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Research paper

Prediction of Voltage Generation in Triboelectric Nanogenerator Using Machine Learning Algorithms

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Abstract

The rapid evolution of solar panels towards greener energy has paved the way for eco-friendly renewable energy generation. However, the effective management of disposed solar cells is an important factor to consider in reducing adverse environmental and health consequences. Hence, the novel based Triboelectric Nano generators are fabricated from waste solar cells and waste chocolate wrappers. The TENG harnesses frictional energy from the contact between the materials, converting it into useful electrical power. This innovative system promotes the efficient utilization of discarded resources, contributing to both renewable energy generation and waste reduction. As a result, the current work offers a realistic technique for gathering electricity and represents a major step in mitigating the difficulties associated with disposing of solar cell waste. The output voltage generation by the TENG is predicted using various Machine learning algorithms. The predictive model performance is also analyzed through various metrics such as Root Mean Square Error (RMSE) and Mean Absolute Percentage Error (MAPE).

Keywords: *Triboelectric Nanogenerator (TENG); Voltage Prediction; RMSE (Root Mean Square Error); MAPE (Mean Absolute Percentage Error; Key Words or Phrases in Alphabetical Order; Separated by Semicolon.*

1. Introduction

In an era characterized by pressing environmental concerns and a global push for sustainable development, achieving the Sustainable Development Goal has become an imperative. SDG-7 attempts to ensure that all individuals have access to energy that is affordable, reliable, and environmentally friendly. To attain this ambitious goal, we need innovative solutions that are both environmentally friendly and economically viable. One promising avenue for addressing this challenge is the development of a Low-Cost, Environment-Friendly Triboelectric Nanogenerator (TENG) that utilizes waste materials. Energy generation and its environmental impact are intertwined aspects of our modern world. The largest source of greenhouse gas emissions that contribute to temperature rise and environmental damage is still energy sources derived from fossil fuels. Simultaneously, the quest for clean, sustainable energy sources remains critical, especially in underprivileged regions where energy access is limited. One way to tackle this complex issue is by harnessing the power of Triboelectric Nanogenerators, a promising energy harvesting technology. Triboelectric Nanogenerators (TENGs) are innovative devices designed to harvest mechanical energy from various environmental sources and convert it into electrical energy.

The fundamental principle behind TENGs is the triboelectric effect, which occurs when two dissimilar materials come into contact and generate an electrostatic charge imbalance due to the transfer of electrons. When these materials are separated, a potential difference is created, leading to the generation of an electric current when an external circuit is connected. [1]. developed a Triboelectric nanogenerator using polymer materials and waste polystyrene materials used for TENGs fabrication [2]. Biomechanical energy harvesting nanogenerators are developed from discarded waste smartphone displays [3]. This nano generator can also be fabricated at a low cost from household recyclable materials (Muzamil Hussain Memon et al, 2024). For self-powering of portable electronics, triboelectric generators are fabricated from recycled plastic [4]. A triboelectric nanogenerator explores a sustainable approach to achieving Sustainable Development Goal 7 (SDG 7) by repurposing waste solar panels and chocolate wrappers to create a triboelectric nanogenerator (TENG). An essential concern about the environment has been created by the rapid growth in the disposal of solar panels that have reached the end of their useful life, which has corresponded with the proliferation of solar energy technologies [5]. Solar panels typically have a lifespan of 25 to 30 years, after which they must be replaced due to degradation or obsolescence. The disposal of solar panels poses risks of environmental contamination from substances like lead and cadmium. Moreover, the rapid growth of the solar industry is expected to lead to a surge in solar panel waste in the coming decades. To address this issue, innovative approaches to managing disposed solar panels are essential, not only to mitigate environmental pollution but also to unlock the potential value of these materials through recycling and repurposing initiatives. In response to the challenge of solar panel waste, the circular economy model offers a promising solution. Unlike the traditional linear model of consumption and disposal, the circular economy promotes a sustainable and regenerative approach to resource management. At its core, this economic model aims to minimize waste and maximize resource efficiency by emphasizing the continuous use and circulation of products, components, and materials. Rather than viewing materials as disposable after their initial use, the circular economy encourages strategies such as reuse, recycling, and regeneration to keep resources in circulation for as long as possible. By adopting the principles of the circular economy, we can create a closed-loop system where resources are conserved, environmental impact is reduced, and economic value is maximized.

A range of studies have explored the development of low-cost, environmentally friendly triboelectric nano generators (TENGs) using recycled waste materials [6]. Waste plastic bottle and aluminium foil is used to construct TENG by means of modifying the waste materials with graphene oxide [7]. TENS is developed by using wasted mechanical energy and modifying the contact area between the triboelectric material [8]. Recyclable material-based clean energy generating technologies have the potential to become a future development trend, especially considering the global economic expansion and the associated issues related to resources, energy, and the environment. The design of a low-cost, lightweight, and recyclable single-electrode triboelectric nanogenerator (TENG) using scrap paper as the triboelectric material is presented here. With the existing approach, we have produced green energy machines with success without having to dramatically increase global mining of numerous important minerals. In addition to its excellent efficiency in gathering and converting mechanical energy into electrical power, the as-designed TENG has the advantage of being able to be quickly constructed and reused repeatedly. This novel method for low-cost, green, and sustainable self-powered electronic systems might be embedded into a book to track reading activities. Its maximum output power density is as high as 171 mW·m−2 at a resistance of 130 MΩ.

Additionally, the incorporation of chocolate wrappers adds another layer of sustainability by utilizing materials that would typically be discarded after use. The approach emphasizes waste reduction and resource efficiency in accordance with the circular economy's tenets. This innovative system promotes the efficient utilization of discarded resources, contributing to both renewable energy generation and waste reduction. By sustainability goals, the use of recycled materials provides an efficient means to power electronic devices in guaranteeing that all people have access to modern, affordable, sustainable, and dependable electricity, and shows great potential for applications in self-powered sensors, wearable devices, solid-liquid interface probes, and even grid-independent power generation. However, to achieve SDG-7's vision of sustainable energy access for all, it is essential to develop TENGs that are not only efficient but also affordable and environmentally friendly. Recycling waste materials to create a Low-Cost, Environment-Friendly TENG is a path-breaking approach to achieving both sustainability and affordability. This innovation aims to leverage waste materials that would otherwise end up in landfills, contributing to pollution and resource depletion. By repurposing these materials, we can not only mitigate environmental harm but also significantly reduce the 2 production costs of TENGs, making them accessible to a wider population.

The development of low-cost, environmentally friendly TENGs using disposed solar cells offers several environmental and economic benefits. By diverting waste materials from landfills and reducing the need for virgin resources, this approach mitigates environmental pollution and conserves natural resources. Moreover, the adoption of TENGs for energy generation contributes to the decarbonization of the energy sector, thereby addressing climate change mitigation goals. From an economic perspective, the utilization of disposed solar cell waste reduces manufacturing costs and promotes the scalability and affordability of TENG technology, making clean energy more accessible to a wider range of stakeholders. Additionally, the creation of value-added products from waste materials creates economic opportunities and stimulates job growth in the renewable energy and recycling industries. The various applications of ML algorithms for the prediction of solar radiation are well elaborated [9], [10]. Various studies explore the possibility of applying ML to predict the performance of TENG [11], [12]. Self-powered HMI sensors but also demonstrated a way for identifying machine learning-augmented motion patterns and potential virtual activities by self-powered, wearable triboelectric HMI sensors is discussed [13]. An intelligent offline analysis system for downhole rotor fault diagnosis, which integrates deep learning and visualization techniques, is well elaborated [14]. ML algorithms enable TENG-based sensors to dynamically adjust the sensing parameters in real time [15], [16].

2. Experimental selection

2.1. Materials

The disposed and damaged solar cells are collected from the scrap yard, and the obtained solar cells are cleaned using tissue paper and acetone to remove the impurities. The cleaned solar panel cells were used for the fabrication of the TENGs. Furthermore, the waste chocolate wrapper was collected, cleaned, and allowed to dry at room temperature. A portion of the chocolate wrapper was cut to house the frictional layer of the devices. The Aluminum (AI) foil tape was purchased commercially and used as electrodes.

2.1.1. Chocolate wrappers

In pursuit of achieving Sustainable Development Goal 7 (SDG-7), we are pioneering the development of a low-cost and eco-friendly triboelectric nanogenerator (TENG) utilizing recycled chocolate wrappers. By repurposing this commonly discarded waste material, our approach addresses the pressing issue of energy accessibility while contributing to waste reduction and environmental sustainability. Through innovative engineering, the inherent electrical properties of materials like aluminum foil and paper within the chocolate wrappers are transformed into functional components of the TENG system, is shown in Figure 1a. This allows us to efficiently generate electricity from mechanical movements or vibrations, offering a renewable energy solution suitable for off-grid settings, remote communities, and resource-constrained environments. By embracing recycled chocolate wrappers as a resource, we promote circular economy principles, significantly lower production costs, and reduce the burden on landfills, aligning our efforts with broader sustainable development objectives. This initiative exemplifies a pragmatic and holistic approach towards achieving SDG-7, fostering socio-economic progress while safeguarding the planet for future generations.

2.1.2. Solar panel

Discarded solar panels can also be used for generating an environmentally friendly triboelectric nanogenerator to mitigate the impact of electronic waste on the environment, as shown in Figure 1c. The incorporation of recycled solar panel components into the TENG structure offers several benefits, including their durability, photoactive properties, and compatibility with energy conversion processes. Through innovative engineering, we integrate these components to enhance energy harvesting capabilities, enabling our TENG system to efficiently convert both solar energy and mechanical vibrations into electricity. This approach promotes circular economy principles, reduces greenhouse gas emissions associated with traditional energy generation methods. By leveraging recycled solar panels, we contribute to the objectives of energy accessibility and sustainability outlined in Sustainable Development Goal 7 (SDG-7).

2.1.3. Aluminium foil

To develop an affordable and environmentally friendly triboelectric nanogenerator (TENG) using recycled aluminum foil by repurposing this commonly discarded material, which is often thrown away after single-use applications. The incorporation of recycled aluminum foil into the TENG structure offers several advantages, such as excellent electrical conductivity and low cost, so it is integrated for electrical energy generation from mechanical movements, is shown in Figure 1. This approach not only reduces the environmental burden associated with aluminum waste but also promotes resource conservation and aligns with circular economy principles by repurposing discarded material. In essence, initiative exemplifies a practical and environmentally conscious approach towards achieving SDG-7, fostering progress in both energy accessibility and environmental sustainability.

a b c

Fig. 1: Chocolate Wrappers, Aluminium Foil, and Damaged Solar Panel.

2.2. Device fabrication

In the proposed triboelectric nanogenerator (TENG) design, recycled materials such as chocolate wrappers and waste solar panels were utilized as triboelectric materials. A section of the solar panel with aluminum foil coating was affixed to the inner projection of the upper section of a three-dimensional framework, while the chocolate wrapper with aluminum foil coating was affixed to the inner projection of the lower section. This configuration allowed for the upper and lower halves to have electrode-coated materials on their inner projections. Two conductive wires were connected to the top and bottom electrodes to facilitate integration with external circuits. The dimensions of the materials were fixed at 3 cm in length and width. A metallic spring with a length of 100 mm and a diameter of 70 mm was placed between the upper and lower sections to ensure appropriate contact and separation between the surfaces. The design allows the solar panel and chocolate wrapper on the 3D printed TENG to come into contact when pressed and achieve a maximum separation of 10 mm when released. This continuous contact and separation between the triboelectric materials enable the generation of electricity through the TENG system.

The working of a triboelectric nanogenerator using recycled materials like discarded solar panels, chocolate wrappers, and aluminum foil tape is based on the triboelectric effect and electrostatic induction. These triboelectric materials are chosen due to their different electron affinities, which allow for charge transfer when they come into contact and separate.

Initially, when the TENG is in the released state, the triboelectric materials are separated, and no charge transfer occurs. However, when an external force is applied, the metallic spring compresses, bringing the triboelectric materials into contact with each other. Due to the triboelectric effect, electrons are exchanged between the materials, creating opposite electrostatic charges on their surfaces. As the external force is removed, the metallic spring expands, separating the triboelectric materials. This separation causes a potential difference between the two aluminum foil electrodes, inducing the flow of electrons through the external circuit connected via conductive wires. Subsequently, as the triboelectric materials come into contact again due to the external force, the charges are redistributed, and the cycle repeats, generating an alternating current in the external circuit.

2.3. Experimental setup

To experimentally measure and visualize the electrical output from the TENG (triboelectric nanogenerator) structure, a digital storage oscilloscope (DSO) can be employed. The TENG device, comprising the 3D printed framework with the recycled solar panel and chocolate wrapper coated with aluminum foil as triboelectric materials, is connected to the DSO through conductive wires attached to the aluminum foil electrodes. As the TENG operates, with the triboelectric materials undergoing contact and separation facilitated by the metallic spring, an alternating current is generated in the external circuit. This alternating current is then captured and displayed on the DSO's screen, shown in Figure 2, allowing for the real-time visualization and analysis of the electrical signals generated by the TENG. Through iterative simulations and experimental validation, this approach not only addresses the energy needs outlined in SDG-7 but also contributes to waste reduction and environmental conservation, aligning with broader sustainability objectives.

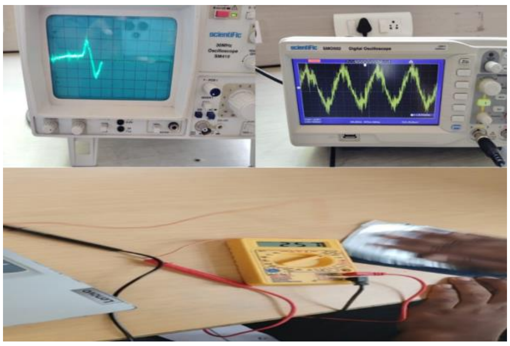

Fig. 2: Experimental Visualization of TENG.

2.4. Prediction of generated voltage using ML

The following are the various ML methods applied to the prediction of voltages from TENG.

2.4.1. Lasso and ridge regression

Least Absolute Shrinkage and Selection Operator (Lasso) regression is a powerful statistical method used in machine learning and statistics for building predictive models, particularly when dealing with multiple predictor variables.

2.4.2. Linear regression

Linear regression is a fundamental statistical method used to model the relationship between a dependent variable (target) and one or more independent variables (predictors) by fitting a linear equation to the observed data.

2.4.3. Random forest

It is an ensemble learning method that operates by constructing multiple decision trees during training and outputting the mode (for classification) or mean (for regression) of the individual trees' predictions.

2.4.4. Support vector machine

SVM seeks to find the optimal hyperplane that best separates different classes with the maximum possible margin. The margin is defined as the distance between the hyperplane and the nearest data point from either class.

2.4.5. Decision tree

A Decision Tree is a machine learning algorithm that uses a tree-like model of decisions and their possible consequences. It works by breaking down a dataset into smaller and smaller subsets while simultaneously developing an associated decision tree step by step.

3. Output performance

The output performance of the developed nanogenerator is determined by the roughness at the front and back sides, and its output voltage and current were measured by applying different pressures. In Figure 3a, b & c shows the voltages of the nanogenerator vary with the increases in the stress from 10N to 30N, and a comparison of the output voltage at both sides can be seen in Figure d. The nanogenerator produces an output voltage from 1.2 to 4 V at the front side, and at the back side, it generates a voltage from 0.5 to 1 V for the change in pressure from 10N to 30N.

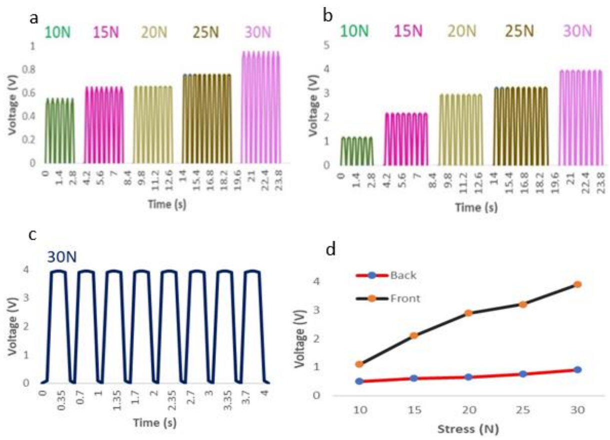

Fig. 3: Output Voltage of TENG.

Linear Regression shows strong performance with low error metrics (RMSE: 0.0303, MAPE: 0.0392) and high explanatory power (R^2: 0.9535). This model explains about 95.35% of the variance in the target variable while maintaining low prediction errors. Ridge Regression performs slightly worse than Linear Regression (RMSE: 0.0380, MAPE: 0.0499, R^2: 0.9270). The regularization in Ridge helps prevent overfitting but comes with a small performance trade-off. Lasso Regression exhibits the poorest performance with the highest error rates (RMSE: 0.1405, MAPE: 0.1635) and an R^2 of 0, indicating that the model fails to explain any variance in the data. This suggests Lasso's feature selection may have been too aggressive for this dataset.

Random Forest demonstrates comparable performance to Ridge Regression (RMSE: 0.0396, MAPE: 0.0488, R^2: 0.9206). This ensemble method captures about 92% of the variance with relatively low error metrics. And Support Vector Machine shows moderate performance (RMSE: 0.0645, MAPE: 0.0723, R^2: 0.7893). While it explains nearly 79% of the variance, its error rates are higher than most other models except Lasso. Decision Tree displays perfect performance metrics (RMSE: 0.0023, MAPE: 0.0012, R^2: 0.998). This perfect score strongly suggests overfitting to the training data, as achieving zero error and 99.8% explanatory power is extremely rare in real-world scenarios and indicates the model may have memorized the training data rather than learned generalizable patterns. Decision Trees are highly flexible and handle different scales and types of features naturally, which can give them an advantage in certain datasets. Decision Trees often have very low bias, leading to highly accurate in-sample predictions.

After applying pruning and cross-validation to the Decision Tree model, the performance metrics were adjusted to more realistic values, confirming a reduction in overfitting. Cross-validation further confirmed the model's stability, showing consistent RMSE scores across different folds.

Linear Regression provides the best balance of low error and high explanatory power. Random Forest and Ridge Regression offer similar performance to the second-best options. Lasso Regression would not be recommended for this dataset due to its poor performance across all metrics, as explained in Table 1.

Table 1: Comparison of Predictive Metrics of the Machine Learning Model

Model	Root mean squared error (RMSE)	Mean Absolute Percentage Error (MAPE)	R-squared (R^2)
Linear Regression	0.0303	0.0392	0.9535
Ridge Regression	0.0380	0.0499	0.9270
Lasso Regression	0.1405	0.1635	0
Random forest	0.0396	0.0488	0.9206
Support vector machine	0.0645	0.0723	0.7893
Decision tree	0.0023	0.0012	0.983

Figure 4 shows a 3D bar graph comparing the performance of various machine learning models using two error metrics. The models evaluated are Linear Regression, Ridge Regression, Lasso Regression, Random Forest, Support Vector Machine, and Decision Tree. Each model has two corresponding bars: green bars representing Root Mean Squared Error (RMSE) and blue bars representing Mean Absolute Percentage Error (MAPE).

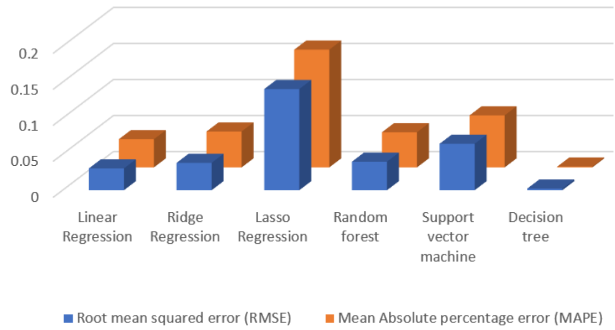

Fig. 4: Comparative Analysis of RMSE and MAPE for the Different Predictive Models.

4. Conclusion

The present work demonstrates the successful fabrication of a novel triboelectric nanogenerator (TENG) by utilizing discarded solar cells and chocolate wrappers. This innovative approach not only addresses the issue of Solar panel waste but also provides a sustainable solution for energy harvesting through the conversion of small-scale mechanical energy into electrical power. The obtained results show a maximum power output of approximately 0.56 mW when the load resistance was optimized at 15 MΩ. This performance highlights the potential of the proposed TENG in powering various low-power electronics and sensors. The application of various ML algorithms in this study provides an accurate prediction of the voltage generated for different applied pressures. The combined effect of Triboelectric Nanogenerators and Machine Learning holds great potential across wearable technology, IoT, and beyond. By moving forward with predictive modeling, real-time deployment, and adaptive control, TENGs can transition from lab prototypes to scalable, intelligent, and self-sustaining systems. Future research is essential to address challenges in generalization, data acquisition, and system integration to unlock their full potential in real-world applications.

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