textiles

Article

Evaluating the Impact of Laundering on the Electrical Performance of Wearable Photovoltaic Cells: A Comparative Study of Current Consistency and Resistance

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Abstract: Wearable photovoltaic technology has been prominent in recent years because electronic devices need to be powered continuously without reliance on traditional methods. However, the practical adoption of wearable PV cells is hindered by the need for laundering, potentially degrading performance. This research compared PV cells' maximum current and electrical resistance before and after laundering testing conditions. This study used eight samples of two types of PV panel cells and laundered them up to five cycles. The current and electrical resistance values were recorded before and after each laundering cycle. This study analyzed the data using a paired sample *t*-test and MANOVA. It was found that laundering cycles significantly affected the current values in both types of samples, with no differential impact between the types; on the other hand, laundering cycles did not significantly affect the electrical resistance values in both types of samples, with no differential impact between the types. These results are crucial for industries developing textile-based PV panels, where maintaining electrical performance after laundering is essential. These findings could pave the way for more sustainable, self-powered wearable PV technologies, ultimately transforming how users interact with electronic devices daily.

Keywords: photovoltaics; laundering; electrical resistance; wearable textiles; durability

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1. Introduction

Wearable electronics are electronic devices that developers design to wear on the user's body. These devices have enhanced functionalities such as detecting, analyzing and transmitting information, and have clothing adaptability alongside considerations of comfort and warmth [1–4]. Also, researchers' continuous efforts to enhance these devices' capabilities have made it possible to harness energy from diverse sources, enabling them to generate and store power. Notably, energy-harvesting technologies, such as triboelectric, piezoelectric, thermoelectric, and photovoltaic power generation, have gained prominence [5–9]. Pursuing sustainable and autonomous devices capable of functioning independently from conventional power sources or frequent battery replacements underscores the importance of energy harvesting [10]. Portable and autonomous devices have become indispensable in various industrial applications, including navigation, communication, and fisheries. For instance, commercial fishermen rely on portable GPS units for navigation and location-based fishing, while autonomous underwater vehicles have sound navigation and range in marine organism detection, which requires a reliable power source to operate their onboard systems [11]. The need for consistent and sustainable power sources for these devices aligns with the growing global concern for sustainability in natural resources [12–14].

Wearable photovoltaic (PV) technology, commonly known as solar technology, has garnered attention from practitioners for its ability to harvest energy from sunlight [15]. For example, wearable PV cells are prominent and widely used because product developers can embed flexible, lightweight PV cells into clothing to store and convert sunlight into electrical energy [16]. These cells enable various applications, from health and fitness monitoring to energy-harvesting clothing, safety gear, protective textiles, and military uniforms [17]. Modern PV cells use N- and P-type semiconductor layers for electron flow generation from direct solar impact to maximize energy production. Semiconductor materials combined with an electrode and counter-electrode make a standard PV cell (see Figure 1).

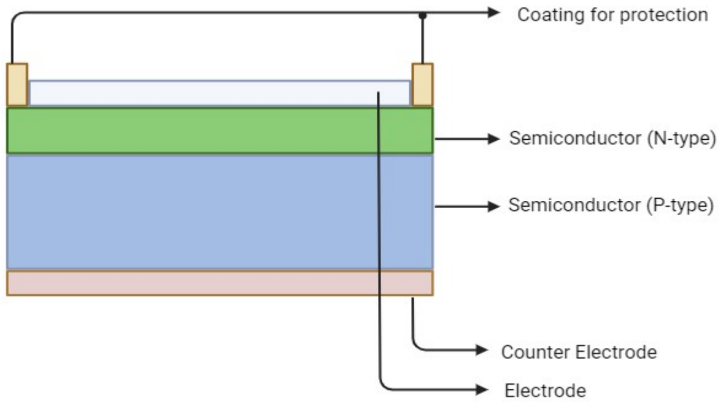

Figure 1. A standard PV cell with two semiconductors (P and N-Type) and two electrodes.

However, it is challenging to practically adopt wearable PV cells in wearable applications due to the need for durability, launderability, and efficiency under varying conditions. Frequent laundering is required to maintain hygiene and usability in any wearable clothing, hinging on the widespread commercialization and adoption of wearable electronics, raising significant user concerns. As the laundering process includes washing and drying, both processes expose electronic devices to unfavorable conditions that could compromise the reliability of electronic components [18]. During laundering, electronic components face four principal forces, encompassing chemical stress (including detergents and surfactants), thermal stress (associated with washing and drying temperatures), exposure to solvents (primarily water), and mechanical stress (involving friction, abrasion, flexion, hydro-dynamic pressure, and garment twist). These forces could affect any electrical components' energy-harvesting efficiency, structural integrity, overall lifespan, and durability. To explore the durability of wearable PV cells, researchers have undertaken experiments involving various laundering cycles, including prolonged laundering [19–21]. Notably, a study conducted by Qiu et al. focused on washable power generation clothing and observed the consistent electrical output (voltage: 110 V, current: 2 A) of their piezoelectric energy-harvesting fabric based on biomechanical body movements, even after up to 2 h of continuous laundering. Following 12 h of prolonged laundering, they noted a marginal degradation in output (voltage: 106 V, current: 1.9 A), emphasizing the potential for durability degradation [21], which is unexpected by the end-users. Despite this research, investigations related to the laundering of wearable photovoltaic (PV) cells remain limited, as standardized tests in this domain remain under development, thus warranting concerns about the post-laundering performance of wearable PV cells. However, several researchers have embarked on non-standardized approaches to assess the launderability and water stability of organic photovoltaic film, a PV cell technology [22,23], helping them learn about the durability of their devices. Whether the laundering method is standard or non-standard, more investigations are needed to develop robust wearable PV cells for sustainable use.

One of the critical considerations in assessing the performance of these wearable PV cells after laundering pertains to the measurement of electrical resistance. Laundering processes may subject wearable PV cells to physical changes, including stretching and shrinking, which can cause an unexpected disruption to the properties of alignment and the connectivity of wearable PV cells. Such alterations have the potential to result in an elevation of electrical resistance, signifying a reduction in the energy conversion efficiency of the wearable PV cell. Consequently, numerous researchers have integrated this evaluation into their post-laundering testing protocols. Notably, a study conducted by Lee et al. employed a method involving the measurement of electrical resistance in each specimen both before and after the laundering procedure, utilizing a four-point probing system with a digital Ohm meter boasting a 1 μΩ resolution [24]. The findings revealed that the alterations in electrical resistance within the materials corresponded to a decreased performance under electrical conditions. Consequently, manufacturers have gained insights into whether the wearable PV cell maintains compliance with the requisite performance specifications by measuring the electrical resistance following a laundering test. Moreover, electrical resistance measurements help to determine if any material composition adjustments are necessary to optimize the performance and reliability of these cells in the face of laundering-induced challenges.

The testing of wearable electronics, particularly wearable PV cells, presents a significant challenge in standardization. While the American Association of Textile Chemists & Colorists (AATCC) has published protocols for assessing the electrical resistance of electronically integrated textiles/clothing after laundering and drying cycles [25], the current literature demonstrates a notable lack of standardized testing procedures designed specifically for wearable PV cells. Researchers and research institutions have sought alternative test methods from related fields, such as textiles, to address this gap. Also, the International Organization for Standardization (ISO) offers standards for domestic washing, as exemplified by ISO 6330 [26], which covers domestic washing and drying methods for electronic textile testing; still, these standards are not tailored to wearable PV cells [27]. Furthermore, IPC International, Inc. (Bannockburn, IL, USA), a nonprofit global association, is presently developing standards related to the mechanical performance of wearable technology, encompassing wearable PV cells; nevertheless, these methodologies are currently in development and await validation [28]. Hence, ongoing research is imperative to enhance the adaptation of existing standards to wearable PV cells' unique characteristics and refine testing protocols, ultimately culminating in a more standardized approach for this emerging technology. On the other hand, there is a standard testing method for electrical resistance tests, which researchers widely adopt from electronically integrated textiles. AATCC EP13 is a standard containing two-point and four-point probe methods to test the fabric's resistance [25]. Therefore, in this study, these standardized tests were used to evaluate the performance of wearable PV cells.

This study aims to compare the maximum current consistency in milliampere (mA) and the electrical resistance in kilo-ohm (kΩ) of commercially sourced wearable PV cells, pre- and post-laundering testing conditions. This study is significant because it directly impacts the development of long-lasting and functional wearable textiles with integrated PV cells. Focusing on the durability and performance of wearable PV cells under typical use conditions—particularly laundering—this research addresses a critical challenge: maintaining energy efficiency and device integrity over extended periods. The insights gained from this study could drive the advancement of robust PV cell designs that are energy-efficient and capable of withstanding the wear and tear associated with everyday use. Consequently, the findings from this research could pave the way for more sustainable, self-powered wearable PV technologies, ultimately transforming how users interact with electronic devices in their daily lives.

2. Materials and Methods

2.1. Samples

This study analyzes two types of thin-film roll-up bendable amorphous PV panel cell samples procured from the JIANG solar company in China, as illustrated in Figures 2 and 3. The technical specifications of these PV cell types differ significantly. The first type, denoted as Sample Type (1), is characterized by its compact size (7.87″ × 3.94″), minimal thickness of 0.04″, lightweight nature (28 g), a wattage rating of 1 watt, and an input voltage of 6 volts. Conversely, the second type, denoted as Sample Type (2), features a larger compact size (14.96″ × 2.56″), similar thickness (0.04″), slightly increased weight (36 g), a higher wattage rating of 1.2 watts, and an input voltage of 6 volts. These divergent specifications, particularly in terms of size, weight, and wattage, serve as crucial factors for a comparative assessment and further investigation (see Figures 2 and 3).

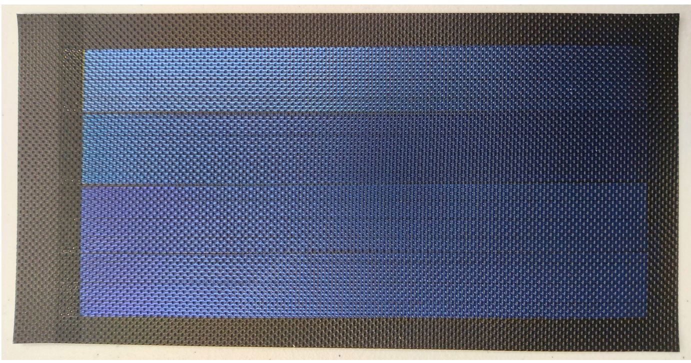

Figure 2. Sample Type (1) of amorphous PV cells.

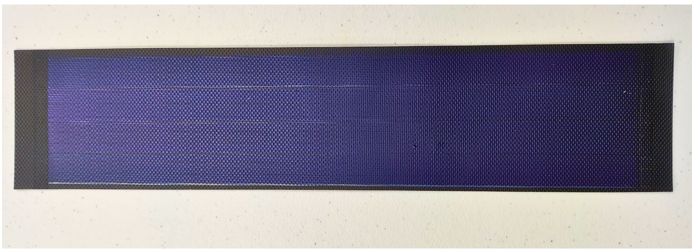

Figure 3. Sample Type (2) of amorphous PV cells.

2.2. Testing Measurements

2.2.1. Current Measurement

The researchers measured the current by connecting two probes with the PV cells with a digital multimeter (Klein Tools® MM600) (Lincolnshire, IL, USA), a versatile instrument for electrical measurements, as demonstrated in a study by Sacco et al. (2016) [29]. Additionally, solar irradiance, a pivotal parameter in PV cell evaluation, was quantified using a specialized solar irradiance meter, specifically the Fluke® IRR1 (Fluke Corporation, Everett, WA, USA), which is capable of providing precise measurements of solar irradiance as well as additional parameters like tilt angle and temperature [30]. In the research context, it is paramount to account for solar irradiance, as Veligorskyi et al. (2018) did in their investigation, employing a photo-resistive sensor to ascertain solar irradiance levels; in their study, these levels were determined to be 950 W/m^2 during favorable weather conditions [31]. These measurements were conducted under various conditions involving the orientation of PV modules concerning the sun's rays, namely, angles of less than 30°, greater than 30°, and shadowing conditions. This study adopted the same approach, initially recording all readings at a consistent PV cell temperature of 29 °C. The PV cell samples were then positioned horizontally atop a surface (0° angle) within an enclosure to ensure controlled conditions (see Figure 4). Subsequently, the digital multimeter was configured in current mode to facilitate direct current measurement. Precise measurements are required to connect the red test led to the PV cell's positive terminal and the black test to the negative terminal. Current values were obtained in milliamperes (mA) and repeated to ensure measurement accuracy.

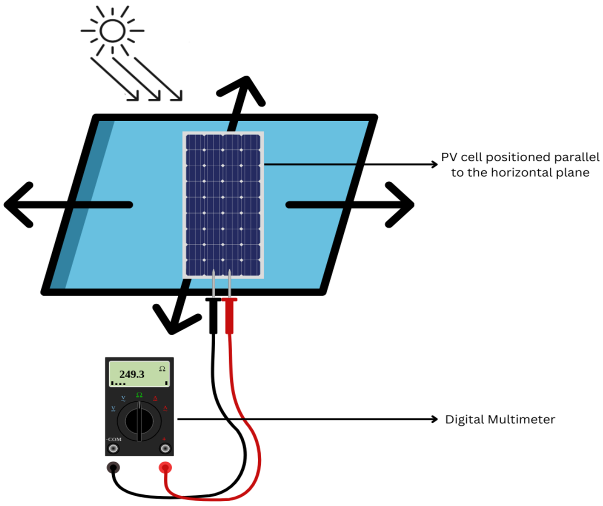

Figure 4. Measuring the current and electrical resistance of wearable PV cells using a digital multimeter.

2.2.2. Electrical Resistance Test

As previously elucidated, the characterization of conductive materials' performance regarding electrical resistance was conducted in alignment with the AATCC EP13, as established by Vu and Kim (2020) [32]. Following the completion of each laundering cycle, the researcher embarked on the evaluation of the electrical resistance values. The procedure commenced with flatly placing the PV cell samples on the surface, ensuring uniformity during the subsequent electrical resistance assessment. In this assessment, the digital multimeter was kept in resistance mode, with two probes linked to it. These probes were meticulously connected to both sides of the cells, with one probe corresponding to the positive terminal and the other to the negative terminal. The measurement was performed three times for each instance, and the resulting values were averaged to ensure robust and precise data. Notably, this assessment was conducted before and after each laundering cycle, adhering to the standardized protocol outlined by ISO 6330 [26].

2.2.3. Laundering Test

In assessing the launderability of wearable electronics textiles, the widely recognized ISO standard, ISO 6330, has been commonly employed, as exemplified in the study conducted by Ilén et al. (2022). This standard, which dictates procedures for the domestic laundering and drying of textiles, was rigorously adhered to, utilizing laundering and dryer machines [20]. However, it is noteworthy that while the study conducted ten-cycle intervals, repeated five times, amounting to 50 cycles of laundry, the present study focused on a more concise examination with five laundering cycles. The laundering machine adopted for this study, a Maytag® appliance (Newton, IA, USA), featured a vertical axis and a top-loading agitator design, while the accompanying dryer machine was vented. Initially, the researchers took the weight of four samples (Sample Type 1) and the required ballast weight was determined, with the specimens weighing 0.112 kg, thereby necessitating the addition of 1.888 kg of ballast (100% cotton Type I) to achieve a total of 2 kg. Then, they used 66 g of 1993 AATCC standard reference detergent without optical brightener (WOB) (reference detergent 1) and selected the permanent-press method. This testing protocol has five laundering cycles, followed by tumble drying. After each cycle, the specimens were transferred to the dryer, and the post-laundering assessments included five readings of current consistency and electrical resistance. Furthermore, photographic documentation of the PV cells was kept for visual observations. It is important to note that the researchers chose these five laundry cycles because the purpose of testing these PV cells is to incorporate them into user textiles. So, these PV cells should withstand this washing because a user will wash a PV-cell-incorporated wearable textile product once a week throughout the month. This rigorous process was conducted for Sample Type (1) and (2), encompassing eight samples, with their respective readings meticulously documented and analyzed.

2.3. Data Analysis

The analysis of the current consistency and electrical resistance data was performed using the Statistical Package for Social Sciences (SPSS) software, version 26.0, developed by IBM, NY, USA. To assess the differences between pre- and post-laundering cycles, a paired sample *t*-test was performed, following the approach outlined by Mayasari et al. in 2019 [33]. The author chose this test because prior researchers had conducted paired sample *t*-tests when they compared data under two different conditions [34]. Additionally, a repeated measures mixed analysis of variance (MANOVA) was conducted to evaluate and compare the performance of the two sample types. This analytical approach was informed by prior research, explicitly drawing from the methodology employed by Allcoat and colleagues in 2021 [35]. The author chose this analysis because Pallant (2020) mentioned this approach when there are two categorical independent variables and a continuous dependent variable. In this study, the author explored two types of PV cells and measured their current consistency and electrical resistance before and after laundering cycles [34].

3. Results

This study aimed to compare PV cells' maximum current consistency and electrical resistance before and after laundering testing conditions. This comparison will provide insights into the durability and reliability of these cells, which are critical factors for their integration into clothing items. As mentioned, a paired sample *t*-test assessed the current consistency and electrical resistance variations before and after the laundering cycles. To gauge the comparative performance of the two sample types, the researcher carried out a repeated measures mixed analysis of variance (ANOVA), drawing inspiration from the methods outlined by Allcoat et al. in 2021 [35].

3.1. Comparison Between the Current Values Pre- and Post-Laundering

Regarding current values, a paired sample *t*-test was carried out to assess the differences between the two types of samples before and after each laundering cycle, using a significance level of $\alpha = 0.05$. The analysis revealed a statistically significant variance between the pre-current consistency (M = 170.70, SD = 10.35) and post-current consistency (M = 166.99, SD = 10.54), t (7) = 4.263, p = 0.004 (two-tailed) (see Table 1). The mean reduction in the current was 3.71, with a 95% confidence interval spanning from 1.65 to 5.77. Additionally, significant differences between the pre- and post-laundering conditions were observed in cycles 2, 3, 4, and 5 for both types of samples (see Figure 5).

Table 1. Significance levels of current readings between the cycles of two sample types in laundering testing conditions.

Samples	Variables	N	M	SD	Df	CI (2-Tailed, α = 0.05)	*p*	*t*
Sample Type (1)	Pre- and Post-CC (Cycle 1)	8	3.71	2.46	7		0.004	4.263
	Pre- and Post-CC (Cycle 2)	8	3.48	3.18	7		0.018	3.091
	Pre- and Post-CC (Cycle 3)	8	4.94	3.01	7		0.002	4.628
	Pre- and Post-CC (Cycle 4)	8	5.93	2.33	7		<0.001	7.186
	Pre- and Post-CC (Cycle 5)	8	7.13	2.96	7	95%	<0.001	6.803
Sample Type (2)	Pre- and Post-CC (Cycle 1)	8	1.55	5.55	7		0.455	0.790
	Pre- and Post-CC (Cycle 2)	8	2.01	1.42	7		0.005	4.012
	Pre- and Post-CC (Cycle 3)	8	4.80	2.72	7		0.002	4.992
	Pre- and Post-CC (Cycle 4)	8	5.46	2.64	7		<0.001	5.848
	Pre- and Post-CC (Cycle 5)	8	5.92	2.72	7		<0.001	6.168

N = No. of samples; M = reductions in mean values; SD = standard deviation; Df = degrees of freedom; CI = confidence interval; *p* = *p*-value; *t* = *t*-static; CC = current consistency.

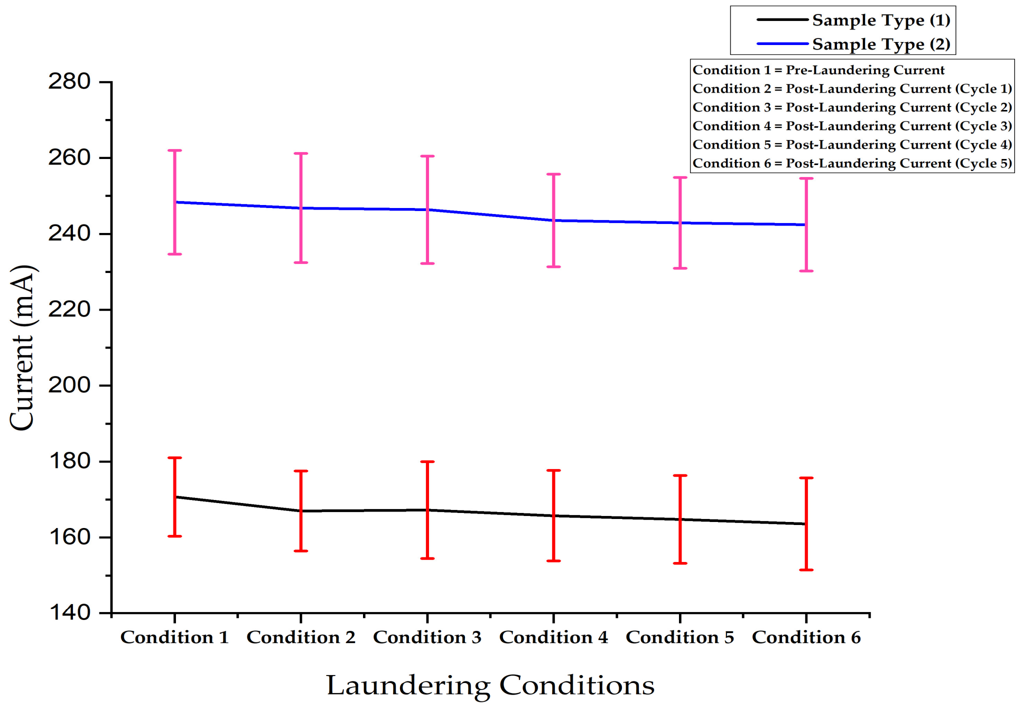

Figure 5. Mean and standard deviation values of current readings of two sample types in laundering testing conditions.

3.2. Comparison Between Electrical Resistance Values Pre- and Post-Laundering

Regarding the electrical resistance values, a similar paired sample *t*-test was performed for both types of samples to compare their pre- and post-laundering conditions for each cycle at a significance level of α = 0.05. For Sample Type (1), as presented in Figure 6, a significant difference was observed between the pre-electrical resistance (M = 0.429, SD = 0.036) and post-electrical resistance (M = 0.447, SD = 0.031), t (7) = −0.993, p = 0.012 (two-tailed) (see Table 2). However, among the other comparisons, no significant differences were found between the pre- and post-laundering conditions for cycles 2, 3, and 5 in the case of Sample Type (1). On the other hand, for Sample Type 2, the results revealed that there were no significant differences between the pre-electrical resistance (M = 0.429, SD = 0.036) and the post-electrical resistance (M = 0.304, SD = 0.30), t (7) = −3.353, p = 0.210 (two-tailed) (see Table 2). The remaining pairs showed no significant differences between both laundering conditions for cycles 2, 3, 4, and 5 in the case of Sample Type (2). Therefore, while a consistent decline was observed in current values, there were no significant differences in the electrical resistance values for both types of samples.

Table 2. Significance levels of current readings between the cycles of two sample types in the laundering testing conditions.

Samples	Variables	N	M	SD	Df	CI (2-Tailed, α = 0.05)	p	t
Sample Type (1)	Pre- and Post-ER (Cycle 1)	8	−0.017375	0.014657	7		0.012	−3.353
	Pre- and Post-ER (Cycle 2)	8	−0.001750	0.027416	7		0.862	−0.181
	Pre- and Post-ER (Cycle 3)	8	−0.029125	0.087365	7		0.377	−0.943
	Pre- and Post-ER (Cycle 4)	8	−0.082625	0.079945	7		0.022	−2.923
	Pre- and Post-ER (Cycle 5)	8	−0.064000	0.108061	7	95%	0.138	−1.675

Table 2. *Cont.*

Samples	Variables	N	M	SD	Df	CI (2-Tailed, α = 0.05)	*p*	*t*
Sample Type (2)	Pre- and Post-ER (Cycle 1)	8	−0.020500	0.041980	7		0.210	−1.381
	Pre- and Post-ER (Cycle 2)	8	0.013625	0.045807	7		0.428	0.841
	Pre- and Post-ER (Cycle 3)	8	−0.048625	0.089065	7		0.166	−1.544
	Pre- and Post-ER (Cycle 4)	8	−0.052625	0.110637	7		0.220	−1.345
	Pre- and Post-ER (Cycle 5)	8	−0.059000	0.109485	7		0.171	−1.524

N = No. of samples; M = reductions in mean values; SD = standard deviation; Df = degrees of freedom; CI = confidence interval; *p* = *p*-value; *t* = *t*-static; ER = electrical resistance.

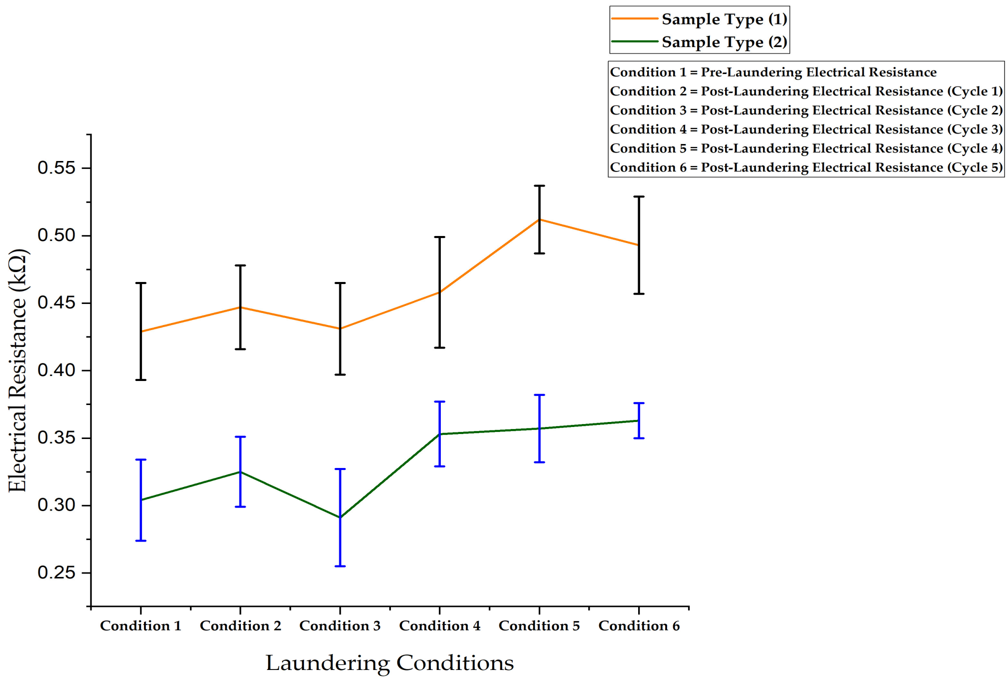

Figure 6. Mean and standard deviation values of electrical resistance readings of two sample types in the laundering testing conditions.

3.3. Comparison Between Current Values Pre- and Post-Laundering in Terms of Types

A mixed between-within-subjects (MANOVA) was conducted to examine the impacts of Sample Types (1) and (2) and cycles (pre and five post-laundering cycles). First, Levene's Test of Equality of Error Variances checked the assumptions of homogeneity of variances, where the significant value for each variable was greater than 0.05. Secondly, from the Box's Test of Equality of Covariance Matrices, the reported significant value was 0.001, which indicates that the assumption was not violated. The results revealed no significant interaction between laundering cycles and types, with Wilks lambda = 0.82, F (5, 10) = 0.44, $p = 0.813$, and partial eta squared = 0.180. There was a substantial main effect for laundering cycles, with Wilks lambda = 0.13, F (5, 10) = 13.46, $p < 0.001$, and partial eta squared = 0.871; both types showed a reduction in current across the laundering cycles (see Table 3). This result suggests a very large effect size from the partial eta squared value. Also, these results suggest that laundering cycles significantly affected the current values, which decreased as the number of laundering cycles increased.

Table 3. Effects on current values pre- and post-laundering for both sample types.

Effect	Wilks' Lambda Value	F	*p*	eta^2
Laundering Cycles	0.13	13.46	<0.001	0.871
Laundering Cycles * Types	0.82	0.44	0.813	0.180

* F = F-statistic; *p* = *p*-value; eta^2 = partial eta squared.

Table 4 shows the significant main effect of laundering cycles, with F (5, 70) = 16.736, $p < 0.001$ and eta^2 = 0.545, which indicates the variation in current values across the laundering cycles. However, there was also a non-significant interaction effect between laundering cycles and types, with F (5, 70) = 0.516, $p = 0.763$ and eta^2 = 0.036, which means that the effect of the laundering cycles on the current values and the outcome measure did not differ between the two types of samples.

Table 4. Significance of current values across the laundering cycles.

	SS	Df	MS	F	*p*	eta^2
Laundering Cycles	464.909	5	92.982	16.736	<0.001	0.545
Laundering Cycles * Types	14.332	5	2.866	0.516	0.763	0.036
Error (Laundering Cycles)	388.909	70	5.556			

* SS = Type III sum of squares; Df = degrees of freedom; MS = mean square; F = F-statistic; *p* = *p*-value; eta^2 = partial eta squared.

3.4. Comparison Between Electrical Resistance Values Pre- and Post-Laundering in Terms of Types

MANOVA was conducted to examine the same impacts between samples and cycles. The results revealed no significant interaction between laundering cycles and types, with Wilks lambda = 0.848, F (5, 10) = 0.359, $p = 0.865$, and partial eta squared = 0.152. There was a substantial main effect for cycles, with Wilks lambda = 0.257, F (5, 10) = 5.77, $p = 0.009$, and partial eta squared = 0.743; both types showed a reduction in electrical resistance across the cycles (see Table 5). These results suggest that the laundering cycles significantly affected the electrical resistance, which decreased as the number of laundering cycles increased. However, further research is needed to determine the specific factors contributing to these effects.

Table 5. Effects on electrical resistance values pre- and post-laundering for both types.

Effect	Wilks' Lambda Value	F	*p*	eta^2
Laundering Cycles	0.257	5.77	0.009	0.743
Laundering Cycles * Types	0.848	0.359	0.865	0.152

* F = F-statistic; *p* = *p*-value; eta^2 = partial eta squared.

Table 6 showed the significant main effect of laundering cycles, with F (5, 70) = 4.35, $p = 0.002$, and eta^2 = 0.236, which indicates the variation in electrical resistance across the laundering cycles. However, there was also a non-significant interaction effect between laundering cycles and types, with F (5, 70) = 0.321, $p = 0.899$ and eta^2 = 0.022, which means that the effect of the laundering cycles on electrical resistance values and the outcome measure did not differ between the two types of samples.

Table 6. Significance of electrical resistance across the laundering cycles.

	SS	Df	MS	F	*p*	eta^2
Laundering Cycles	0.077	5	0.015	4.35	0.002	0.236
Laundering Cycles * Types	0.006	5	0.001	0.321	0.899	0.022
Error (Laundering Cycles)	0.248	70	0.004			

* SS = Type III sum of squares; Df = degrees of freedom; MS = mean square; F = F-statistic; *p* = *p*-value; eta^2 = partial eta squared.

4. Discussion

This study compared the current and electrical resistance of PV cells before and after laundering testing conditions. The findings will provide potential insights into the performance of these cells. Therefore, the researcher conducted home laundering tests according to the standard protocol and analyzed the data. The findings indicated a significant difference in current values, which means that the current values decreased significantly after the laundering cycles. However, regarding electrical resistance, the researcher concluded that the laundering cycles had no significant effect on the electrical resistance, which means that the more laundering was conducted, the more there was no clear indication of decreasing electrical resistance values. From visual observations during the laundering test, the PV cell's condition deteriorated cycle by cycle. This might be because of friction with the ballast, which was the requirement of the standard testing procedure (see Figures 7 and 8). This deterioration potentially leads to interface degradation between different layers in the photovoltaic cells, contributing to a lower current despite the same resistance.

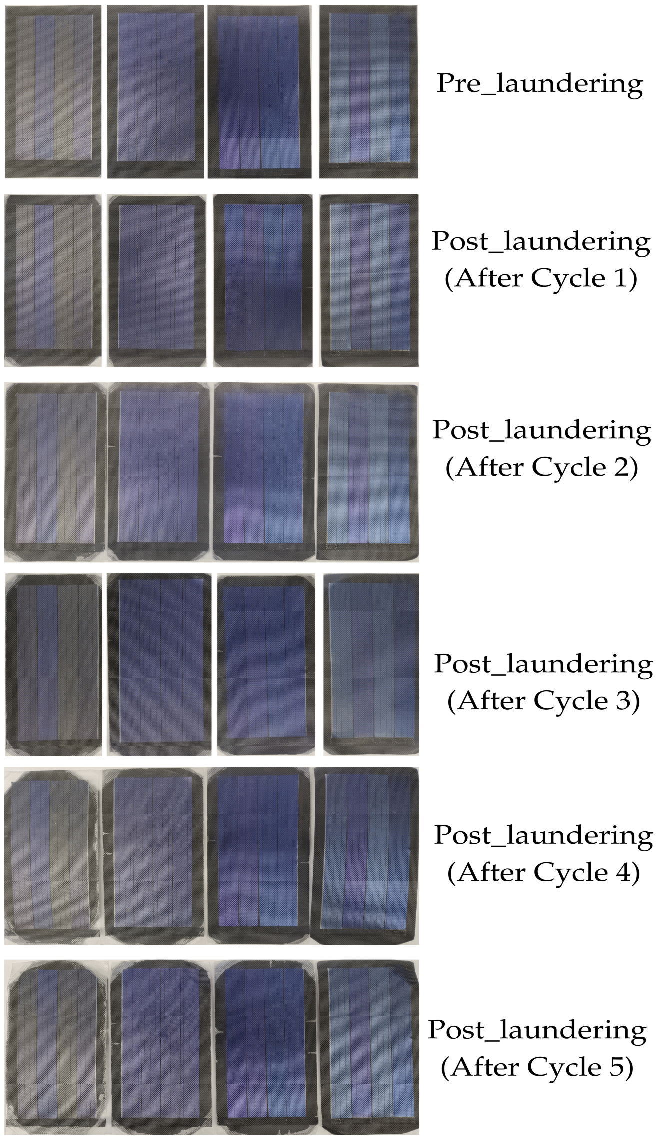

Figure 7. Conditions of wearable PV cells pre- and post-five laundering cycles, respectively: Sample Type (1).

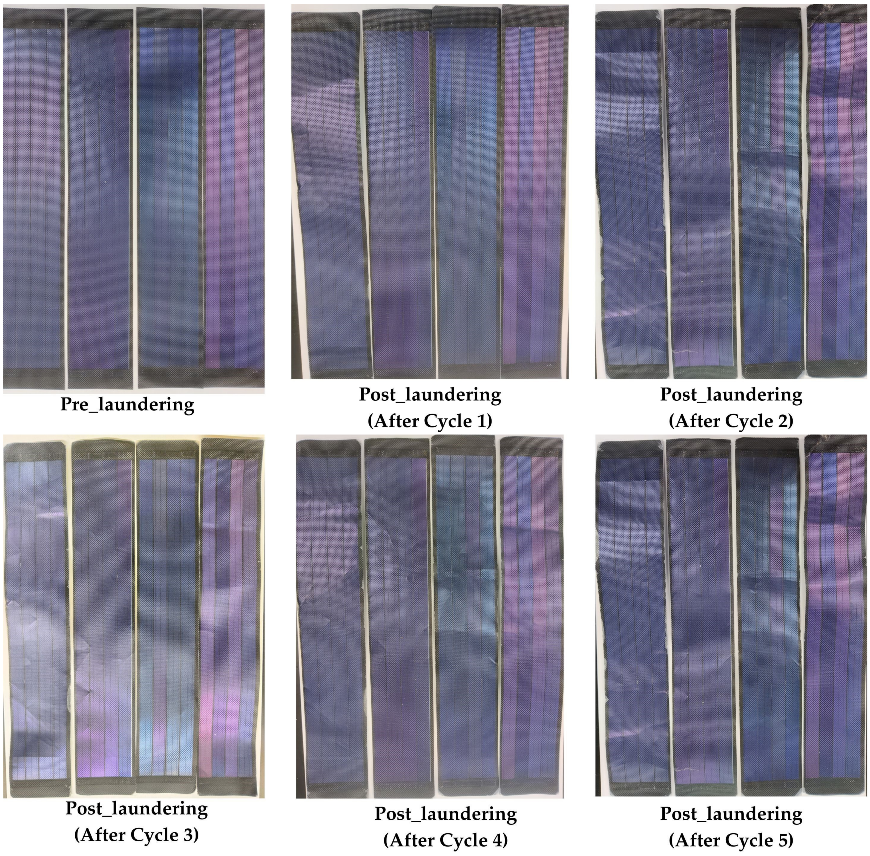

Figure 8. Conditions of wearable PV cells pre- and post-five laundering cycles, respectively: Sample Type (2).

4.1. Comparison Between Current Values Pre- and Post-Laundering

The results from the paired sample *t*-test showed a significant difference in current values after laundering cycles, which supports the prior literature. Qiu found 2 h of continuous laundering; after 12 h of prolonged laundering, the output degraded marginally (voltage: 106 V, current: 1.9 A) [21]. The reason behind this phenomenon was the better robustness of the composite materials. So, these results support prior research and significantly increase the difference, which grows the more the researcher launders. As it can be seen that the current values decreased significantly, this might be because of the properties of the detergents used in the laundering procedure. These detergents might leave some residues on the surface of the PV cells, potentially hindering the amount of sunlight that could reach the cells [36]. Detergent residues create a thin coating that affects the cells' optical and electrical characteristics. Surfactants in detergents, including anionic, nonionic, and cationic types, engage with cell surfaces via their hydrophilic heads and hydrophobic tails. These residues on the surface might diminish light absorption by scattering or reflecting incoming light, because of the reduction in the number of photons and electron–hole pairs that reach the active layer and reduce the current production. Ionic interactions from the residue can elevate the surface resistivity of the cell, thus impeding charge carrier mobility and diminishing the overall efficiency of the photovoltaic cell. The obstructive influence of detergent residues results in reduced light absorption and compromised current generation [36]. This could also be due to the physical changes induced by repeated laundering, such as changes in the material composition or mechanical wear. It could be concluded that manufacturers should prioritize PV cell materials that can withstand repeated mechanical stresses due to laundering without compromising their electrical performance, potentially increasing their usability in wearable textiles.

Also, the data from the MANOVA analyses revealed the significant main effect of laundering on current values, indicating that the current changes significantly across different cycles. However, the interaction effect between laundering cycles and types of samples was not significant, suggesting that the types of samples do not differentially influence the impact of laundering cycles on current values. This non-significant interaction effect could be because the sample has a similar material composition but has different dimensions, which might affect sunlight absorption. However, this similar material composition could make them equally resistant to the effects of laundering conditions. Therefore, if the materials used in both PV samples have similar properties, they may not exhibit significant changes in performance after laundering. It could be concluded that both types are equally susceptible to changes induced by laundering.

4.2. Comparison Between Electrical Resistance Values Pre- and Post-Laundering

The results from the paired sample *t*-test showed no significant difference in the electrical resistance values after laundering cycles, which does not support the prior literature. There is no clear indication of a decreasing electrical resistance after several laundering cycles. As mentioned in the introduction, Lee et al. (2019) reported that the alterations in electrical resistance within the materials corresponded with a decreased performance under electrical conditions [24]. There could be some possible reasons for these observations. First, as mentioned earlier, some residues might be on the surface of the PV cells, but electrical resistance is less likely to be influenced by the presence of such detergents, which may not interact with the materials in the cells in a way that affects their electrical resistance. Therefore, after laundering, the electrical resistance does not change significantly.

Also, the data from the MANOVA analyses revealed the significant main effect of laundering cycles on electrical resistance, indicating that the electrical resistance decreased significantly as the number of cycles increased. However, the interaction effect between cycles and types was not significant, suggesting that both types showed similar trends. This reduction in resistance with more cycles could be due to factors like improved contact between conductive elements, a reduction in surface contaminants, changes in the material structure, or changes in the material properties due to repeated exposure to laundering conditions. Also, the laundering conditions, such as the water temperature, detergent choice, agitation intensity, and drying methods applied to the samples, may not have been severe enough to observe significant differences in performance, which leads to both sample types remaining largely unaffected. Finally, only eight samples from each type were used, which may not have been large enough to detect minor differences in performance between the two sample types.

One main limitation of this research is that measuring current at different angles, such as 15°, 30°, and 45°, could guide more robust results, which could be achieved in the future. Additionally, the number of samples was less than in the prior literature, limiting the results' generalizability. More diversified samples could lead to more robust decisions. Future research could include more samples from different brands and then compare them to assess which one is performing well.

5. Conclusions

Wearable photovoltaic (PV) technology has grown in popularity in recent years; developers are using this technology in various applications, from health and fitness monitoring to energy-harvesting clothing, safety gear, protective textiles, and military uniforms; this is because electronic devices need to be powered continuously without requiring frequent recharging or bulky energy storage. However, it is challenging to practically adopt wearable PV cells in wearable applications due to laundering requirements, which can degrade durability and performance. This study compared PV cells' maximum current and electrical resistance before and after laundering testing conditions. The findings from this study indicated that the current values decreased significantly after laundering cycles. However, the laundering cycles had no significant effect on the electrical resistance. Also, there was no significant difference in the current values and electrical resistance between the two sample types before and after laundering. These results are crucial for industries developing textile-based PV panels, where maintaining electrical performance after laundering is essential. Manufacturers should consider using protective coatings techniques to mitigate the impact of laundering on electrical properties that could protect them. Also, they should focus on enhancing the current retention capabilities of PV cells through improved material compositions, surface treatments, or better integration with substrates to ensure enhanced functionality. Finally, these results serve as a reference point for practitioners working on future wearable photovoltaic cells, as similar mechanical and environmental stresses are likely to affect other material systems similarly.

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