness values [36] [37]. Then, the fabrics' mechanical and surface properties were measured by the KES-F and FAST systems [38] [39] [40]. Fabric physical test and chemical test results of two different routes are shown in **Table 3** and **Table 4**.

3. Results

3.1. Energy Savings

Electricity and natural gas are used to meet the facility's energy needs. The industrial zone's current power network system meets the facility's total electricity requirement. The heat setting machine uses an average of 130 kW per hour of power, and the singeing machine uses 40 kW per hour. The heat setting and singeing unit also fulfill the processes' thermal energy needs. In these burners, much natural gas is used. The average natural gas consumption for the heat set and singeing machines is 205 m^3/hour and 45 m^3/hour, respectively. The facility's average specific electricity and natural gas consumption values are 0.08

kWh/meter of product and 0.115 m^3/meter of product, respectively. The total energy consumption is also an average of 4.70 MJ/meter of product. Total energy savings due to process optimization are shown in Table 5. So, saving more than 34% of energy consumption in the singeing machine in a day and more than 39% in a heat setting machine is possible.

3.2. Potential Savings

3.2.1. For Singeing Process

From the collected data, the researchers found that they could save 8.30 hours of process time, 320 kW electricity, and 373.5 m^3 of natural gas savings for 20 K meters of fabric bypassing this process where these researchers used bio-polishing enzyme during the de-sizing process. Previously, the researchers used a standard desizing agent such as Bactasol. The cost of the bio-polishing enzyme is 12%

Table 3. Fabric physical test report of the regular process and experimental process.

Finishing Process	Fabric Name	Fabric Wt (oz/yd^2)	Ends/inch(EPI) × Picks/inch (PPI)	Stretch (%)	Tensile Strength (KG) (Warp × Weft)	Tear Strength (KG) (Warp × Weft)
Regular Process[1]	E0001	9.17	91 × 65	35.2	80.93 × 71.05	3.67 × 5.40
	E0002	10.21	78 × 51	46.2	99.03 × 70.12	5.55 × 9.09
Experimental Process[2]	E0001	9.11	91 × 65	36.4	88.53 × 77.16	3.10 × 4.87
	E0002	10.54	78 × 51	46.8	107.13 × 86.72	4.95 × 8.19

[1]Regular Process—(Brushing-Singeing-Desizing-Mercerizing—Heat set-Softening-Drying Sanforizing); [2]Experimental Process—(Brushing-Desizing-Mercerizing—Softening-Drying-Sanforizing).

Table 4. Fabric chemical test report of the regular process and experimental process.

Finishing Process	Fabric Name	Shrinkage (%) (Warp × Weft)	Stiffness (KG)	Skew Movement (%)	Spirality (%)	Rubbing (Dry × Wet)
Regular Process[1]	E0001	(−1.42) × (−11.40)	1.24	−0.4	(−1) × (−1.6)	3.5 × 1
	E0002	(−1.42) × (−9.97)	1.2	−0.6	(−0.2) × (−1)	3.5 × 1
Experimental Process[2]	E0001	(−1.49) × (−11.68)	1.2	−0.4	(−0.2) × (−2.8)	3.5 × 1
	E0002	(−0.28) × (−10.83)	1.16	−0.6	(−0.2) × (−1.4)	3.5 × 1

[1]Regular Process—(Brushing-Singeing-Desizing-Mercerizing—Heat set-Softening-Drying Sanforizing); [2]Experimental Process—(Brushing-Desizing-Mercerizing—Softening-Drying-Sanforizing).

Table 5. Total energy savings due to process optimization.

Fabric Name	Fabric Length (m)	Singeing Process Time (Hour)	Heat-Setting Process Time (Hour)	Power Savings (kW)[1]	Natural Gas Savings (m^3)[2]	Total Energy Savings (MJ)
E0001	10,000	4.15	4.75	783.5	1160.5	47,267.75
E0002	10,000	4.15	4.75	783.5	1160.5	47,267.75
						Total—94,535.5 MJ

[1]1 kWh = 3.6 MJ; [2]1 m^3 = 38.3 MJ.

higher than the previous agent, but they could potentially save more than 34% energy and increase productivity by more than 33% in the singeing machine. Details of potential savings are shown in Table 6.

3.2.2. For Heat-Setting Process

Similarly, from the collected data, the researchers showed that they could save 9.50 hours of process time, 1235 kW power savings, and 1947.5 m^3 natural gas savings for 20 K meters of fabric to omit this process where they used 2.0 drafts of weft yarn instead of 2.8 drafts of yarn. Here, the 2.0 draft of yarn is slightly more expensive than the 2.8 drafts of yarn, costing a variation of around 13%. Similarly, the productivity improvement in the stenter machine is around 38%, and the energy consumption is reduced by more than 40%, as shown in Table 7.

4. Discussion

4.1. Evaluation of Potential Energy in Finishing Unit

The finishing unit has high electrical and thermal energy needs. The finishing unit accounts for 32% and 56% of the plant's total electrical and thermal energy usage. High electricity use occurs in the finishing unit, particularly during the drying and thermos-fixing processes. In stenters, a significant portion of natural gas is utilized directly, and the finishing unit accounts for, on average, 68% of natural gas usage. Heat is lost significantly in the finishing unit through hot waste steams, hot waste gas flows, product vapor in finishing processes, and machine surface heat. In the finishing unit's process flow, there were also extraneous steps where some strategies for process improvement could be used. Two operations were eliminated from the finishing unit, considerably decreasing the facility's energy use and emissions.

4.2. Process Optimization in the Finishing Unit

Stenters are among the most crucial steps in the textile finishing process. Stenters

Table 6. Total potential savings due to singeing process optimization.

Fabric Name	Fabric Length (m)	Singeing Speed (MPM)	Previous Energy Consumption (MJ)	Energy Savings (MJ)	Productivity Increasing (%)
E0001	10,000	40	7728.5	7728.5	33
E0002	10,000	40	7728.5	7728.5	

Table 7. Total potential savings due to heat setting process optimization.

Fabric Name	Fabric Length (m)	Heat Set Speed (MPM)	Previous Energy Consumption (MJ)	Energy Savings (MJ)	Productivity Increasing (%)
E0001	10,000	35	39,517.625	39,517.625	38
E0002	10,000	35	39,517.625	39,517.625	

provide the chemical application of finishing agents, the fixing of colors after dyeing, and the stability of textile materials [41]. Stenters can use steam and natural gas and often use much energy. The finishing unit of the company included unnecessary stenter procedures, according to the thorough onsite energy efficiency analysis. Process optimization studies were carried out at the finishing unit, and extra heat-setting steps were eliminated from the manufacturing process. In the optimization studies, textile quality tests were also carried out, and this procedure had no detrimental effects on the product's quality. By this process optimization method, productivity rose by 38%, and energy usage was cut by 40%.

Similarly, the process optimization practice increased productivity by 33%, and the finishing unit's energy consumption was reduced by 34%. The plant used 17% less energy overall as a result. The payback period of these process optimization techniques was about four months. These results supported the study of Hasanbeigi and Price (2015), where they stated that up to 65% of energy savings could be achieved in stenters by implementing various energy efficiency techniques [42].

4.3. Monthly Potential Savings

The fabric test results for both processing routes are similar and have been approved by an ITS-accredited laboratory in Bangladesh, as shown in **Table 3** and **Table 4**. In this work, we got the experimental result that we can save 94,535.5 MJ of energy and approximately 18 hours of processing time based on the number of fabric samples taken due to optimizing two processes. In terms of monthly calculation, a denim plant with 400 looms can produce 5 million meters of fabric monthly. The chosen construction method yields approximately 1 million meters of fabric, as shown in **Table 1**. So, the researchers could get the monthly savings by optimizing these two processes, equivalent to 211,560 MJ energy and a monthly processing time of around 900 hours, by producing the same construction for 1 million meters of fabric.

5. Conclusion

This research involved changing raw materials and a bio-polishing enzyme to optimize the denim finishing. The outcome demonstrates that the modified denim fabric's properties are superior to the current methods. Additionally, it was found that the modified process outperformed the current process in terms of cost reductions and process speed. By analyzing this value, it could be concluded that this modified method increases the profit from a similar product. The findings of this study are anticipated to enhance the understanding of energy-saving approaches for other denim factories around the globe. According to the research, the denim industry offers a 35% potential for energy savings. Realizing this potential will significantly impact the environment, preserving limited energy resources and manufacturing sustainable denim finishing processes. It should be stated that this study's results may apply to specific denim fabrics used in this study. In the future, more investigation can be utilized to verify these findings with different denim fabric structures.

6. Recommendations

Factories can use several approaches to reduce energy waste and save significant amounts without significantly investing. However, setting up new gear and equipment necessitates a significant investment. Therefore, the recommendations in this section are highlighted.

- Energy usage should be tracked for each finishing machine, both process- and machine-wise, and action should be taken when it is disproportionately high.
- During fabric manufacturing, such as the weaving process, the pre-winder air pressure and sub-nozzle pressure should be high to minimize the hairiness problem from the fabric surface and optimize the singeing process.
- Future work can be done by increasing the spandex yarn draft, where materials cost will be reduced.
- Increasing the yarn fineness value of cotton yarn can also optimize the singeing process in 100% cotton fabric.
- Future experiments can be done in the heat setting machine to update the burner and lower the temperature, where energy consumption can be decreased.

CRediT Authorship Contribution Statement

Md. Enamul Haque: Investigation, Formal analysis, Writing-review & editing. **Kaisul Kabir:** Investigation, Formal analysis, Writing-review & editing. **Md. Asib Khan:** Investigation, Formal analysis, Writing-review & editing. **Mohammad Abu Syed Nizami:** Investigation, Formal analysis, Writing-review & editing. **Rajib Kabiraj:** Investigation, Formal analysis, Writing-review & editing. **Mohammed Fakhruddin:** Investigation, Formal analysis, Writing-review & editing. **Md. Golam Arif:** Investigation, Formal analysis, Writing-review & editing. **Md. Abu Hanif:** Investigation, Formal analysis, Writing-review & editing.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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