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Use of Natural and Synthetic Materials in Denim Washing Process as an Alternative to Pumice Stone

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ABSTRACT

In this study, the use of synthetic stones and peach kernels in the denim stone washing process instead of pumice stone was investigated. The performance of each alternative was identified with different washing methods, i.e. conventional, low liquor, and spraying methods. The stone washing effects of each alternative were compared. Moreover, energy and water consumption and equivalent carbon dioxide emission of each method were analyzed. The results indicated that although pumice stone led to the best aging effect in the conventional method, synthetic stones and peach kernels showed better performance when the low liquor method was used. Additionally, the energy consumption and carbon dioxide emission of the low liquor method was shown to be lower. Therefore, it was concluded that synthetic stones or peach kernels could be a sustainable alternative to pumice stone and the selection of low liquor method for this application would be advantageous.

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Denim washing, pumice stone, ecological stone washing, sustainability, synthetic stone

1. INTRODUCTION

The concepts of sustainability, product life cycle, and ecological production are of great importance considering the environmental impacts of the textile and apparel industry. Therefore, many countries, companies, and organizations around the world have started to implement innovative initiatives and technologies in order to re-evaluate their activities and produce their products both using less water, less energy, and causing low carbon emissions [1]. Within the very complex structure of the textile supply chain that includes a wide variety of raw materials, processes, and therefore products, denim washing emerges as an important production route capable of responding quickly to the needs of the fashion market [2]. However, although denim washing provides added value to the product, it also has the potential to harm the environment [3] due to water and energy consumption and the production of waste emissions and effluents [4, 5].

In order to create a desired aged effect on the denim garments; whiskers, laser, stone wash, spray, bleach, etc. processes are implemented which are called dry and wet processes [6]. The conventional stone washing process is carried out with pumice stone or similar volcanic stones in order to achieve the desired worn, aging effect on denim products. The desired appearance is obtained by abrading the dyestuffs on the product with the mechanical effect created by rubbing the stones on the clothes in the drum washing machine. The use of pumice stones has problems such as the difficulty of removing the stones from the products, hairiness in the products, decreasing the strength of the fabric and tearing problems, clogging of the machine pipes [7, 8]. In addition, pumice stone is the biggest waste load for waste treatment plants since it decomposes over time after each wash and becomes completely unusable after a certain number of washings [9].

In order to reduce or eliminate the disadvantages of denim washing, some applications such as use of enzymes, use of bleaching agents with pumice, ozone applications, laser treatment, ultrasonic treatment and low temperature plasma have been the subject of denim research [7, 10-16]. In example, to reduce the usage of pumice stone, Telli and Babaarslan [17] combined stone washing with neutral cellulase enzymes in their research. Another application for sustainable denim washing is the total elimination of the

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pumic stone by the use of a stainless-steel rough drum in the machine [18]. An effective measure for sustainable denim washing against stone washing with pumice might be the investigation of the use of synthetic and natural stones, while only a few studies appeared in the literature on the use of alternative materials for stone washing. Alam et al. [19] used post-used shoe soles for stone washing of denim garments instead of pumice stone. Chattopadhyay and Pachauri [20] produced a series of synthetic stones composed of different amounts of calcium carbonate as filler material and silicon dioxide and aluminum as abrasive materials. Cement and sand were used as bonding agents. It was reported that the use of synthesized stone with certain composition in stone washing was found to be a better substitute for conventional pumice stones in terms of strength, wetting time, and fading of denim garments. In the study of Hoque et al. [21], in which waste wood and wood composite was investigated for the use in acid washing as an alternative to pumice stone, it was reported that pumice stone and wood composite led to higher fading compared to waste wood. Maryan and Montazer [22] investigated the use of organo-montmorillonite in denim washing and indicated that an old-look of fabric could be produced. They concluded that the best concentration is the use of 30% of organo-montmorillonite per 1 kg of denim product. In this study, the potential use of peach kernels and polyethylene-based synthetic materials for stone washing processes alternative to pumice stone was investigated for the first time in the literature.

One of the ways to reduce water and energy consumption in denim washing processes is to make improvements in drum washing machines. The conventional stone washing process is carried out in drum washing machines with a liquor ratio of around 1:10. The denim products are tumbled with pumice stones and auxiliary chemicals at 30-60°C for a certain period of time. A faded look and soft hand is obtained due to the physical abrasion force created by the pumice stones on the denim garments. In the low liquor method, the washing principle is the same; however, the liquor ratio can be reduced to 1:5. In low liquor denim washing machines, the distance between the drum and the wall of the washing machine is lower compared to conventional machines, therefore the desired washing effect can be achieved by using less water and chemicals. There is also a spraying method using an improved version of the classical drum washing machine, which includes spray nozzles as well as a drum. The diameter of the nozzles of the spray nozzles is between 0.1-0.4 mm. In this method, the denim products and pumice stones are loaded into the drum and the liquor including bleaching and auxiliary chemicals is sprayed inside the drum onto the products by the spraying nozzles placed on the drum cover. Therefore, the liquor ratio can be reduced to very low values, such as 1:2, which leads to a very low water consumption. In this study, the comparison of this three types of drum machines (conventional, low liquor and spray-type machines) was also investigated. The appearance and strength of the resultant materials were examined considering the stones and machines used. Furthermore, energy and water consumption and equivalent CO_2 emissions of each application were identified.

2. MATERIAL AND METHOD

2.1 Material and Machines

Indigo dyed denim fabric (98/2 CO/EL, 3/1 Z twill weave, 12 oz/yd^2, 24% elasticity) was purchased from Matesa Denim AŞ., Turkey. The amylase enzyme and dispersing agent for the desizing process were supplied from Dystar, Singapore. Cellulase enzyme obtained from Fourkim San. Tic. A.Ş., Turkey. It was used to provide a chemical stone washing effect to denim garments.

Natural and synthetic materials that can replace pumice stone and aging processes were carried out by conventional drum washing, spraying, and low liquor ratio methods. Synthetic stones were first developed with a 3D printer in different constructions. After creating the mold according to the specified design, it was produced in multiple quantities. As a natural material, peach kernels were used. Figure 1 shows the stones used for the alternative stone washing processes.

Drum-type washing machines (Tolkar, model 3700) were used for pre-washing and stone washing processes both in conventional and low liquor methods. Both drum-type washing machines and spray systems (Method Makine, Turkey) were used for the spraying method.

Figure 1. Synthetic stone and peach kernel used in the study

2.2 Method

In all methods, pre-treatments were carried out at 60°C degrees. Stone-washing processes are carried out at 40 °C for both conventional and low liquor methods while room temperature was used for the spraying method.

The general process flow and the energy sources used for each process are shown in Figure 2. Each trial was carried out for 50 pairs of trousers. Fixed recipes for laser pretreatment, rinsing, centrifuging, and drying was applied for each trial (laser pretreatment for 50 min; centrifuging for 20 min for conventional and low-liquor washing and 30 min for spraying, drying at 70 °C for 50 min, rinsing at room temperature). The parametric study plan applied for different methods and stones in washing processes (shown as Rinse washing, RW; Stone washing, SW) is shown in Table 1. The industrially applied general processing time of stone washing process with a pumice stone in conventional and low-liquor ratio is 30 min, however, in the preliminary trials, it was observed that 30 min process with synthetic stones and peach kernels was found to be inadequate for the desired stone wash effect. Therefore, the processing time of stone washing with synthetic stones and peach kernel was extended to 60 minutes.

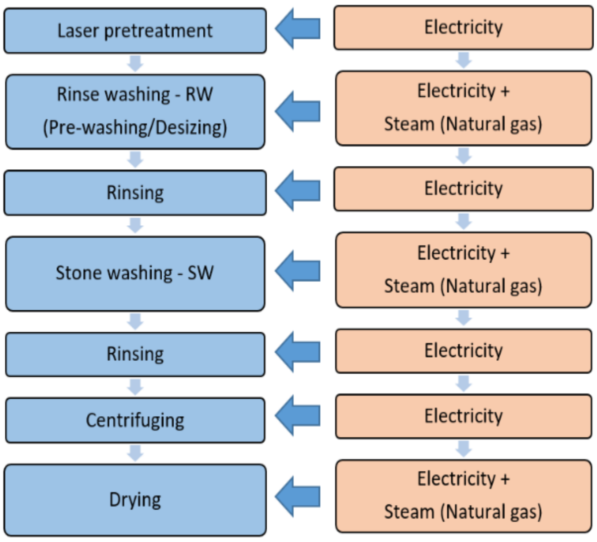

Figure 2. General process flow with energy inputs

Table 1. Washing process parameters

Machine	Stone type	Process	Temperature, °C	Time, min	Stone amount, kg	Water consumption, litres	Notation
Conventional	Pumice	RW SW	60 40	5 30	- 50	250 200	C-P
	Synthetic	RW SW	60 40	5 60	- 50	250 200	C-S-50
	Synthetic	RW SW	60 40	5 60	- 75	250 200	C-S-75
	Peach kernel	RW SW	60 40	5 60	- 50	250 200	C-PK-50
	Peach kernel	RW SW	60 40	5 60	- 75	250 200	C-PK-75
Spray	Pumice	RW SW	60 Room temp.	5 55	- 50	250 18	S-P
	Synthetic	RW SW	60 Room temp.	5 55	- 50	250 18	S-S-50
	Synthetic	RW SW	60 Room temp.	5 55	- 100	250 18	S-S-100
	Peach kernel	RW SW	60 Room temp.	5 55	- 50	250 18	S-PK-50
	Peach kernel	RW SW	60 Room temp.	5 55	- 100	250 18	S-PK-100
Low-liquor	Pumice	RW SW	60 40	5 30	- 50	125 125	L-P
	Synthetic	RW SW	60 40	5 60	- 50	125 125	L-S-50
	Synthetic	RW SW	60 40	5 60	- 75	125 125	L-S-75
	Peach kernel	RW SW	60 40	5 60	- 50	125 125	L-PK-50
	Peach kernel	RW SW	60 40	5 60	- 75	125 125	L-PK-75

In order to evaluate the differences between the application methods, light cabinet analysis to evaluate the aging effect (according to ISO 3664:2009 standard), elasticity and recovery test (according to ASTM D3107-07 standard), tear strength test (according to ISO 13937-2:2000 standard) were applied to the resultant products. Physical testing data were analyzed statistically by one-way ANOVA followed by Duncan post-hoc test SPSS 2015 programme. Differences of $p < 0.05$ were considered statistically significant.

In addition to the effect and quality parameters, energy and water consumption, and greenhouse gas emissions were also examined. For analysis, electricity consumption is calculated using machine data. In wet processes and drying processes, heating is carried out with steam (saturated steam at 6 bar gauge pressure). The amount of steam (m_s) required for heating up to the process temperature was calculated by Equation (1). Here, m_m is the amount of material (water, fabric, and stones), T is the process temperature, T_0 is the ambient temperature, and h_{fg} is the enthalpy of evaporation. It is assumed that the steam condenses during heating and turns into saturated water at the same pressure.

$$m_s = \frac{\sum(m_m C)(T - T_0)}{h_{fg}} \tag{1}$$

In order to calculate the amount of steam used due to the heat losses from the machine surfaces, the heat losses from the surface ($\dot{q}$, kJ/h) were calculated according to Equation (2), where h_c and h_r are the convective and radiative heat transfer coefficient, T_s machine surface temperature and T_0 ambient temperature, respectively [23].

$$\dot{q} = (h_c + h_r)A(T_s - T_0) \tag{2}$$

$$h_c = 5{,}22\sqrt[4]{T_s - T_0} \tag{2a}$$

$$h_r = \frac{20{,}4\ \varepsilon}{T_s - T_0}\left[\left(\frac{T_s}{100}\right)^4 - \left(\frac{T_0}{100}\right)^4\right] \tag{2b}$$

The amount of natural gas (m_{ng}) required to produce the steam used was calculated using Equation (3), where h_s is the enthalpy of the steam, h_w is the enthalpy of the feed water, η is the boiler efficiency and LHV is the heating value of the fuel.

$$m_{ng} = \frac{m_s(h_s - h_w)}{\eta LHV} \tag{3}$$

As well as energy consumption investigation, equivalent CO_2 emissions (CO_2e) due to energy use of each process were calculated. CO_2e emission due to fuels (Scope 1) and purchased electricity (Scope 2) were calculated based on Intergovernmental Panel of Climate Change (IPCC) guidelines using GHG protocol calculation tools [24] with Equation (4), where, CE is the CO_2e emission (kg), FC the activity data (amount of fuel or electricity consumption, kWh for electricity and m^3 for natural gas) and EF the CO_2e emission factor ($kgCO_2e/kWh$ for electricity, $kgCO_2e/m^3$ for natural gas).

$$CE = FC \times EF \tag{4}$$

Specific energy consumption (kWh/piece), specific equivalent carbon dioxide emissions ($kgCO_{2e}$/piece), and specific water consumption values (liter/piece) were calculated by dividing consumption and emission values by the number of trousers processed. Thus, the energy and water used and the equivalent carbon dioxide emissions due to the energy consumption released to nature for the processing of 1 piece of trousers were reported and compared.

3. RESULTS AND DISCUSSION

3.1 Light Cabinet Analyses

Stone washing trials were carried out according to three different techniques and compared each other using a pumice stone, synthetic stone and peach kernel and the resultant aging effects were visually investigated. Figure 3 shows the resultant samples after each trial.

In the conventional method (Figure 3-a), it was observed that similar aging effects were obtained in the trials using a pumice stone and peach kernels. For synthetic stones lower aging effects were obtained, however, it was investigated that the aging effect was improved as the number of synthetic stones increased.

In the trials conducted with the low liquor method, it was observed that the use of pumice stone and peach kernels gave similar results, as in the conventional system. On the other hand, it was indicated that better aging effects can be achieved compared to the standard pumice stone application when the amount of peach kernel was increased. A lower aging effect was achieved with synthetic stones, and it was shown that the increase in the number of synthetic stones led to an increase in the aging effect, which was close to those of pumice stones.

In the spraying method, the increase in the amount of material in the experiments with alternative materials provided a better aging effect. However, a paler and greener effect was obtained compared to pumice stone. It could be concluded that peach kernels showed better results compared to synthetic stones possibly due to the rougher surface structure. The low liquor method was found to be appropriate for the use of alternative materials in denim stone washing processes.

(a)

(b)

(c)

Figure 3. Stone washed denim trousers with pumice stones, synthetic stones and peach kernels in (a) conventional method, (b) low liquor method and (c) spraying method (Figure sequence for conventional method from left to right; C-P, C-PK-50, C-PK-75, C-S-50, C-S-75; Low liquor method from left ro right; L-P, L-PK-50, L-PK-75, L-S-50, L-S-75; Spraying method from left to right; S-P, S-PK-50, S-PK-100, S-S-50, S-S-100)

3.2 Physical Analyses

Table 2 shows the tear strength, elasticity and recovery analysis results. When the tear strength values were statistically examined, it was observed that the type of machine used in stone washing process is important in terms of tear strength. Accordingly, it was observed that the tear strength in both weft and warp directions was statistically significantly lower than the others in the spraying method. Since the liquor ratio is lower compared to other methods, there is less water in the drum in this method. Thus, the denim products have a high direct physical contact with both the stones and the machine surfaces. The elasticity analysis results of the processes were found to be statistically insignificant according to the machine used.

It was investigated that the effect of the stone type (pumice, synthetic and peach kernel) on the tear strength varies according to the machine type. It was seen that the effect of both stone type and amount on the tear strength in the weft and warp direction was insignificant in the spraying and low liquor methods. On the other hand, in the conventional method, it was indicated that the stone type has an effect on the tear strength results. Accordingly, the highest tear strength was provided by the peach kernel, followed by the synthetic stone and the pumice stone, and the difference between them was found to be statistically significant. This result was attributed to the lower density of the peach kernel compared to the pumice stone and the synthetic stone. On the other hand, the amount of stone was found to be statistically insignificant. Statistical analyses on elasticity values showed that the effect of the stone type and amount was statistically insignificant for both methods.

3.3 Energy and Water Consumption and CO_2e Emissions

In the preliminary studies, it was observed that the processing time should be extended in order to achieve the desired effect when synthetic materials and peach kernels were used as an alternative to pumice stone in the stone washing process. Prolonging the processing time leads to both an increase in energy consumption and an increase in greenhouse gas emissions. For this reason, energy and carbon dioxide emission analysis was carried out to determine to what extent the use of synthetic stone and peach kernel affected the energy consumption and carbon dioxide emission of the total process in different types of machines.

In Figure 4, the energy consumption of each step of the denim washing process by the use of pumice stone, synthetic stone or peach kernels in different devices (conventional, spray and low liquor machines) were illustrated. As can be seen, more than half of the energy consumption of the total process was used for the drying process.

When the conventional system was examined, it was observed that both electricity and natural gas consumption increased with the use of synthetic stones or peach kernels as the processing time increased compared to the use of pumice stone. This increase was at the range of 33-36% when only the washing processes are considered and 7.8-8.6% for the entire process. The energy consumption of using synthetic stone or peach kernel for the conventional system is similar. The increase in the amount of stone increased energy consumption to a certain extent.

In the spraying system in which pumice stone is used, although the processing time is shorter and the natural gas consumption is lower due to the processing at room temperature, the total process energy consumption was found to be higher than the conventional system, due to the higher electricity use. On the other hand, in the case of using synthetic stone or peach kernels in the spraying system, there is no difference in energy consumption compared to the use of pumice stone. Moreover, considering the use of alternative stones, it was observed that the energy consumption in the spraying system was lower than in the conventional application.

The lowest energy consumption was achieved with low liquor device and using pumice stone. When synthetic stones or peach kernels were used, although the processing time is longer, the energy consumption was similar to the conventional system with pumice stone, due to the lower natural gas consumption for heating since less water is used in the low liquor system. Therefore, from the energy consumption point of view, it was shown that spraying or short liquor devices are more suitable for the use of synthetic stones or peach kernels.

Table 2. Tear strength, elasticity and recovery of the samples

Method	Process	Tear Strength (N)		Elasticity (%)	Recovery (%)
		Warp	Weft		
Conventional	C-PK-50	19.7	31.1	20.7	4.0
	C-PK-75	22.7	27.9	19.7	4.0
	C-P	8.2	27.2	18.3	4.0
	C-S-50	16.2	22.8	18.5	3.8
	C-S-75	14.8	25.4	18.8	3.8
Low-Liquor	L-PK-50	10.4	28.6	19.6	2.8
	L-PK-75	10.8	26.4	19.4	2.5
	L-P	8.3	30.0	19.5	2.5
	L-S-50	11.6	32.2	19.3	3.3
	L-S-75	12.4	33.0	18.4	2.8
Spraying	S-PK-50	9.8	23.4	21.3	3.8
	S-PK-100	10.9	21.9	19.7	3.5
	S-P	10.3	21.5	19.5	3.5
	S-S-50	8.8	19.0	18.1	4.3
	S-S-100	9.4	22.1	22.9	3.8

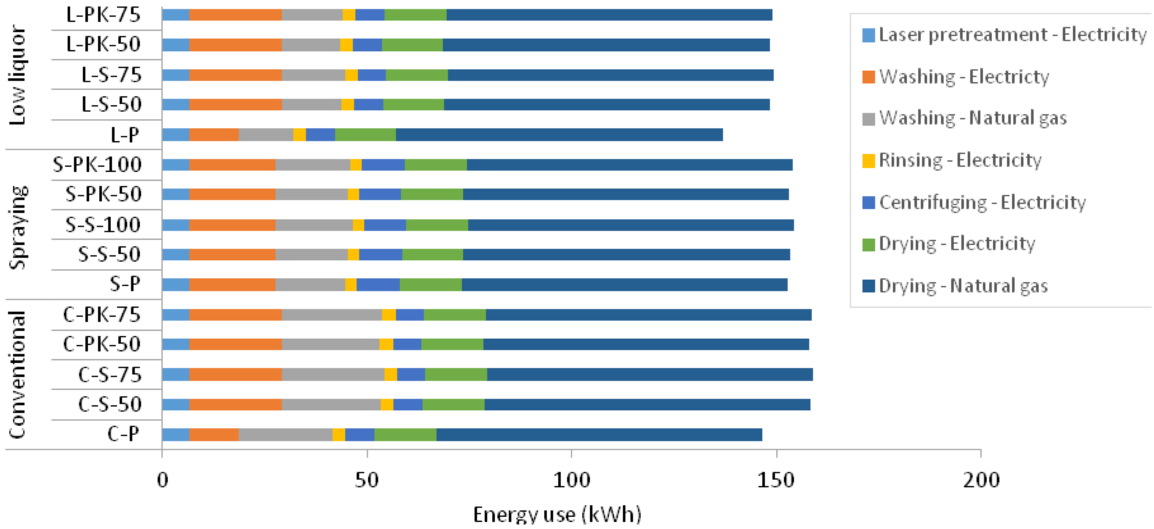

Figure 4. Energy use in each step of the denim washing process

Figure 5 shows the equivalent carbon dioxide emissions originating from energy consumption of each step of the denim washing process by the use of using pumice stone, synthetic stone or peach kernels in different devices (conventional, spray and low liquor). Depending on the type of machine and stone used, it has been observed that carbon dioxide emissions are in the range of 44-50 kg CO_2e. Similar to energy consumption, the highest emission source was the drying step. This was followed by washing processes.

The lowest emission was achieved with the low liquor device and the use of pumice stone. This is followed by the conventional device using pumice stones. The use of alternative stones in these systems led to an increase in carbon dioxide emissions. These increases are about 52-54% in the conventional system and 63-66% in the low liquor system for washing steps. On the other hand, considering the entire process, it was calculated that the use of alternative stone instead of pumice stone showed an emission increase of approximately 13% in the conventional system and 14% in the low-liquor system. In the spray system, it has been observed that the use of pumice stone or alternative stones was not different in terms of emissions, since the electricity consumption of the system was high. For alternative stones, spraying and low liquor systems were found to result in similar values and lower carbon dioxide emissions than the conventional system. In terms of greenhouse gas emissions caused by energy consumption in the denim washing process, it was revealed that it would be advantageous to choose one of the spraying or low liquor systems when synthetic stones or peach kernels are used as an alternative to pumice stone.

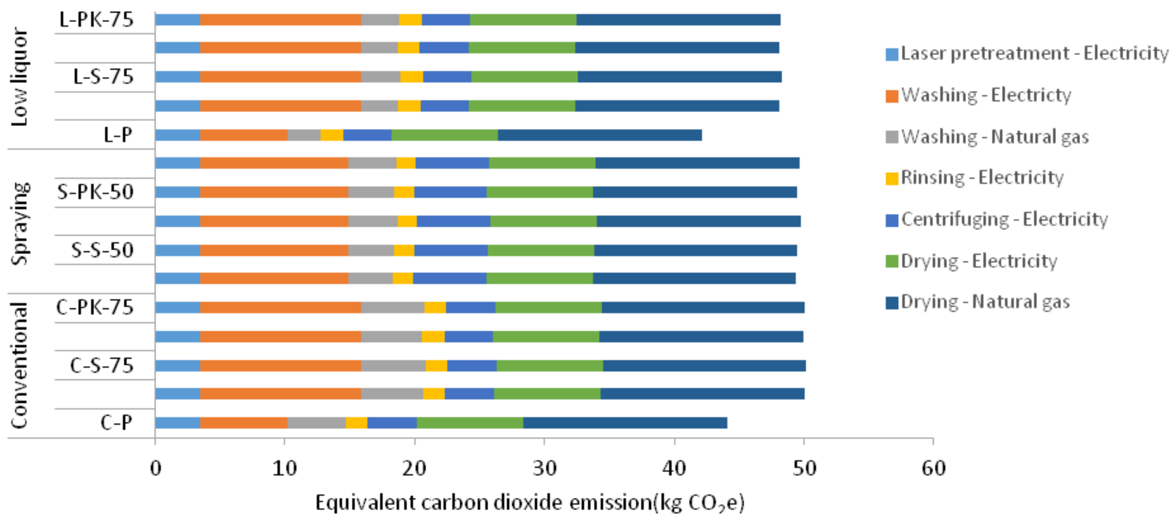

Figure 5. Equivalent carbon dioxide emissions in each step of the denim washing process

Specific energy use (kWh/piece) and water use (liter/piece), and specific equivalent carbon dioxide emission ($kgCO_2e$/piece) of the entire denim washing process were given in Table 4. Water consumption was not affected by the type of stone used. The specific water consumption of the spraying and low liquor systems (10 liters/piece and 11 liters/piece, respectively) is half the water consumption of the conventional system. Specific energy consumption varies between 2.73-3.17 kWh/piece depending on the process parameters. It was investigated that the low liquor system has lower specific energy consumption compared to other systems for all types of stones. The specific equivalent carbon dioxide emission originating from energy consumption was in the range of 0.84-0.98 $kgCO_2e$/unit. Therefore, similar to energy consumption, the selection of a low liquor system will be advantageous for the use of alternative stones in denim washing.

4. CONCLUSION

In this study, the potential of using synthetic stones and peach kernels in the denim washing process alternative to pumice stone was investigated. Additionally, the performance of each material was investigated in three different stone washing methods, which are conventional, spraying and low liquor washing. With the advantage of using less water and chemicals in spraying and low liquor methods, the specific water consumption in the stone-washing process is reduced from 22 liters/piece to 10-11 liters/piece. The pumice stone melts within an average of 2 washes. However, synthetic and natural materials can be used more than 100 times. Therefore, compared to pumice stone in conventional, low liquor and spraying methods, the cost of stone used per unit product was reduced by 45% by the use of natural and synthetic materials.

For the conventional method, the best aging effects were obtained by pumice stone. On the other hand, when the low liquor method was used, synthetic stones and peach kernels showed better effects compared to pumice stone. The reason for this was interpreted as the peach kernel and synthetic stones are less affected by the high rib effect caused by low liquor machine drums. However, the pumice stone was easily broken down by the rib effect. Energy consumption and carbon dioxide emission of the processes were found to be lower in the low liquor method compared to the conventional method. Therefore, the selection of the low liquor method for the use of alternative stones was revealed to be appropriate due to both higher effecting performance, and reduced energy consumption and carbon dioxide emission.

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Table 3. Specific energy and water consumption and specific carbon dioxide emission in denim washing processes

Machine	Process	Specific energy consumption kWh/piece	Specific water consumption liter/piece	Specific carbon dioxide emission $kgCO_2e$/piece
Conventional	C-P	2.93	22	0.88
	C-S-50	3.16	22	1.00
	C-S-75	3.18	22	1.00
	C-PK-50	3.16	22	1.00
	C-PK-75	3.17	22	1.00
Spraying	S-P	3.03	10	0.98
	S-S-50	3.04	10	0.98
	S-S-75	3.06	10	0.98
	S-PK-50	3.04	10	0.98
	S-PK-75	3.06	10	0.98
Low liquor	L-P	2.73	11	0.84
	L-S-50	2.97	11	0.96
	L-S-75	2.99	11	0.97
	L-PK-50	2.96	11	0.96
	L-PK-75	2.98	11	0.96

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