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Assessment of Environmental and Economic Impacts Made by the Reduced Laundering of Self-cleaning Fabrics

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Abstract: Despite the belief that self-cleaning fabrics would be environmentally friendly for their reduced laundering needs, little research provides feasible evidence of it. The purpose of this study was to develop a logical assessment method for providing quantitative evidence of environmental and economic impacts made by reduced laundering efforts when self-cleaning fabrics were used in daily life. The assessment method developed included: 1) evaluation of functional effectiveness and functional lifetime of soil resistant fabrics, 2) measurement of the reduced laundering frequency and the resulting saving in electricity and water consumption, and 3) conversion of savings to CO_2 equivalent (CO_2 eq.) and monetary utility cost. To examine the self-cleaning ability in practical soiling situation, the treated fabrics were tested for self-cleaning ability against two types of food soils and cleaned by water-spraying using the modified AATCC test method 22-2005. The self-cleaning ability was evaluated by the subjective visual assessment and the quantitative measurement of color difference ΔE. The level of ΔE that gave the discernible color difference by the visual assessment was about 3.7, and ΔE of 3.7 was used as the criteria to determine the laundering needs. From the developed assessment method, the self-cleaning fabrics saved up to 84 % of water and electricity during lifetime laundering of 50 cycles. This study provides an objective assessment methodology that can be applied to functional textiles to determine the quantified environmental and economic impacts such as CO_2 eq. and monetary cost.

Keywords: Self-cleaning, Laundering, Monetary cost, CO_2 equivalent (CO_2 eq.)

Introduction

Self-cleaning function of fabrics can be achieved by two different mechanisms: 1) photocatalytic decomposition of soils; and 2) easy detachment, or rolling off of soils from superhydrophobic surfaces [1-3]. Photocatalytic self-cleaning occurs when soils and microorganisms are degraded into water and carbon dioxide through photocatalytic reaction under UV light in the presence of metal oxides such as TiO_2, ZnO and CuO [4-7]. Rolling off of soils, the second mechanism, occurs on a superhydrophobic surface in which a water contact angle is high ($>150^{\circ}$) and a contact angle hysteresis is low ($<10^{\circ}$). Such surface also exhibits a low roll-off angle; a roll-off angle is the tilting angle of a stage where a mounted water drop begins to roll off from the surface [8-11]. As the water drop rolls along the surface, it adheres to soils attached on the surface and they roll off together, giving a self-cleaning effect. Owing to such properties, superhydrophobic or highly repellent surfaces can be cleaned with minimal efforts; sprinkling water itself can create self-cleaning action.

Various studies have been conducted to produce superhydrophobic textiles to achieve self-cleaning function, by lowering the surface energy of textile surfaces and introducing surface roughness [12-22]. Lowering the surface energy is very simple, effective, and low-cost approach for achieving highly repellent textiles with self-cleaning property, and the repellent finishing agents such as pyridine, silicone and fluorocarbon have been used to reduce surface energy of materials [12,13]. However, decreasing the surface energy is often not enough to attain superhydrophobic self-cleaning surfaces, and it requires an additional treatment to create surface roughness to reduce the contact area between the solid surface and liquid drop. For this purpose, a micro/nano binary roughness structure, which is observed in lotus leaf, has been reported to be effective to achieve the superhydrophobic property and self-cleaning function. In previous studies, binary roughness structures were created by depositing TiO_2, SiO_2, ZnO and CNT nanoparticles [14-17], or by etching the material surfaces using a UV-laser or a plasma technique [18-22]. For textile fabrics, there exists an inherent roughness coming from the woven or knitted structures, and due to this, the reduction of surface energy alone, without additional roughness creation, may achieve high level of surface repellency [23,24].

Self-cleaning textile is regarded as an environmentally sustainable material because the laundering needs of this material can be possibly reduced, therefore the consumption of detergent, water and electricity can be also reduced. This, in turn, is associated with less production of CO_2 equivalent and less spending on monetary cost (utility and detergent) [2,25]. Despite the conceptual belief that self-cleaning fabrics would be environmentally more responsible due to their reduced laundering needs, little study provides the quantitative evidence for this assumption, partly due to the absence of adequate methodology to assess the impacts.

Thus, we intend to develop a method to assess the environmental and economic impacts made by the reduced laundering efforts when self-cleaning fabrics are used. Specific research objectives include determination of end of

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self-cleaning functionality and laundering needs. Also, the saved electricity and water from the reduced laundering will be quantitatively measured, and the measurement will be converted to CO_2 eq. and utility cost. The developed methodology could be applied extensively to other functional textiles, providing quantifiable information on environmental and economic impacts occurring in maintenance and use phase of textile products' lifecycle.

Experimental

Materials

Cotton fabrics (bleached and desized cotton print cloth, ISO 105/F02) were purchased from Testfabrics Inc. (USA). Two kinds of commercially available finishing agents were used for repellent treatment of fabrics: one was a dipping type treatment with GOYENCHEM-840 (Go Yen Chemical Industrial Co., Ltd., Taiwan) and the other was a spray type (the product name and brand were not disclosed purposely). Both finishing agents are based on fluorochemicals. As practical model soils, barbecue sauce (viscosity; 15.5 Pa·s at 20 rpm / Ingredients; high fructose corn syrup, distilled vinegar, tomato paste, modified food starch, etc. / Sweet Baby Ray's) and tomato ketchup (viscosity; 12.2 Pa·s at 20 rpm / Ingredients; tomato concentrate from red ripe tomatoes, distilled vinegar, high fructose corn syrup, corn syrup, salt, spice, onion powder, natural flavouring / H. J. Heinz Co., L. P.) were used to soil and stain cotton fabrics. Those soiling materials were determined as adequate for this study because: 1) they can be cleaned by wet-cleaning process, 2) their colors are visually discernible to decide the laundering needs, 3) their soiling is not too harsh to be able to test the self-cleaning ability, and 4) their availability in real-life situations.

Sample Preparation

For repellent finishing of cotton fabric samples to eventually confer a self-cleaning function, two finishing agents were applied to fabrics according to the manufacturer's recommendation. The spray type (treatment A) was applied to fabric samples both face and back surfaces by spraying three times with an interval of an hour, and then the treated samples were air-dried for 24 hours. The average pick-up ratio of this treatment was 1.16. A dipping type (treatment B) was applied by a dip-pad-dry-cure process. Samples were dipped in 20 g/*l* solution of GOYENCHEM-840, then squeezed by a clothes wringer with paper towels inserted between the squeezers. The treated samples were dried at 110 °C for three minutes and cured at 150 °C for 2 minutes. The average pick-up ratio for this treatment was 1.30.

Fabric Properties

Wetting properties of fabrics were evaluated by measuring water contact angle and shedding angle via optical tensiometer (Theta; Attension, USA). The shedding angle is the tilting angle of a stage where a water drop starts to roll off. The fabric sample was fixed on a stage and the stage was tilted at 85 °. As the tilting angle of a stage was reduced by 5 ° at a time, the minimal tilting angle that water drop starts to roll off was recorded as the shedding angle [26].

Changes in fabric weight, thickness, color, stiffness, water vapor transmission rate and fabric structure were observed after finishing to check the suitability of finishing for clothing application. Fabric weight was measured by an analytic balance (Entris224, Sartorius Lab Instruments GmbH & Co. KG). Fabric thickness was measured using a digital thickness gauge (Mitutoyo, Japan). Fabric stiffness was tested after finishing by a cantilever fabric stiffness tester (SDL Atlas Inc., USA). Water vapor transmission rate was obtained by PERME W3/031 (Labthink, USA). The fabric structure was observed using a stereo microscope (SZX16, Olympus, Japan).

Self-cleaning Test

One m*l* of barbecue sauce and tomato ketchup was applied using a syringe to cotton fabric of 10 cm×10 cm. Water repellency spray tester of AATCC Test method 22-2005 was modified to test the self-cleaning ability. The soiled sample was placed at the center of tester on a 45 ° slope, and then 50 m*l* of distilled water was sprayed from a distance of 150 mm. Illustration of AATCC spray tester is shown in Figure 1.

The color change before soiling, after self-cleaning, and after laundering was quantitatively analyzed using a colorimeter (RM200QC, X-rite), measuring the *L*, *a*, *b* values. The color difference between samples 1 and 2 are calculated by Δ*E* as the following equation (1):

$$\Delta E = \sqrt{(L_1 - L_2)^2 + (a_1 - a_2)^2 + (b_1 - b_2)^2} \tag{1}$$

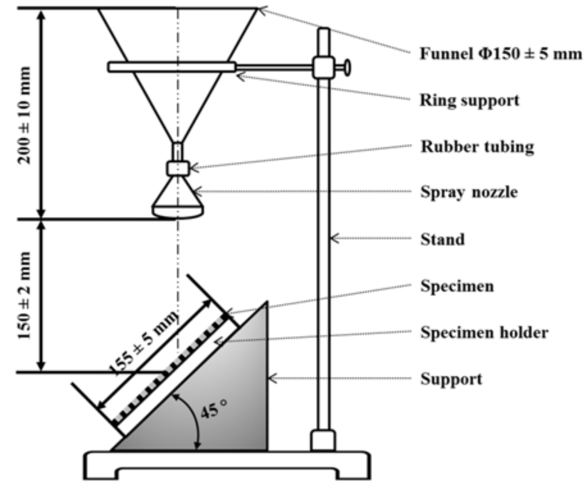


Figure 1. AATCC spray tester [27].

Table 1. Conversion factor for electricity and water (U.S. National) [28]

	Electricity	Water
Tariff	0.0994 \$/kWh	0.0008 \$/*l*
CO_2 eq.	0.7086 kg CO_2 eq./kWh	0.0006 kg CO_2 eq./*l*

The color change between prior to soiling and post self-cleaning was examined by the visual assessment (Gray scale; ISO R105/I, part 3), and it was related with ΔE value by the colorimeter. The subjective visual assessment was conducted by a panel of five independent evaluators, under the light source of CIE standard illuminant D65. When the color difference between the unsoiled and post self-cleaning (soiled and self-cleaned by water-spraying) fabric is not discernible by the visual assessment, the color difference will be graded as 5. If human subject can detect any color or shade difference between samples, it will be graded as 4.5 or lower. The samples that produced color difference of 4.5 grade was measured for their ΔE, and the average ΔE value for grade 4.5, at which human subject begins to perceive the color difference between the unsoiled fabric and soiled/water-sprayed fabric, was used as the criteria that requires laundering.

Environmental and Economic Impacts

Water and electricity consumption for clothes washer (FFFW5000QW0, Frigidaire; front-loading type, 3.9 cu. ft. capacity) and dryer (WED72HEDW0, Whirlpool; 7.3 cu. ft. capacity) were measured using a balance and a powermeter (WT1600, Yokogawa, Japan). The laundering experiment was conducted with 3 kg of laundry in order to duplicate the use conditions in daily life. The number of reduced laundering needs for self-cleaning fabrics was associated with the saving in electricity and water usage, and the following conversion to CO_2 eq. and monetary cost. The water and electricity consumption was converted into monetary cost and CO_2 eq. by the conversion factors offered by United States Environmental Protection Agency and shown in Table 1.

Results and Discussion

Wettability

Two kinds of repellents that are commercially available were indicated as A and B, not revealing the name of the respective agents. It should be noted that this study aimed to develop an assessment method for self-cleaning fabrics, not to develop a highly-performing self-cleaning fabrics.

Water contact angle and shedding angle were measured for fabrics before and after repellent treatments, and results are shown in Figure 2. The untreated cotton fabric, which had been bleached and desized by supplier, gave 54° of contact angle and 55.0° of shedding angle, exhibiting hydrophilic property. A 4 *μl* of water drop was quickly spread and wicked across the fabric surface within 10 seconds. Sample B exhibited superhydrophobic property, with 156° of contact angle and 8.6° of shedding angle; it is notable that a high level of repellency was achieved by simply lowering the surface energy of fabric surface, without creating additional surface roughness. Although sample A did not satisfy the criteria for superhydrophobicity which is contact angle >150°, and shedding angle <10°, it did show enhanced water-repellency compared to the untreated, with 153° of contact angle and 15° of shedding angle.

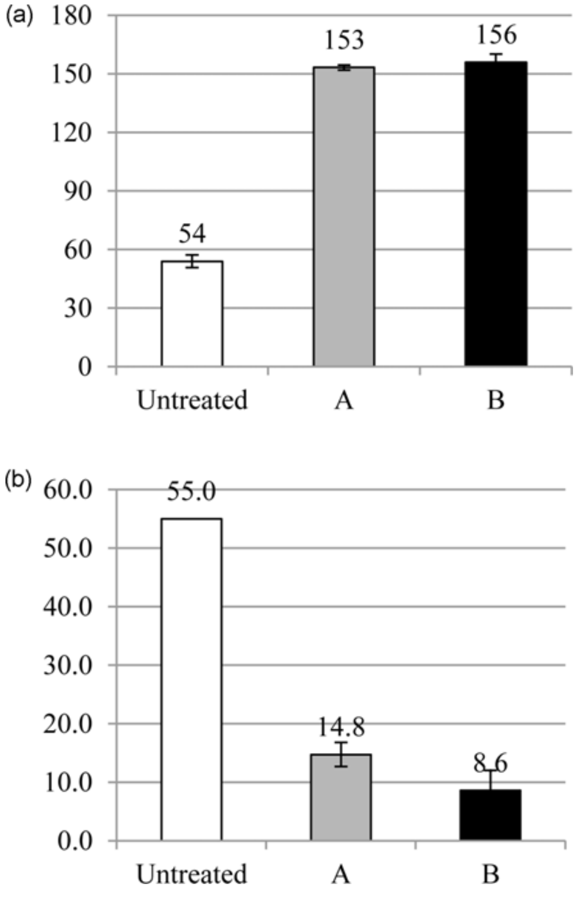


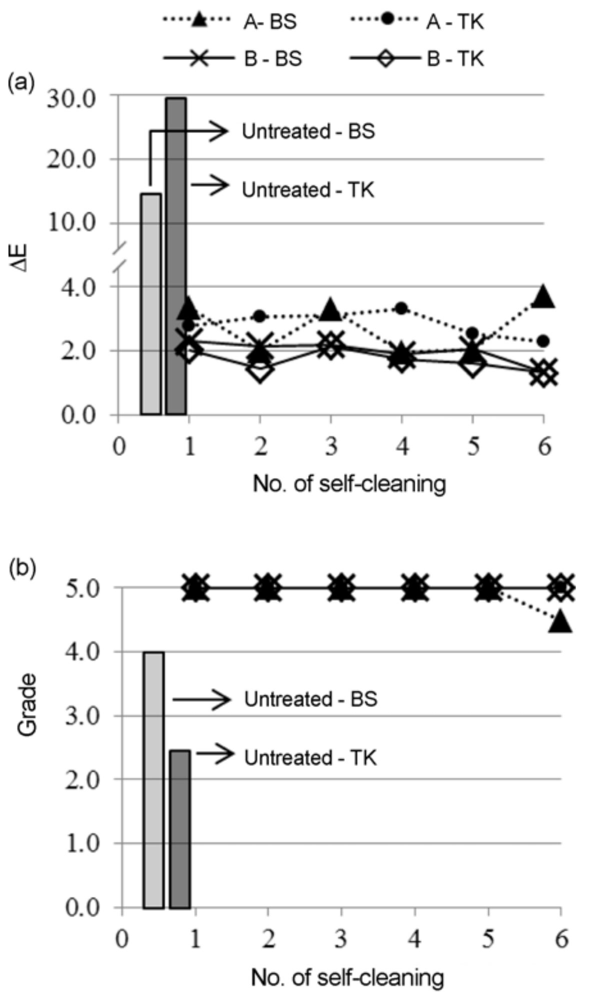
Figure 2. Wettability before and after repellent finishing using finishing agents A and B; (a) contact angle (°) and (b) shedding angle (°).

Self-cleaning Function

A new self-cleaning test method was designed by modifying AATCC Test Method 22-2005 (Water Repellency: spray test) [27]. The soiled specimen was placed on a stand with 45° slope, then 50 m*l* of distilled water was poured into the funnel of the tester within 10 seconds to simulate the rolling off of water as the self-cleaning action. The results of self-cleaning test are shown in Figure 3.

Sample A showed good self-cleaning performance with repeated soiling and self-cleaning action, giving mostly grade 5 in subject evaluations. Tomato ketchup on sample A was removed successfully even after 6 times of self-cleaning action; evaluating panel could not detect any stain or dirt. However, when Sample A went through 6 cycles of barbecue sauce-soiling and self-cleaning, the visual grade was dropped to 4.5, and the ΔE was measured as 3.7. As this level of ΔE was discernible to human eye, ΔE of 3.7 was determined as the criteria for laundering.

For all sample B's results, ΔE after soiling (with barbecue sauce or tomato ketchup) and self-cleaning was equal or lower than 2.3; the largest ΔE was shown when it was soiled with barbecue sauce and self-cleaned. However, ΔE at this level was not discernible by subjective visual evaluation, and it was graded as 5. Sample B achieved an excellent self-cleaning function against barbecue sauce and tomato ketchup, due to its superhydrophobic property (contact angle of 156° and shedding angle of 8.6°).



BS: Barbecue Sauce / TK: Tomato Ketchup

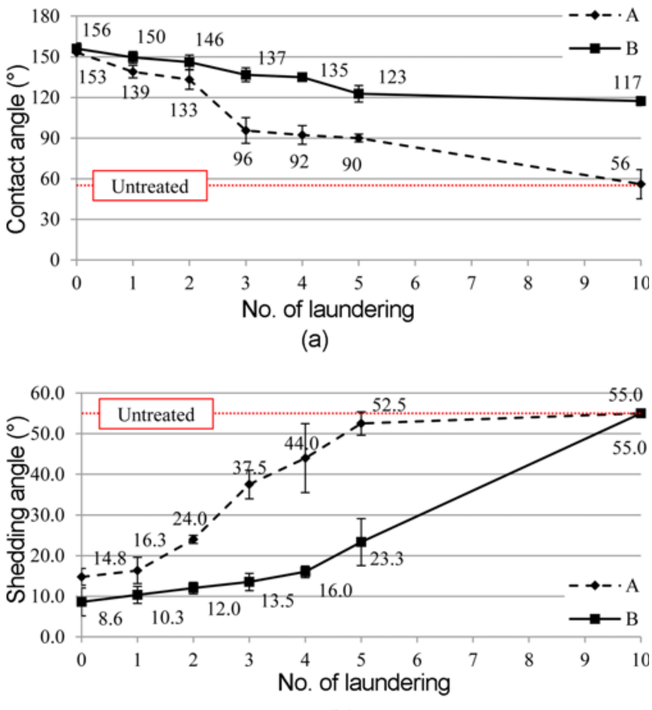
Figure 3. Self-cleaning ability by the number of self-cleaning test; (a) colorimeter evaluation and (b) subject evaluation.

Durability of Repellency and Self-cleaning Function

In order to examine the applicability of the treated fabric in daily life, the durability of self-cleaning function was observed against 1) the repeated laundering with detergent and 2) time lapse after soiling.

The change of wettability after repeated laundering (without soiling between laundering processes) was observed from contact angle and shedding angle measurements (Figure 4). While sample B treated by dip-pad-cure method somewhat maintained its repellency over ten times of laundering (in terms of contact angle, Figure 4(a)), sample A lost its repellency in a faster rate than sample B, finally reaching to the contact angle of untreated fabrics. For sample A, the spray type repellent agent on the fabric surface would have been removed more quickly by the physicochemical and mechanical action of laundering, losing its repellent property after repeated laundering.

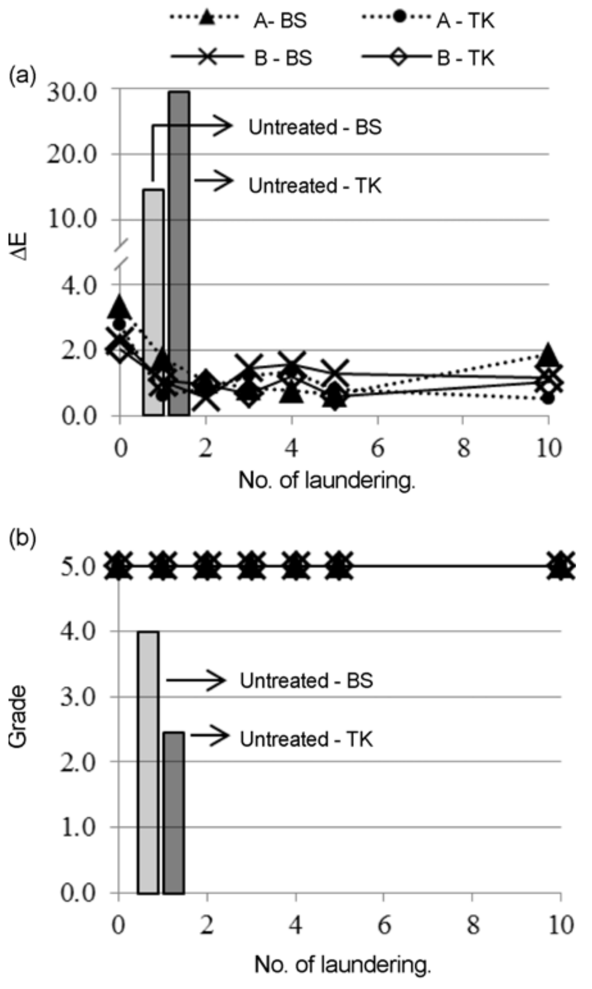
The self-cleaning functionality with the repeated laundering is shown in Figure 5. During the repeated laundering, soiling or self-cleaning was not done between the laundering. The repeatedly laundered samples were ironed in order to remove wrinkles to avoid their influence on *L*, *a*, and *b*. The laundered (up to ten times) and ironed samples were then soiled and self-cleaned to test the self-cleaning functionality. For example, the test procedure for 3 times of laundering was as follows; 1st washing and drying → 2nd washing and drying → 3rd washing and drying → ironing → soiling → self-cleaning.



(a)

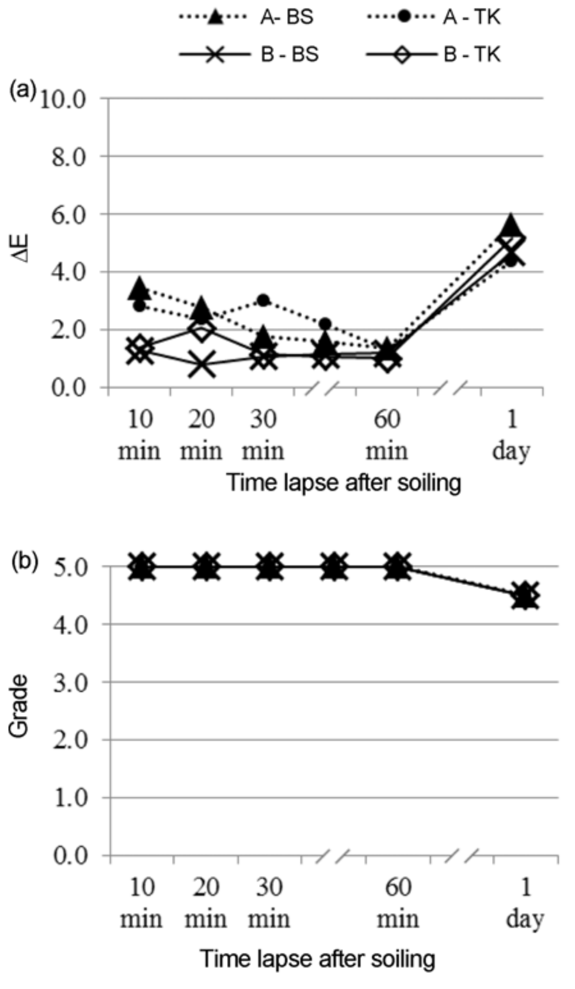
(b)

Figure 4. Wettability changes after repeated laundering; (a) contact angle (°) and (b) shedding angle (°).



BS: Barbecue Sauce / TK: Tomato Ketchup

Figure 5. Self-cleaning ability according to the number of laundering; (a) colorimeter evaluation and (b) subject evaluation.



BS: Barbecue Sauce / TK: Tomato Ketchup

Figure 6. Self-cleaning ability with time lapse after soiling; (a) colorimeter evaluation and (b) subject evaluation.

Interestingly, the finished fabrics that went through laundering and ironing exhibited better self-cleaning performance, in terms of quantitative measurement of ΔE, than the unwashed samples. It seemed that the repellent agent applied to fabrics got spread more evenly by the heat and pressure applied during the ironing process, to enhance performance. The repellent-treated samples maintained their self-cleaning ability after ten times of laundering, though the wettability kept increasing with the repeated laundering. It was supposed that a high level of repellency, or superhydrophobicity, may have a decisive effect on self-cleaning function, but the self-cleaning effect does not always require superhydrophobic property. It should be noted that the result could vary depending on the soil kinds, and the soils used in this study did not require superhydrophobicity to give a self-cleaning effect.

Figure 6 demonstrates the self-cleaning function with the time lapse after soiling. This simulates the real-life situation where the soils on fabric are not removed immediately after soiling. One m*l* of food soil was applied to a sample fabric using a syringe. After each time lapse, the soiled sample was placed on a water repellency spray tester at 45 ° slope, and 50 m*l* of distilled water was sprayed from a distance of 150 mm. The self-cleaning ability with time lapse after soiling was determined by the visual assessment and the colorimeter measurement.

Until 60 min after soiling, self-cleaning was effectively performed (ΔE=3.4), and it did not require laundering. However, self-cleaning effect after one day past soiling was deteriorated. From the subject evaluation, all tested samples were evaluated to require laundering, and ΔE values were greater than 3.7 in these conditions. Upon soiling, samples were placed in the condition of 25±3 °C and 65±10 % RH for one day. During one day period, tomato ketchup and barbecue sauce penetrated through the fabric structure, strongly adhered and completely dried on fabrics; this made it difficult to completely remove the soils by water-spraying alone. Instead, it will need additional mechanical and physicochemical actions by laundering to remove strongly adhered soils. For the soils and finishing included in this study, it is recommended that the repellent-treated samples be rinsed or water-sprayed as soon as they are soiled.

Relevancy of Clothing Application

Considering the applications of self-cleaning fabrics to clothing, the fabric properties after finishing were examined for weight, thickness, color, water vapor transmission rate, and stiffness (Figure 7). Both repellent treatments A and B made fabrics heavier and thicker, while the dipping method added more weights to the fabric than the spraying method. After both A and B treatments, the fabrics turned slightly yellow, as was confirmed by ΔE. The color change of sample B were more apparent while experiencing drying and curing at high temperature.

Sample B decreased water vapor transmission rate (WVTR) compared to the untreated fabric, probably because the pore size of fabrics were reduced by the coating with finishing agent B. The reduced pore size of sample B is shown in Figure 8(c). On the other hand, water vapor transmission rate of sample A remained similar or increased slightly. Considering a smaller add-on ratio of treatment A, it was speculated that: 1) with a thin coating, pores of the treated fabric remained as similar as that of the pristine fabric as shown in Figure 8, and 2) vaporous water molecules could rather quickly pass through the repellent fabric, not costing time on absorption into cotton fibers. The finished cotton fabric became stiffer than the untreated, and this phenomenon was obvious in sample B. From the results, self-cleaning treatment may have a negative influence on fabric properties, thus it needs a balance between the self-cleaning ability and other properties required for clothing textiles.

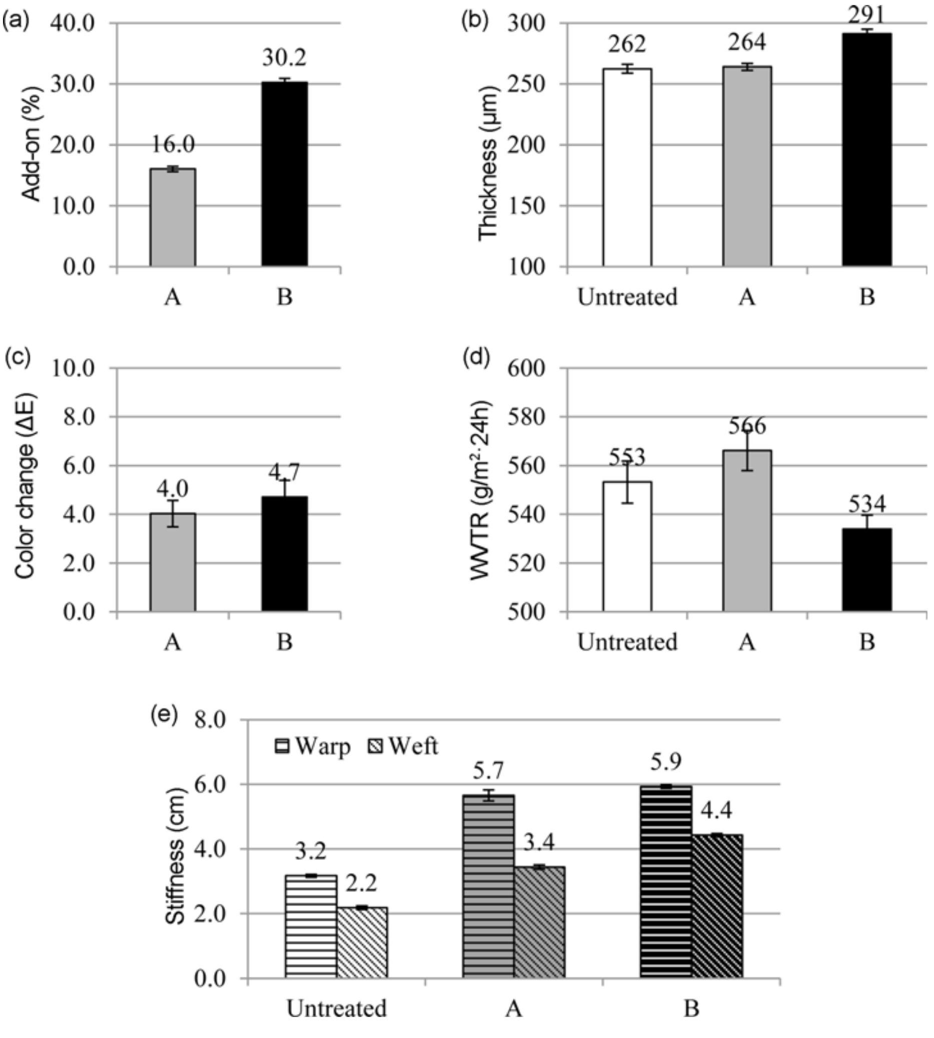


Figure 7. Changes in sample characteristics by self-cleaning treatment; (a) add-on (%), (b) thickness (μm), (c) color change (ΔE), (d) water vapor transmission rate ($g/m^2 \cdot 24$ h), and (e) stiffness (cm).

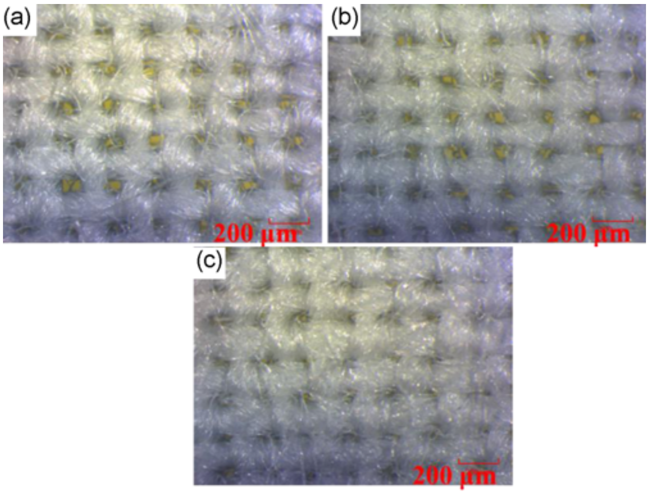


Figure 8. Microscopic images of fabric samples; (a) untreated, (b) sample A, and (c) sample B.

Environmental and Economic Impacts

The repellent fabrics A and B showed self-cleaning effect for two kinds of food soils used in this study until five times of soiling and self-cleaning simulating action as shown in Figure 3, and they did not need the conventional wet laundering. At the 6th time of soiling and self-cleaning, fabric sample A soiled with barbecue sauce showed the discernible remains of food soil, requiring laundering. This worst case of self-cleaning performance in this study- self-cleaning fabric A soiled with barbecue sauce- was used to calculate the saved electricity and water from the reduced laundering needs.

From previous studies, textile products are expected to go through 25 to 80 times of laundering during their entire lifetime [29-31]. In our study, it was assumed that normal clothing experience 50 times of laundering in their whole life, and this assumption was applied to the calculation for environmental and economic impacts. From the example case, the first five launderings could be replaced with self-cleaning actions of the repellent fabric, and the fabric needs the conventional laundering at the 6th soiling. As the example case would need only 1/6 of laundering, the repellent treated fabric A would need only 8 times of laundering, while non-treated fabric would need 50 times of laundering for its lifetime. It should be noted that the treated samples maintained their self-cleaning ability until 10 times of laundering (Figure 5), thus the assumption of effective self-cleaning until 8 times of laundering is valid.

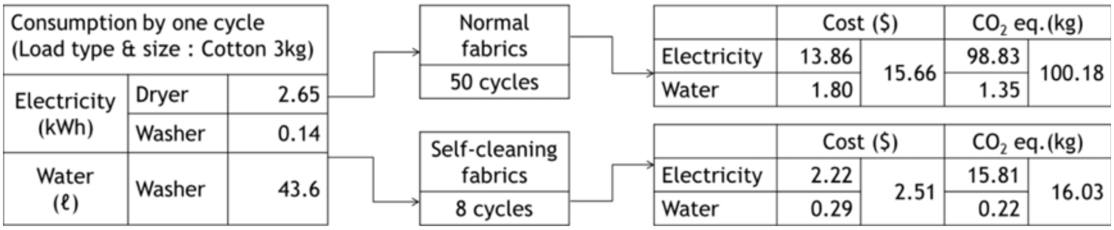
Finally, by using the treated fabric A against barbecue soil, 42 times of laundering can be saved among the assumed 50 times of lifetime laundering for normal fabrics. From our experiment, one cycle of laundering used 43.6 *l* of water and 2.79 kWh of electricity for 3 kg of cotton fabrics; if we convert this usage for 50 times of laundering, a total of 2179.0 *l* of water and 139.46 kWh of electricity will be consumed for 3 kg of normal (untreated) fabrics during their lifetime laundering. By using the repellent fabric A against the example soiling situation, a total of 1830.4 *l* of water and 117.15 kWh of electricity could be saved from the saved 42 times of laundering.

These values of water and electricity consumption were converted into monetary cost and CO_2 equivalent using the conversion factors shown in Table 1 (Figure 9). From this calculation, a self-cleaning fabric could save up to 84 % of monetary cost and CO_2 equivalent emission during their lifecycle. However, the conversion factors used in this study were specific to the USA, and the conversion factors will vary for other countries, depending on the source of power generation and water processes [32]. In other words, CO_2 equivalent is calculated differently even for the same amount of electricity depending on whether the power is generated from fossil fuels, renewable energy, or nuclear power; because the conversion factor for electricity is generally calculated by dividing the CO_2 generated in power plants by the end electricity use.

In this study, the environmental and economic impacts of laundry detergents or ironing process were not counted. By reducing the laundering frequency, the lifespan of fabrics is expected to extend due to the reduced fabric damage by laundering. This factor could also be counted in environmental and economic impacts. Furthermore, the impacts during the finishing were out of scope in this study. If further study can be conducted considering both finishing and maintenance, it will provide a thorough overview of environmental and economic aspects of sustainability for self-cleaning fabrics.

Conclusion

The objective of this study was to develop a quantitative



Consumption by one cycle (Load type & size : Cotton 3kg)		
Electricity (kWh)	Dryer	2.65
	Washer	0.14
Water (ℓ)	Washer	43.6

	Cost ($)		CO_2 eq.(kg)	
Electricity	13.86	15.66	98.83	100.18
Water	1.80		1.35	

	Cost ($)		CO_2 eq.(kg)	
Electricity	2.22	2.51	15.81	16.03
Water	0.29		0.22	

Figure 9. Flow chart for monetary cost and CO_2 eq. by normal and self-cleaning fabrics.

assessment method of environmental and economic impacts made by the reduced laundering efforts when self-cleaning fabrics are used in daily life. To evaluate the self-cleaning function and functional lifetime of repellent-treated fabrics in practical soiling situation, the fabrics were treated by two commercially available repellent agents then tested for self-cleaning ability against two types of food soils, barbecue sauce and tomato ketchup. The self-cleaning action was simulated by the modified AATCC test method 22-2005.

The self-cleaning ability was examined by the subjective visual assessment and the quantitative color measurement by CIE Lab method. The level of ΔE that gave the discernible color difference by the visual assessment was about 3.7, thus $\Delta E \geq 3.7$ was considered as the criteria that require laundering. Based on the criteria, the reduced laundering frequency was determined and the resulting saving in electricity and water consumption was calculated. As the worst case self-cleaning performance in this study, the repellent-treated sample A that was soiled with barbecue sauce was taken as an example. For this case, 84 % of water and electricity could be saved during lifetime laundering of 50 cycles. The reduced consumption of electricity and water was then converted into CO_2 eq. and utility cost by the conversion factors that are specific to USA. This assessment method and underlying logics can be applied to evaluate the impacts of other functional fabrics. However, this study used two specific types of finishing agents, and did not provide thorough evaluation of different types of finishing agents. The effect of repeated laundering on durability of finished fabrics might differ depending on finishing types and soil types, and further study is necessary to include a wide range of finishing agents and soil types. In addition, an expanded scope of study on self-cleaning fabrics is recommended to consider the cost and benefit of production phase.

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