

**APPLICATION OF KIRIGAMI AUXETIC MEMBRANES
FOR ENHANCING THE RAINDROP ENERGY
HARVESTER PERFORMANCE**

BY

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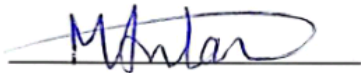
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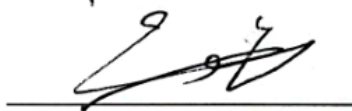
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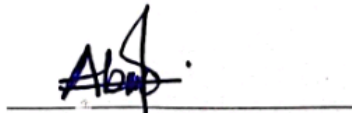
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2024

*Dedicated to My Parents and
My Family*

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LIST OF ABBREVIATIONS

<i>EH</i>	: Energy Harvesting
<i>PREH</i>	: Piezoelectric Raindrop Energy Harvesting
<i>PVDF</i>	: Polyvinylidene Fluoride
<i>PZT</i>	: Lead Zirconate Titanate
<i>REH</i>	: Raindrop Energy Harvesting
<i>NPR</i>	: Negative Poisson's Ratio
<i>MetaMems</i>	: Metamaterial Membranes
<i>PENG</i>	: Piezoelectric Nanogenerator
<i>TENG</i>	: Triboelectric Nanogenerator
<i>PyNG</i>	: Pyroelectric Nanogenerator
<i>RED</i>	: Reverse Electrodialysis
<i>MEMS</i>	: Microelectromechanical Systems
<i>NASA</i>	: National Aeronautics and Space Administration
<i>LSR</i>	: Light Stratiform Rain
<i>MSR</i>	: Moderate Stratiform Rain
<i>HT</i>	: Heavy Thunderstorms
<i>DOF</i>	: Degree of Freedom
<i>ZCH</i>	: Zigzag unit Cell with Hole

<i>MPS</i>	: MetaMems Pressure Sensor
<i>CPS</i>	: Conventional Pressure Sensors
<i>KAM</i>	: Kirigami Auxetic Membrane
<i>PLA</i>	: Polylactic Acid
<i>AC-DC</i>	: Alternating Current - Direct Current
<i>CAD</i>	: Computer Aided Design
<i>ABS</i>	: Acrylonitrile Butadiene Styrene
<i>PETG</i>	: Polyethylene Terephthalate Glycol
<i>TPU</i>	: Thermoplastic Polyurethane
<i>FEA</i>	: Finite Element Analysis
<i>LED</i>	: Light Emitting Diode

ABSTRACT

Full Name : Muhammad Awaluddin Harahap

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Raindrop impact energy as one of the mechanical energy sources is available to be converted to electrical energy utilizing piezoelectric elements powering low-power devices that can operate in distant areas without the need for battery replacement or other associated maintenance. However, inadequate power production becomes the primary issue of the raindrop energy harvesting system. We identified that restriction and studied the kirigami auxetic membrane (KAM) to address the issue using simulation and experimental methods. The proposed KAM is comprised of a complex kirigami pattern named KAM Type A, B, C and possesses negative Poisson's ratio (NPR) which enables them to more effectively expand the piezo-element equipped in raindrop energy harvester in both longitudinal and transverse directions. Polyvinylidene fluoride (PVDF) is observed to be the ideal material for the piezo-element in this research and polylactic acid (PLA) is chosen as the constituent material for the kirigami auxetic membranes, substrate, and supporting structure.

The conducted experiment demonstrates that KAM Type B and C will experience the biggest deflection after receiving waterdrop pressure at 1.47 nm and 1.49 nm. In other words, the KAM Type B and C will transfer more stress deformation to the PVDF layer, and therefore the electricity output will be enhanced. Then, the raindrop energy harvester enhancement equipped with a combination of KAMs is studied and tested as well. The results showed that combining the KAMs with a C+B+A configuration will enhance the electricity output with a power multiplication up to 3 at 73.2 mV compared to the raindrop energy harvester equipped plain membrane that only can generate 24 mV. The combination of KAM C+B+A is also recognized as the most efficient configuration and charges the electrical storage (capacitor) faster than other combinations to flash a small bulb. The flexible auxetic membrane on raindrop energy harvesting proposed in this research will introduce a new class of developing technology for piezoelectric application. Additionally, especially in areas with a lot of rainfall, the suggested raindrop energy harvester might power various public facilities including tents, temporary roofs, coverings, and tarps to power digital displays, lighting, sensing, and other features.

مستخلص

الاسم الكامل: محمد أول الدين هاراهاف

عنوان الرسالة: استخدام أغشية كيريجامي المساعدة لتعزيز أداء حصاد طاقة قطرات المطر

المجال الرئيسي: الهندسة الميكانيكية

تاريخ الحصول على الدرجة: جمادى الأولى 1446هـ

طاقة تأثير قطرات المطر باعتبارها أحد مصادر الطاقة الميكانيكية متاحة لتحويلها إلى طاقة كهربائية باستخدام عناصر كهروضغطية تعمل على تشغيل الأجهزة منخفضة الطاقة التي يمكن أن تعمل في مناطق بعيدة دون الحاجة إلى استبدال البطارية أو أي صيانة أخرى مرتبطة بها. ومع ذلك، يصبح إنتاج الطاقة غير الكافي هو المشكلة الأساسية لنظام حصاد الطاقة من قطرات المطر. لقد حددنا هذا القيد ودرسنا الغشاء المساعد كيريجامي kirigami المقترح من نمط KAM لمعالجة المشكلة باستخدام الأساليب النظرية والتجريبية. يتكون (KAM) والتي تمكنهم من توسيع عنصر (NPR) ويمتلك نسبة بواسون سالبة C و B و KAM Type A معقد يسمى الضغط الانضغاطي المجهز في حصاد طاقة قطرة المطر بشكل أكثر فعالية في كلا الاتجاهين الطولي هو المادة المثالية للعنصر الانضغاطي في هذا البحث (PVDF) والعرضي. لوحظ أن فلوريد البولي فينيلدين كمادة مكونة لأغشية كيريجامي المساعدة والركيزة والبنية الداعمة. بعد (PLA) وتم اختيار حمض عديد اللبنيك ذلك، يتم تجميع المكونات بالكامل لإنشاء وحدة تجميع طاقة قطرات المطر.

سيواجهان أكبر إزاحة بعد تلقي ضغط قطرة الماء C و KAM Type B توضح التجربة التي تم إجراؤها أن بنقل المزيد من تشوه C و KAM Type B عند 1.47 ميكرومتر و 1.49 ميكرومتر. بمعنى آخر، سوف يقوم ، وبالتالي سيتم تعزيز إنتاج الكهرباء. بعد ذلك، تمت دراسة واختبار تعزيز حصاد PVDF الإجهاد إلى طبقة C + وتكوين KAMs أيضاً. أظهرت النتائج أن الجمع بين KAMs طاقة قطرات المطر المجهز بمجموعة من سيعزز إنتاج الكهرباء بمضاعفة الطاقة حتى 3 عند 73.2 مللي فولت مقارنة بغشاء عادي مجهز B + A بأنه KAM C+B+A بحصاد طاقة قطرات المطر والذي يمكنه توليد 24 مللي فولت فقط. يُعرف أيضاً مزيج التكوين الأكثر كفاءة ويشحن وحدة التخزين الكهربائية (المكثف) بشكل أسرع من المجموعات الأخرى لوميض لمبة صغيرة. إن الغشاء المساعد المرن لتجميع طاقة قطرات المطر المقترح في هذا البحث سوف يقدم فئة جديدة من التكنولوجيا النامية للتطبيقات الكهروضغطية. بالإضافة إلى ذلك، خاصة في المناطق التي تكثر فيها الأمطار، قد يعمل جهاز تجميع طاقة قطرات المطر المقترح على تشغيل العديد من المرافق العامة بما في ذلك الخيام والأسقف المؤقتة والأغطية والأقمشة لتشغيل شاشات العرض الرقمية والإضاءة والاستشعار وميزات أخرى.

CHAPTER 1

INTRODUCTION

1.1 Background

The issue of energy availability is the primary difficulty encountered by humanity today. A rapidly growing population, along with rising demand for energy-intensive services, has worsened the current energy resources condition. Moreover, Indonesia as the 4th largest population (278 million people) in the world has encountered the same issue [1]. The Ministry of Energy and Mineral Resources reported in 2022 that Indonesia's total power consumption was 360 TWh shown in Figure 1.1, marking an increase of approximately 17% from 2020 [2].

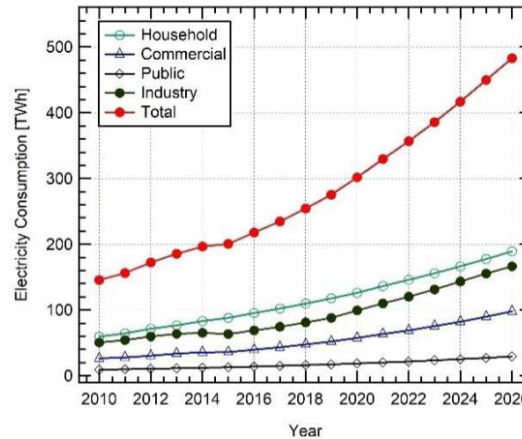


Figure 1.1 Indonesia's electricity consumption trend from 2010 to 2026 as predicted [2].

As one of many solutions, the implementation of energy harvesting is one of the suggested solutions to overcome energy availability issues [3]. Energy harvesting, or EH, is the process of obtaining energy from outside sources such as the sun, wind, or other sources. Indonesia as a tropical country has an intense rain annual frequency which can be utilized as an external energy source to generate electricity power [4]. Piezoelectric material is a smart material and energy provider at a micro-level that can be a consideration to convert the vibrations caused by raindrops' kinetic energy into electricity through a direct piezoelectric effect which is mentioned as piezoelectric

raindrop energy harvesting (PREH) [5]. The direct piezoelectric effect is a phenomenon when a piezoelectric material is exposed to a mechanical force, and the crystal lattice within the material deforms. This deformation causes a displacement of the positively and negatively charged ions within the crystal structure as depicted in Figure 1.2. Under unstressed conditions, these charges are symmetrically balanced, resulting in no net polarization. However, when mechanical stress is applied, the symmetry is disturbed, and the charge centres shift. This shift leads to a net polarization, creating an electric field or voltage across the material [6].

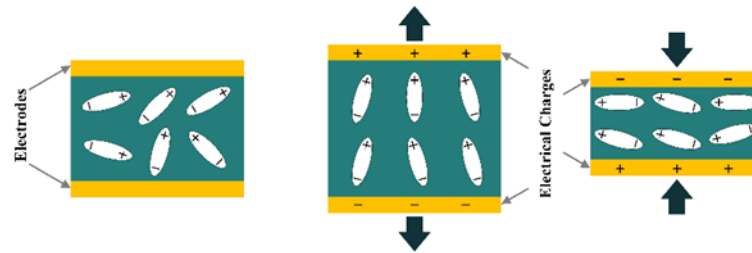


Figure 1.2 Illustration of a displacement of the positively and negatively charged ions within the material [7].

A unique renewable energy device, the piezoelectric raindrop energy harvester (PREH) uses a piezoelectric generator to capture the kinetic energy of raindrops. This system converts raindrop impacts into electrical energy, commonly employing piezoelectric materials like Polyvinylidene Fluoride (PVDF) and Lead Zirconate Titanate (PZT). Moderate to heavy rainfall, or precipitation, occurs in many places and can be used to produce power. With 2702 mm of precipitation annually, Indonesia is in the top 10 countries in terms of average precipitation in 2017 and increasing to 3148 mm/year in 2022 as illustrated in Figure 1.3 [8].

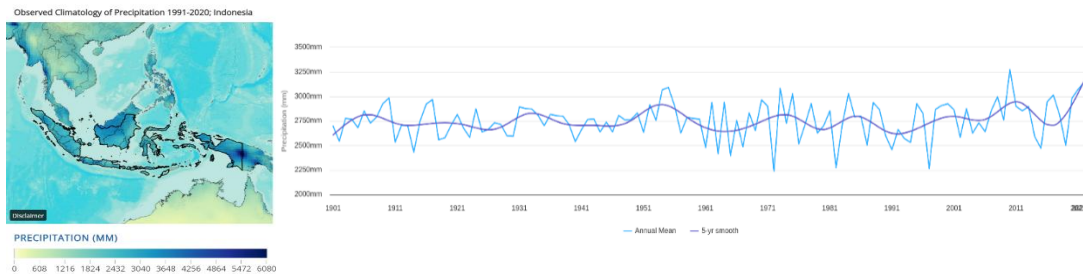


Figure 1.3 Observed annual precipitation of Indonesia for 1901-2022 [8].

Compared to Kingdom of Saudi Arabia (KSA) where this research was conducted, precipitation varies over space and time and of the amounts of precipitation over particular regions of KSA are also diverse as illustrated in Figure 1.4. From the seasonal analysis of rainfall, the periods of rainfall over KSA can be divided into two main periods. The first period includes November, December, January, February, March, April and May. About 80% of the total rainfall over KSA occurs during these months. The second period includes the other five months (June through October) [9]. Therefore, placement of the raindrop energy harvester needs to be adjusted when it is implemented in KSA area.

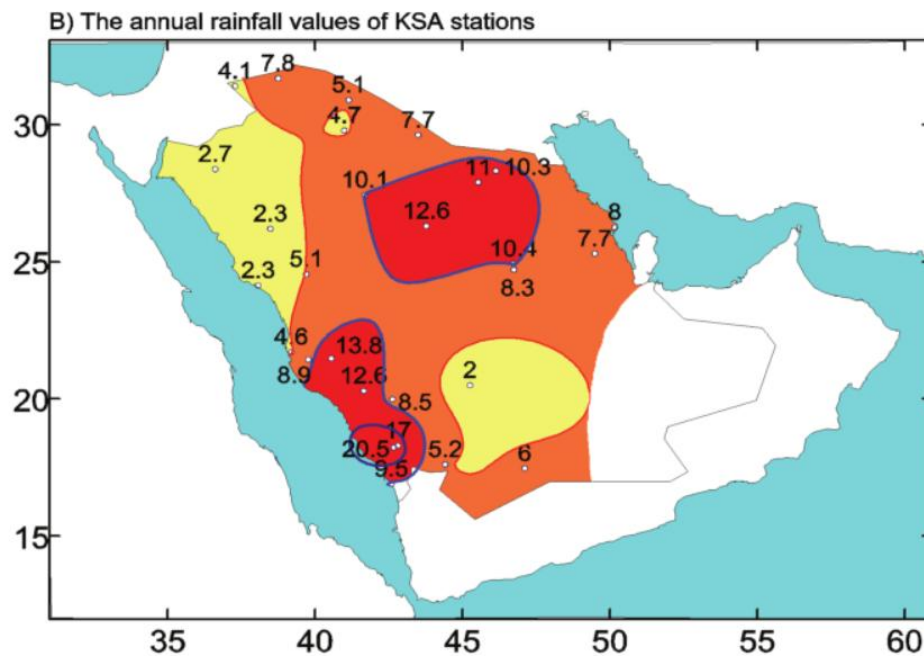


Figure 1.4 The average amounts of rainfall at KSA station [9].

On the other hand, Indonesia's high and increasing average annual precipitation is a product of its equatorial location, tropical climate, diverse topography, and the impacts of global climatic phenomena and climate change. Utilizing the existing situation, the research about raindrop energy harvesting (REH) is felt feasible to be implemented in this area. Although harvesting energy from raindrop impacts has attracted considerable research attention in recent years, its full potential remains

untapped. This is caused by an assumption that mechanical energy of raindrop is not strong enough and plentiful to be converted and produce another form of energy. In addition, when it is converted by using piezoelectric material, poor energy conversion efficiency as a result of inadequate vibration energy transduction to generator components is a significant concern in this research. One of the methods to counter the conversion efficiency issue of raindrop energy harnessing is by employing metamaterial-inspired membranes for better functionalities of piezoelectric material such as energy absorption, sensitivity, and stretchability [10]. Metamaterials are artificial structures designed to exhibit unique mechanical properties, including enhanced energy absorption, specific mass and density, controlled deformation, static modulus, advanced functionality, and a negative Poisson's ratio (NPR) [11]. According to their altered characteristics, metamaterials are divided into a number of different categories, including mechanical, electromagnetic, and acoustic/transport, as seen in Figure 1.5 [12].

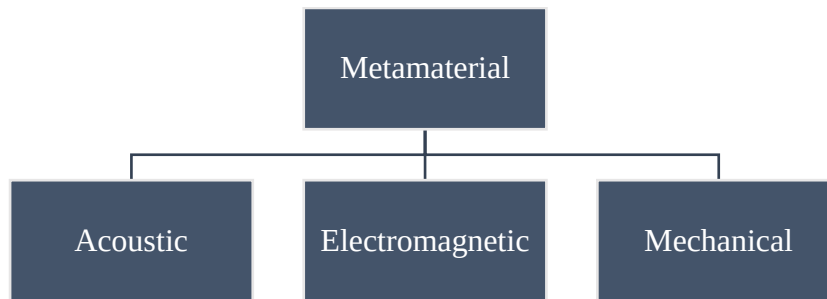


Figure 1.5 Types of metamaterials [12].

Materials with a negative Poisson's ratio, often known as auxetic materials, are a widely researched category within mechanical metamaterials, displaying unusual deformation behavior. Unlike conventional materials, which expand (contract) perpendicularly to the applied load under uniaxial compression (tension), auxetic materials instead contract (expand) in the transverse direction, as seen in Figure 1.6.

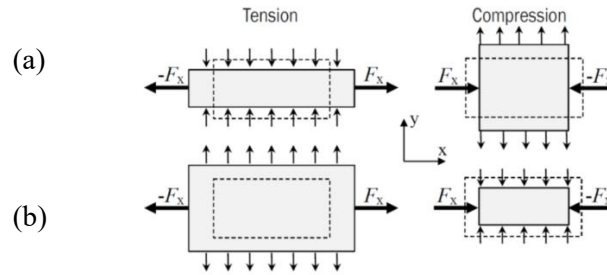
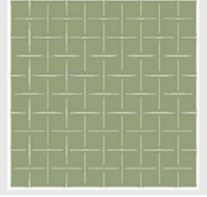
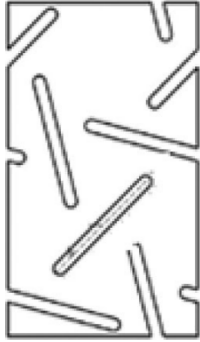


Figure 1.6 Tensile and compressive load behaviors: (a) conventional (non-auxetic) material; (b) auxetic material [13].

Alongside their unusual deformation behavior under compression and tension, auxetic materials and structures possess a range of beneficial properties, including enhanced shear resistance, indentation resistance, fracture resistance, synclastic behavior, adjustable permeability, and improved energy absorption capabilities. Among various auxetic designs is the perforated sheet structure. The main characteristics of the various kinds of perforated auxetic structures and models are summarized in Table 1.1 [14]

Table 1.1 Outlines the main characteristics of the numerous types of perforated sheet auxetic structures and patterns [14].

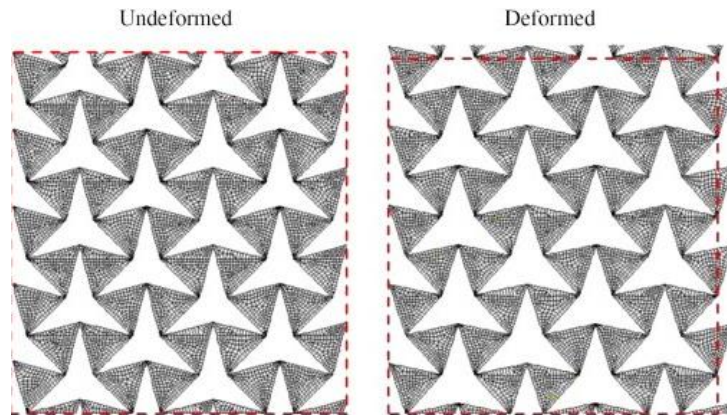
Classification	Auxetic structure kinds	Geometry	Relevant Details
Perforated Sheets	Perpendicular oriented cuts [15]		1) The perforations are designed to imitate a rotating squares mechanism. 2) It demonstrates auxetic behavior.
	Randomly oriented cuts [16]		1) Drawing inspiration from cuts oriented perpendicularly, it has been demonstrated that sheets with randomly oriented cuts also display auxetic behavior.
	Diamond perforations [17]		1) The diamond-shaped perforations in the sheets are designed to replicate the rotating quadrilateral model.

	Star perforations [17]		1) The star-shaped perforations in the sheets are created to imitate the rotating triangle model.
	A two-dimensional sheet with hexagonally patterned holes [18]		1) Through arranging holes and perforations in a hexagonal pattern inside a 2D sheet, auxetic activity is produced. 2) Porous auxetic material. 3) It features an omnidirectional Poisson's ratio. 4) Because of the hexagonal periodic arrangement of the pores, the structure displays isotropic behavior.

Membranes with auxetic behavior were created in this study as a highly delicate substitute for the conventional configuration (without applying auxetic membrane) to address the poor energy conversion efficiency challenge. Three density levels of perforated sheet models with perpendicular-oriented cuts type of auxetic structure are created by using the fractal-cut kirigami method [19]. The upcoming version of very flexible Metamaterial Membranes (MetaMems) for the sensitivity enhancement of raindrop energy harvesters was developed by using those "kirigami auxetic membranes [10]. With the objective to accomplish this, a plain membrane and three kirigami auxetic membranes were used to examine the energy harvester's performance through simulation and experiment. For collecting the initial amount of electricity generated by the harvester, we first employed a traditional setup consisting of a PVDF layer linked to a plain membrane. The electrical augmentation of the raindrop energy harvester was correspondingly demonstrated using the three kirigami auxetic membranes, which were dependent on the required stretchability and energy absorption brought on by the negative Poisson's ratio behavior.

1.2 Problem Statement

Raindrop energy harvesting was chosen as a potential energy solution due to the abundant and high-intensity rainfall in Indonesia, as a tropical country which the implementation of the raindrop energy harvester in whole regions of that country becomes very possible. However, the current low performance and efficiency of piezoelectric materials, commonly used in raindrop energy harvesters, present significant challenges. These materials, while capable of converting mechanical energy from raindrops into electrical energy, exhibit low energy conversion efficiency, especially under variable environmental conditions such as the diameter and velocity of raindrops which affect the amount of mechanical energy exposed to the piezoelectric [20]. This limits the viability of raindrop energy harvesting as a reliable and scalable renewable energy source. To address these limitations, a novel approach is proposed through the implementation of MetaMems technology in the form of auxetic membranes created using the fractal kirigami method. Auxetic materials, characterized by their negative Poisson ratio, can enhance energy absorption and mechanical flexibility, making them ideal for harvesting the kinetic energy from raindrops more efficiently [21]. Auxetic behaviour is achieved by specific topologies, such as reentrant geometry units, rigid or semi-rigid rotational units, spiral systems, and circular shapes forming voids which are illustrated in Figure 1.7.



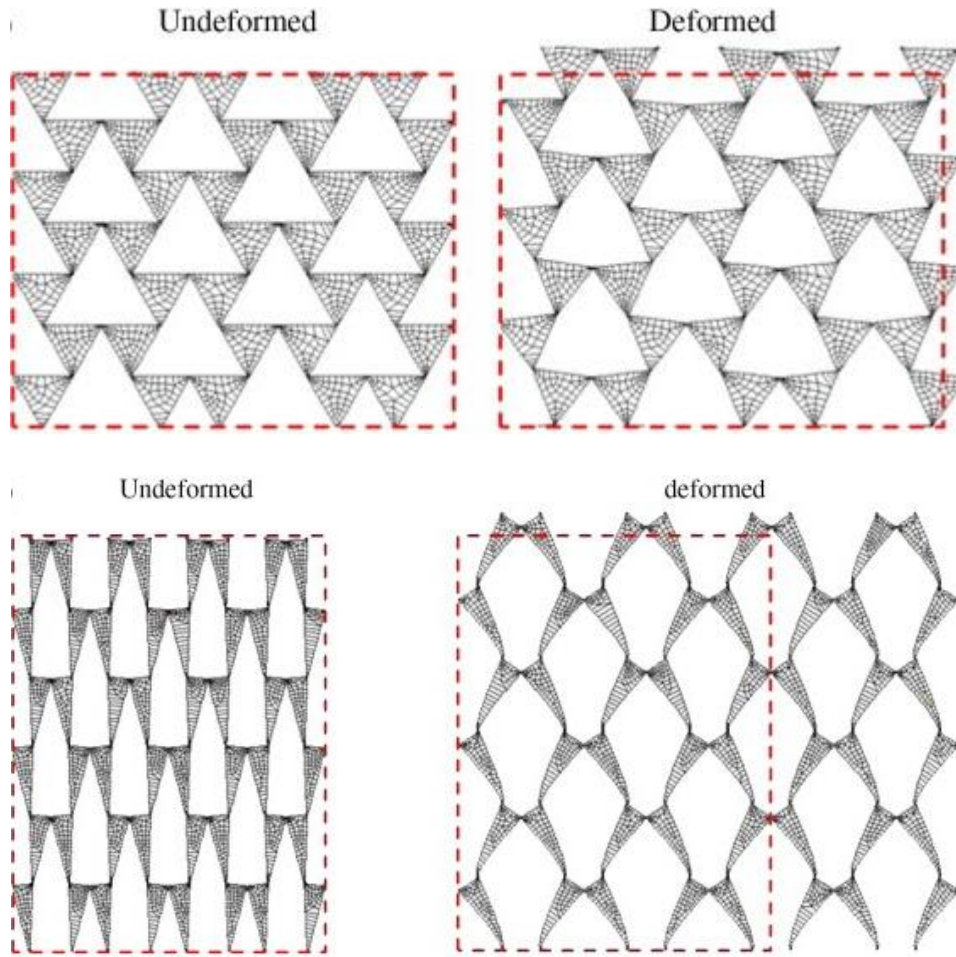


Figure 1.7 Geometries with auxetic behaviour in the original and stretched shape [22].

The fractal kirigami technique further amplifies these properties and geometries (shown in Figure 1.5) by creating intricate, reconfigurable patterns that allow for superior adaptability and energy dissipation. This study aims to explore how the integration of these kirigami auxetic membranes can significantly improve the performance of raindrop energy harvesting systems and pave the way for more efficient, scalable, and sustainable energy solutions in regions with high rainfall intensity.

1.3 Objectives

The intention of this research is to create a raindrop energy harvester integrated with a membrane exhibiting auxetic behaviour. The goal is to enhance the electricity

produced and the efficiency of the energy harvester. Specifically, the research objectives are as follows:

a. Optimize design and configuration: Develop and refine the structural design of the raindrop energy harvester, including the geometry and material properties of the kirigami auxetic membrane, to maximize its deformation and interaction with falling raindrops.

b. Analyze the efficiency of the energy harvester: The simulation of the membranes when exposed to the raindrops will be determined to see the response of the membranes to the raindrop's mechanical force. After that, experimental and numerical studies will be conducted to assess the performance of the raindrop energy harvester. The analysis will focus on measuring the amount of energy generated per raindrop impact, the influence of different environmental conditions, and the responsiveness of the kirigami auxetic membrane in energy harvesting.

c. Evaluate the transferred energy to the storage: Determine the amount of power generated relative to the number of raindrops and how efficiently that energy can be stored and utilized. As part of this assessment, the required power to illuminate a small light source will be measured, providing insight into the practical application of the harvested energy for low-power devices.

1.4 Thesis Outline

Chapter 1 Introduction: This section consists of background information, a problem statement, objectives, an outline, and a completion timeline.

Chapter 2 Literature Review: Presents an important review of raindrop energy harvesting, metamaterial-inspired membranes, and a review of existing research related to raindrop energy harvesting systems.

Chapter 3 Methodology: Includes the study's methodology. This chapter outlines the experimental and simulation process, along with the design and underlying assumptions needed to meet the study's objectives.

Chapter 4 Process Design Development: This chapter delves into the design of the raindrop energy harvesting device and kirigami auxetic membranes. The fabrication process of the raindrop energy harvester and experimental setup will be added as well.

Chapter 5 Results and Discussions: This section will provide the outcomes of the simulation of the kirigami auxetic membrane's response to raindrop impact, analyzing the effects of waterdrop distance to the harvester and harvester inclination on power generation. It also explores the performance of various combinations of kirigami auxetic membranes, evaluates the energy harvester's efficiency, and determines the impact of the number of raindrops on the rate of energy storage.

Chapter 6 Conclusions: presents the concluding remarks and suggestions for further studies.

CHAPTER 2

LITERATURE REVIEW

2.1 Utilization of Piezoelectric Material to Convert Mechanical Energy into Electrical Energy

Energy harvesting (EH) technologies have been the topic of extensive research and development. Mechanical energy is abundant in many environments, with vibration sources like ocean waves and human motion offering promising opportunities for converting mechanical energy into electrical power [23]. Figure 2.1 illustrates potential vibrational sources in settings such as the manufacturing industry, transportation, and the precipitation process, specifically rain.

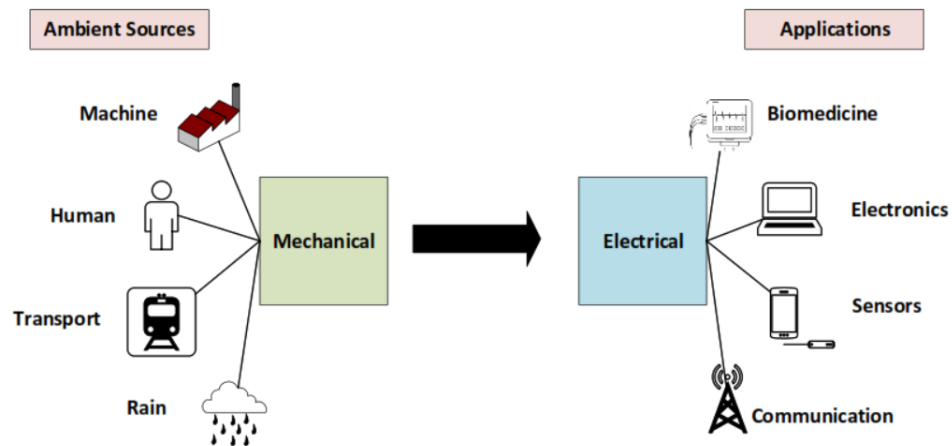


Figure 2.1 Selecting sources of collecting and investigating possible uses for piezoelectric devices [24].

Piezoelectric materials are among the most effective methods of converting mechanical energy into electrical energy. These materials lack atomic-scale symmetry, placing them in a unique class capable of generating an electrical charge when subjected to mechanical stress or strain, and conversely, producing mechanical deformation when exposed to an electric field [25].

2.1.1 Fundamental of Piezoelectricity

In 1880, the Curie brothers used quartz (SiO_2) single crystals to discover the direct piezoelectric effect [26], which indicates a material's ability to transform mechanical stress into electrical responses such as an electric displacement, electric field, or polarization. After this discovery, the Curie brothers also exhibited the indirect piezoelectric effect, in which applying an electric field to specific crystals can produce a mechanical response. A variety of ceramic materials and compositions, as well as other material classes like polymers, bone, wood, and even viruses, have been found to exhibit piezoelectricity, which was previously believed to exist only in a few numbers of unique crystals [27]. Surprisingly, the piezoelectric effect is not restricted to spontaneously polarized materials; it may also be seen in nonpolar materials that lack a center of symmetry, like zincite (ZnO), which has a non-centrosymmetric hexagonal wurtzite crystal structure [28]. However, the highest piezoelectric properties have been found in perovskite crystals, with some single crystals exhibiting piezoelectric coefficients that are more than three orders of magnitude greater than those of quartz, as initially shown by the Curie brothers [29]. The versatility and tunability of piezoelectric materials, combined with their ability to be integrated through various processing methods such as polycrystalline forms, single crystals, and thin films have made piezoelectricity a crucial enabling technology across multiple industries, including transportation, healthcare, military, energy, and consumer goods.

Principally, when a piezoelectric material is subjected to an external force or pressure, its crystal structure deforms, leading to a redistribution of positive and negative charges within the material, a process known as polarization, as illustrated in Figure 2.2 [30]. This results in an electrical potential difference across the material, which can be measured and utilized in energy harvesting applications. This process is called the direct piezoelectric effect. Conversely, the reverse piezoelectric effect, or converse piezoelectric effect, occurs when the material deforms in response to an applied electric field as shown in Figure 2.2. Most energy transducers and sensors rely on the direct effect, while actuators typically operate based on the converse effect [31].

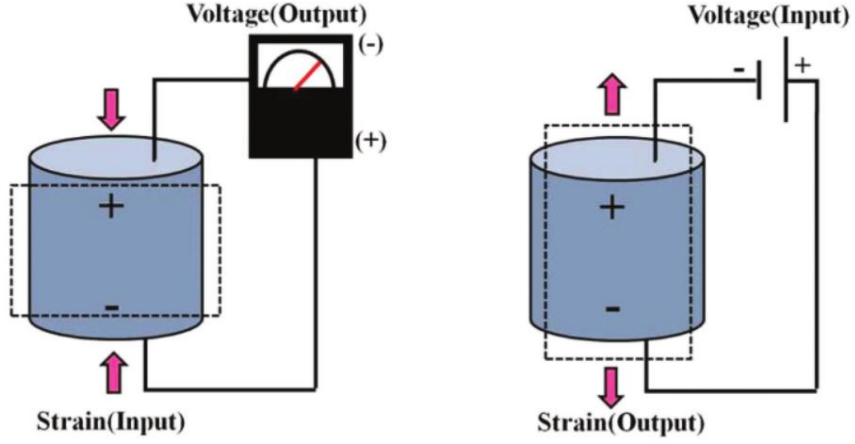


Figure 2.2 Direct and converse piezoelectric effect [30]

The output charge density from an impact and induced strain can be calculated using the electromechanical relationships for piezoelectric materials, as described in Equations (2.1) and (2.2) [32]:

$$D_i = d_{ijk}T_{jk} + \varepsilon_{ik}^T E_k \quad (1)$$

$$\begin{Bmatrix} D_x \\ D_y \\ D_z \end{Bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 & d_{25} & 0 \\ 0 & 0 & 0 & d_{24} & 0 & 0 \\ d_{31} & d_{32} & d_{33} & 0 & 0 & 0 \end{bmatrix} \begin{Bmatrix} T_{xx} \\ T_{yy} \\ T_{zz} \\ T_{yz} \\ T_{xz} \\ T_{xy} \end{Bmatrix} + \begin{bmatrix} \varepsilon_{11}^T & 0 & 0 \\ 0 & \varepsilon_{22}^T & 0 \\ 0 & 0 & \varepsilon_{33}^T \end{bmatrix} \begin{Bmatrix} E_x \\ E_y \\ E_z \end{Bmatrix}$$

$$S_{ij} = s_{ijk}^E T_{jk} + d_{ijk} E_k \quad (2)$$

$$\begin{Bmatrix} S_{xx} \\ S_{yy} \\ S_{zz} \\ S_{yz} \\ S_{xz} \\ S_{xy} \end{Bmatrix} = \begin{bmatrix} s_{11} & s_{12} & s_{13} & 0 & 0 & 0 \\ s_{12} & s_{22} & s_{23} & 0 & 0 & 0 \\ s_{13} & s_{23} & s_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & s_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & s_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & s_{66} \end{bmatrix} \begin{Bmatrix} T_{xx} \\ T_{yy} \\ T_{zz} \\ T_{yz} \\ T_{xz} \\ T_{xy} \end{Bmatrix} + \begin{bmatrix} 0 & 0 & d_{31} \\ 0 & 0 & d_{32} \\ 0 & 0 & d_{33} \\ 0 & d_{24} & 0 \\ d_{15} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{Bmatrix} E_x \\ E_y \\ E_z \end{Bmatrix}$$

In this context, T (Pa) represents the stress applied to the material, d (C/N) is the piezoelectric constant, and S denotes the strain resulting from the deformation. D (C/m²) and E (V/m) correspond to the electric displacement and electric field, respectively, while s^E (m²/N) is the mechanical compliance at a constant electric field E , and ε^T is

the material's permittivity at constant stress T . Identical to the Cartesian axes (x, y, z), the subscripts i, j , and k denote distinct directions inside the material's coordinate system and range from 1 to 3. A piezoelectric energy harvesting device primarily operates in two modes: mode 33, where the applied stress aligns with the direction of polarization (Figure 2.3a), and mode 31, where the applied stress is perpendicular to the polarization direction (Figure 2.3b) [33], [34].

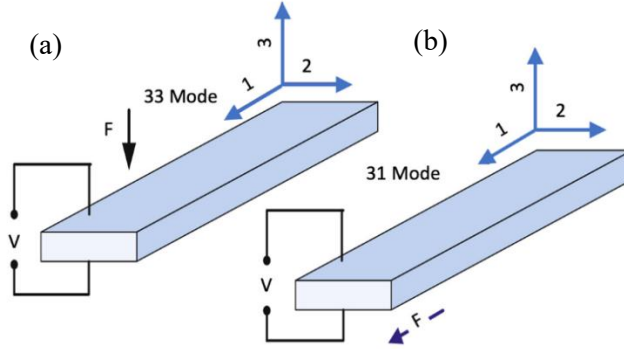


Figure 2.3 Operation modes of piezoelectric transducer (a) 33 mode (b) 31 mode [33].

Energy harvesting applications frequently employ a variety of piezoelectric materials, such as lead zirconate titanate (PZT), zinc oxide (ZnO), barium titanate (BaTiO_3), polyvinylidene fluoride (PVDF), aluminum nitride (AlN), PMN-PT ($\text{Pb}[\text{Mg}_{1/3}\text{Nb}_{2/3}]\text{O}_3\text{-PbTiO}_3$), PZN-PT ($\text{Pb}[\text{Zn}_{1/3}\text{Nb}_{2/3}]\text{O}_3\text{-PbTiO}_3$), and distinctive piezoelectric composites [35]. Table 2.1 provides a summary of these materials' characteristics.

Table 2.1 Piezoelectric Material Properties [36], [37], [38], [39], [40]

Properties	BaTiO ₃	PZT-4	PZT-5A	PZT-5H	PZT-8	PVDF	PMN-33%PT	PZN-6%PT
d_{31} (10^{-12} C/N)	78	-123	-171	-275	-97	-23	-920	-1,400
d_{33}	149	289	374	593	225	33	2200	2,400
d_{15}		496	584	741	330			
g_{31} (10^{-3} Vm/N)	5	-11.1	-11.4	-9.1	-11	216	-17.1	24.3
g_{33}	14.1	26.1	24.8	19.7	25.4	330	44	41.7
g_{15}		39.4	38.2	26.8	28.9			
k_{33}	0.48	0.7	0.71	0.75	0.64	0.15	0.93	0.9
Mechanical Q_M	300	500	75	65	1,000	3–10	69	

Dielectric loss	0.4%		2%		0.4%		0.42%	
Curie	115	328	365	193	300	100	145	100
Temperature (°C)								

The piezoelectric effect of ZnO and AlN is much weaker than that of the other materials mentioned. They are typically used in microscale thin-film configurations, where performance metrics differ from those of bulk materials. For this reason, their properties are not included in the comparison here [41]. As illustrated in Table 2.1, the piezoelectric constants follow the trend $d_{15} \gg d_{33} > d_{31}$, and for PZT, $d_{31} \approx 0.5 d_{33}$. PMN-PT and PZN-PT are examples of single crystals that possess the best piezoelectric characteristics; however, they are more vulnerable to changes in temperature, more prone to fatigue, and particularly challenging to create than lead zirconate titanate (PZT) [42]. Consequently, PZT remains the most widely used piezoelectric material in energy harvesters. Vatansever et al. conducted a study on raindrop energy harvesting utilizing a cantilever structure, where they compared two varieties of cantilever piezoelectric transducers: PVDF and PZT, both measuring $16 \text{ mm} \times 4 \text{ mm} \times 0.2 \text{ mm}$ [43]. When compared to PVDF-based materials, PZT, a ceramic piezoelectric material, often generates a higher voltage. However, because the mass of the water droplet was inadequate to efficiently trigger the PZT material, PZT produced a lower peak voltage than PVDF in raindrop applications. PZT's rigidity and fragility limit its application range, while PVDF offers several advantages, including lead-free, cost-effective, easy to process, lightweight, flexible, and smooth. When a 50 mg droplet of water fell from a height of one meter onto a $16 \text{ mm} \times 4 \text{ mm} \times 0.2 \text{ mm}$ unimorph cantilever, the PVDF cantilever produced a peak voltage of 12 V, whereas PZT only produced 3 V [44].

2.2 Harvesting Energy from Water

Energy harvesting can be achieved through water dynamics, where the mechanical energy of water such as kinetic and gravitational potential energy is converted into usable forms like electricity [45]. Some devices that may be utilized for energy generation or storage are depicted in Figure 2.4.

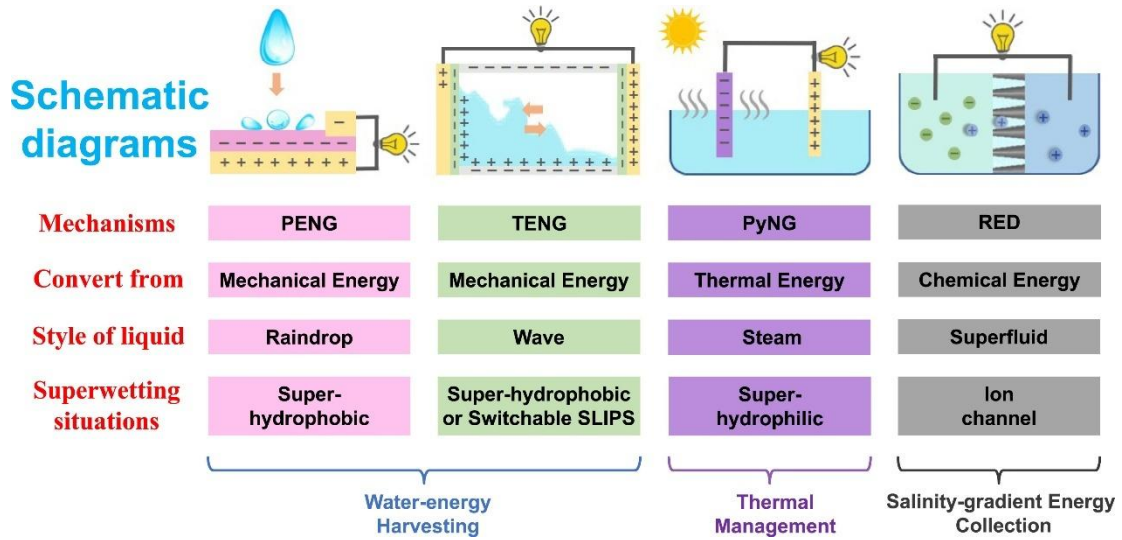


Figure 2.4 Energy conversion methods using water include PENG (piezoelectric nanogenerator), TENG (triboelectric nanogenerator), PyNG (pyroelectric nanogenerator), and RED (reverse electrodialysis) [46].

Those materials are effective for harvesting significant energy from water sources. Converting raindrop energy to electricity is typically done with piezoelectric materials such as polyvinylidene fluoride (PVDF), lead zirconate titanate (PZT), or ZnO, using a piezoelectric cantilever beam or bridge impacted by raindrops [47]. Farhangdoust et al. proposed a metasurface membrane attached to the top side of the PVDF to overcome the low efficiency of PENG when it is used to harvest raindrop energy. It was shown that the sum of the axial and lateral stress tensors for the PVDF employing metasurface membrane (1.56 MPa) is larger than the PVDF attached plain membrane (1.42 MPa), which is a proof of concept for performance improvement. In other words, stress deformation (mechanical energy) transferred to the PVDF layer will be greater, therefore the power output will be enhanced compared to an equivalent conventional PENG-attached plain membrane [48], [49]. This concept will be adopted and considered in this study.

Elastic electroactive materials, such as dielectric elastomers with high friction, are frequently employed in energy harvesting applications as well. Zaltariov et al. investigated the effects of rubber-based wave energy harvesters in marine environments as well as the durability of both synthetic and natural rubbers in seawater.

Their findings indicate that most rubber harvesters remain stable in seawater and are unlikely to negatively affect microorganisms [50]. Observing that increasing hydrophobicity might improve electrical output, Li et al. created a high-friction polypropylene (PP) film coating on an electrode [51]. For pyroelectric materials, thermodynamics induced by water behavior can also be leveraged for electricity generation. In recent years, solar steam generation, originally used for water purification, has emerged as a promising approach for designing steam-based electric power systems using pyroelectric materials [52], [53]. Additionally, researchers have generated electricity from salinity-gradient energy via reverse electrodialysis (RED). A net current is created when a selectively ion-permeable membrane connects two solutions varying in salinity. Only ions with opposing charges are able to flow across this membrane [54]. In this study, raindrop mechanical energy will be utilized by the PENG mechanism to generate electricity. A new metasurface membrane will be employed to enhance the generated power and efficiency of the PENG.

2.2.1 Raindrop Energy Harvesting

Raindrop energy harvesting (REH) has attracted increasing research interest in recent years, though its full potential remains fully unlocked. This study focuses on REH, a promising approach given that many regions experience moderate to heavy rainfall, which could be harnessed as an alternative to existing and widely used renewable energy sources. While energy output from such systems is lower compared to other renewable methods, it can be sufficient to charge specialized low-power devices in applications where battery replacement is impractical. Additionally, battery-free solutions are becoming more common due to concerns about size, weight, environmental impact, and battery longevity. Emerging technologies that incorporate energy harvesting techniques embrace wireless microsensor networks and MEMS (microelectromechanical systems) as an option [55], [56].

2.2.2 Types of Rain

Warm, humid air rises, cools and condenses form liquid droplets to produce rain and other types of precipitation. A number of variables, including temperature, humidity, and atmospheric pressure, can affect this mechanism [57]. Rainfall can generally be classified as either convective or stratiform. Convective rainfall primarily takes place in the area near the equator, where ground moisture is heated above the temperature of surrounding areas, increasing evaporation. As the water vapor rises, it condenses to form clouds, which can then produce rain [58]. According to the NASA website, rain is categorized into 4 types: light stratiform rain (LSR), moderate stratiform rain (MSR), heavy thunderstorms (HT) and Violent [59]. Table 2.2 shows some measured and typical raindrop size and velocity statistics.

Table 2.2 Types of rain [59].

Type of Rain	Rate [11]	Drop Size (mm) [4]	Terminal Velocity (m/s) [45]
Light Rain	2 – 4 mm/h	2	6.49
Moderate Rain	5 – 9 mm/h	2.5	7.57
Heavy Rain	10 – 40 mm/h	5	9.09 – 10
Violent	> 50 mm/h	N/A	N/A

2.2.3 Impact of Droplet Parameters on the Generated Energy

Several factors influence the output of a raindrop energy harvesting (REH) device, with the key parameters being the volumetric size, mass, and impact velocity of the droplets. A raindrop in free fall experiences two vertically acting forces: an upward drag force and a downward gravitational force, which accounts for the droplet's weight. The drag force acting on the droplet is described by Equation (3), where ρ_a is the air density, A is the droplet's projected frontal area, v is the velocity of the droplet and C is the coefficient of drag [60].

$$F_{air} = \frac{1}{2} \rho_a A C v^2 \quad (3)$$

The droplet's weight is represented by Equation (2), where ρ_w denotes the water droplet's density, r represents the radius of the droplet, and g is the acceleration due to gravity [60].

$$F_{gravity} = \frac{4}{3}\pi r^3 \rho_w g \quad (4)$$

When these forces are in equilibrium, the water droplet attains its terminal velocity, v_t , which is the maximum speed it can reach if no other forces act on it. The impact velocity of the raindrop is influenced by both the height from which it falls, H and its diameter, D . For a droplet with a diameter of D , the falling velocity increases with height until it reaches a threshold of 20 m, beyond which it becomes constant, referred to as the rainfall terminal velocity, expressed in m/s. This relationship is represented in Equation (5), where d indicates the diameter of the droplet [60].

$$v_t = \sqrt{\frac{\pi d^3 \rho_w g}{6 \rho_a A C}} \quad (5)$$

The spherical shape of all raindrops is assumed in this investigation. In actuality, this can change depending on air resistance and the kind of rain shower. Most laboratory experiments using standard burette or pipette setups typically produce droplets with diameters ranging from 0.5 mm to 2 mm, within which the droplets maintain a spherical shape. However, as the diameter of the droplet increases, its shape can change due to wind speed and air resistance [61]. Nonetheless, this aspect is not addressed in this study.

2.2.4 Raindrop Impact Mechanism

Another important factor that has a big impact on the harvesting device's power output and energy transfer function is the impact mechanism. In general, there are three primary categories into which droplet impacts on solid surfaces can be divided: 1) bouncing, 2) spreading, and 3) splashing. A water droplet can either bounce completely, leaving the surface without any remains, as illustrated in Figure 2.5a, or partially bounce, leaving some water behind, as shown in Figure 2.5b. In the spreading category, the droplet adheres to the surface upon impact, as can be seen in Figure 2.5c. The

splashing category occurs when the droplet breaks apart and spreads over the surface, as shown in Figure 2.5d. It is expected that a droplet's influence on a harvesting device will show one or more of these mechanisms. Research has documented these categories of droplet impact behaviors on solid surfaces [62], [63].

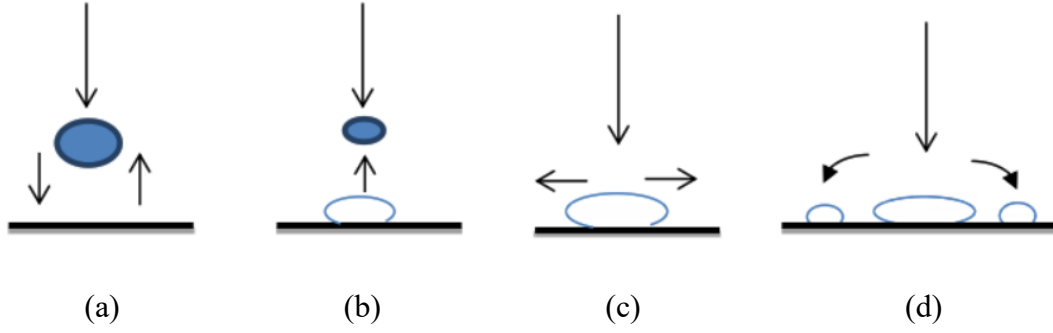


Figure 2.5 A water droplet's effect on a solid surface (a) Rebound (b) Partial rebound (c) Spreading (c) Splashing [60].

According to several studies, splashing is the primary impact mechanism of a water droplet [64]. Stow et al. [65] and Mundo et al. [66] have derived an empirical relation, expressed in Equation (6), based on experiments. In this formula, Re represents the Reynolds number (a dimensionless value expressing the proportion of inertial and viscous forces), We is the Weber number (a dimensionless factor indicating the significance of fluid inertia as opposed to surface tension), and K is characterized as a constant (varying based on the solid surface's roughness and the layer's thickness) [60].

$$K = We^{1/2} + Re^{1/4} \quad (6)$$

Reynolds and Weber numbers are determined using Equation (7) provided below, where ρ_w represents the fluid density, μ_a is the viscosity, σ is the fluid's surface tension, and v denotes the velocity [60].

$$Re = \frac{\rho_w v d}{\mu_a}; We = \frac{\rho_w v^2 d}{\sigma} \quad (7)$$

This study's objective was to gain insight into how a piezoelectric energy harvester device can turn the kinetic energy of water droplets and transfer the vibrational and impact energy of the device to electrical energy. As the droplet descended from rest, it

accelerated along a trajectory, progressively gaining velocity. Equation (8) then shows the relationship between the droplet's kinetic energy, velocity, and size [60].

$$E_{KE} = \frac{1}{2} \rho_w \left(\frac{4}{3} \pi \left(\frac{d}{2} \right)^3 \right) v^2 \quad (8)$$

Even with optimal harvesting, it will not be expected that the raindrop energy harvester can extract all of this energy. However, we still can manage to enhance the harnessing of raindrops' energy potential by employing a metasurface attached to the PENG.

2.3 Metamaterial-Inspired Membrane

Established piezoelectric sensors often face sensitivity constraints due to their inherent inability to expand [67]. To improve mechanical flexibility and stretchability, there is a rapid growth in the use of metamaterial-inspired membranes for piezoelectric devices [68], [69]. Metamaterials are artificial structures that exhibit unique mechanical features related to capturing energy, mass, density, deformation, static modulus, smart functionality, and negative Poisson's ratio (NPR) [69]. Over the past decade, there has been significant interest in employing metamaterials in one-dimensional (1D), two-dimensional (2D), and three-dimensional (3D) structures, including lenses, photonic crystals for light manipulation, and soft acoustic metamaterials [70], [71], [72]. Poisson's ratio defines the relationship between transverse and longitudinal strain in a material, and NPR behavior has been observed in auxetic materials, which expand (or contract) in the transverse direction when stretched (or compressed), in contrast to conventional materials, as illustrated in Figure 2.6 [73].

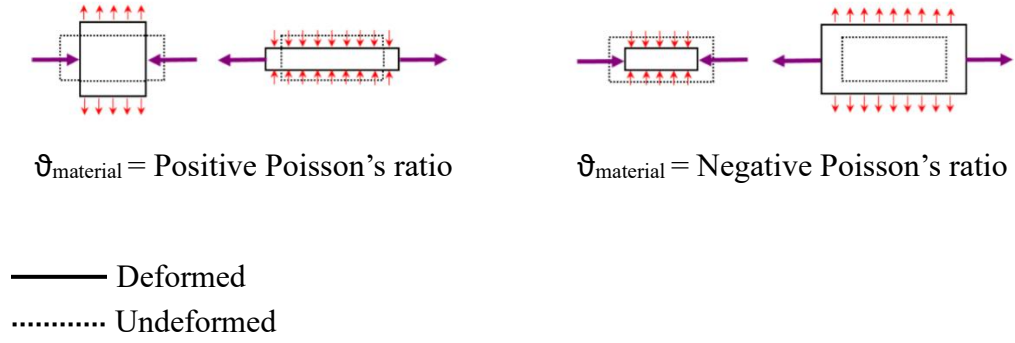


Figure 2.6 Schematic representation of the deformed and undeformed states of conventional materials (left) and metamaterials (right) [73].

Such auxetic behavior is observed in uniaxial kirigami patterns [74]. Designs based on auxetic characteristics for flexible membranes and substrates are gaining popularity in the creation of the next generation of piezoelectric sensors and harvesters with outstanding performance. Hu et al. conducted an experimental investigation of uniaxial kirigami patterns to enhance the stretchability and compliance of piezoelectric materials [75]. They used kirigami techniques to enhance the capabilities of PVDF piezoelectric materials as sources of energy for portable and implantable devices. Recently, a range of flexible and stretchable devices have been manufactured for applications such as energy harvesting, self-power generation, spatiotemporal cardiac measures, finger-tracking motion, high-strain sensors, and wearable electronic devices [76].

2.3.1. Metastructures and Metamaterials Inspired by Kirigami

The term "kirigami" refers to the ancient Chinese and Japanese art of paper cutting, which dates back approximately fifteen centuries [77], [78], [79]. Kirigami is a technique employed to create (meta)materials and (meta)structures with remarkable properties, such as a negative Poisson's ratio [80]. A material or structure is changed into a metamaterial or metastructure by this method, displaying properties that were absent from the original material or structure. Kirigami metastructures, known for their exceptional flexibility and stretchability, have been utilized to manufacture macro and micro materials, devices, structures, and systems [81].

For example, the development of mechanical metamaterials that can transform single-layer graphene sheets into deformable components with microscale dimensions and improve graphene's ductility were the objectives of the introduction of kirigami graphene [82], [83]. Since then, kirigami has created new opportunities for graphene research and uses. Cut-only kirigami and cut-and-fold kirigami are the two primary types of kirigami patterns. As shown in Figure 2.7, this overview divides these categories into five categories of kirigami objects: fractal-cut kirigami, ribbon kirigami, lattice kirigami, zigzag kirigami, and closed-loop kirigami [84].

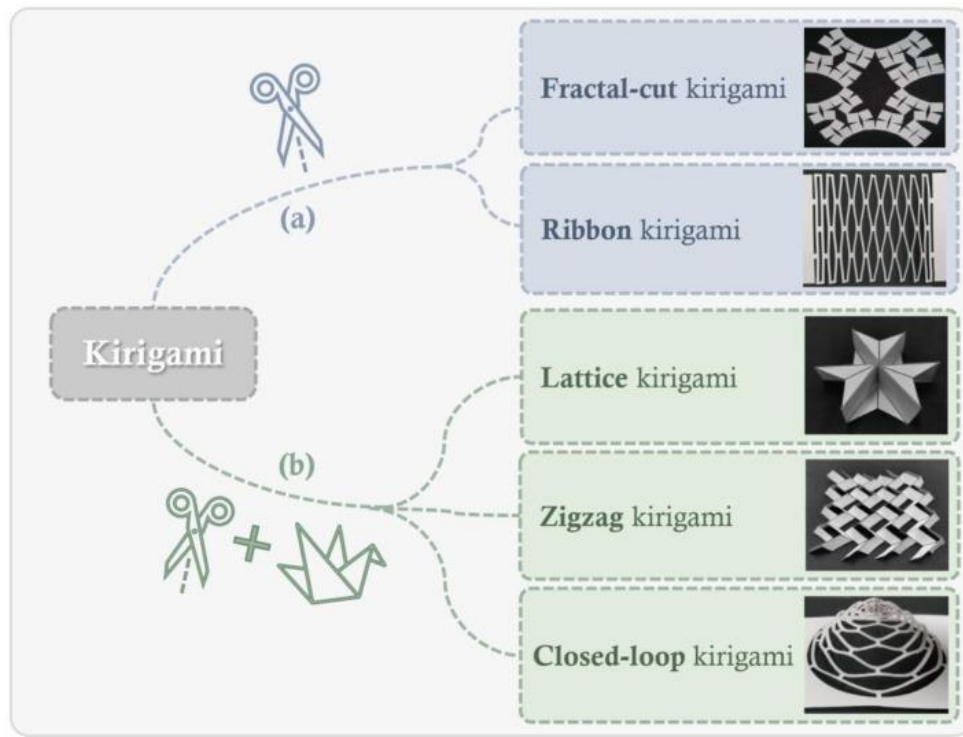
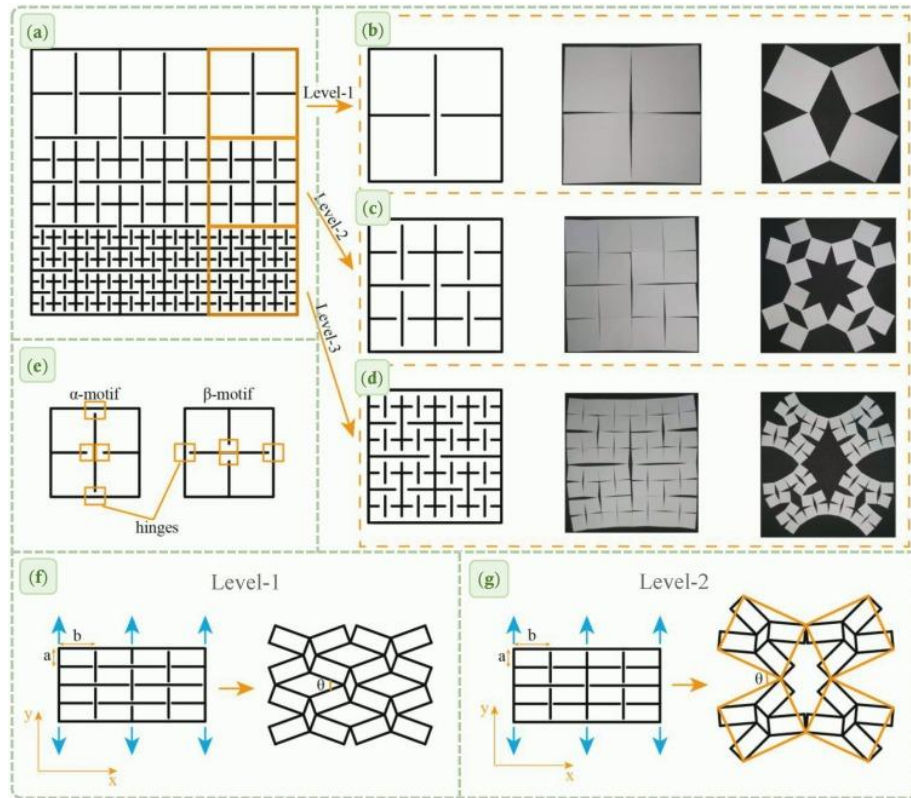


Figure 2.7 A general category of kirigami structures is created through (a) cutting only and (b) cutting and folding [84].

a. Fractal-Cut Kirigami

Cutting-only kirigami techniques are commonly used to produce 2D materials and designs with increased elasticity. Two types of cut-only kirigami patterns can be distinguished: one uses a technique known as "fractal cut" [85] to produce spinning units, while another approach cuts the paper into strips to produce a curved unit. Both

approaches can achieve large strains that the original material cannot attain through external tension or compression. The fractal cut approach enables a sheet to conform to a wide range of graphic boundaries, including 2D and 3D shapes, as observed by Cho et al. [85]. The rotating units produced by hierarchical cut patterns take the form of polygons, as shown in Figure 2.8 (a) – (d). For instance, a square can be hierarchically cut into square rotating units that are connected by hinges, while a hexagon can be similarly cut into triangles. Due to its hierarchical cutting technique, fractal-cut kirigami exhibits exceptional fitting capability and stretchability. The maximum possible lateral strains for the level-1 and level-2 structures, using the square hierarchical cutting as an example, are 43% and 62%, respectively.



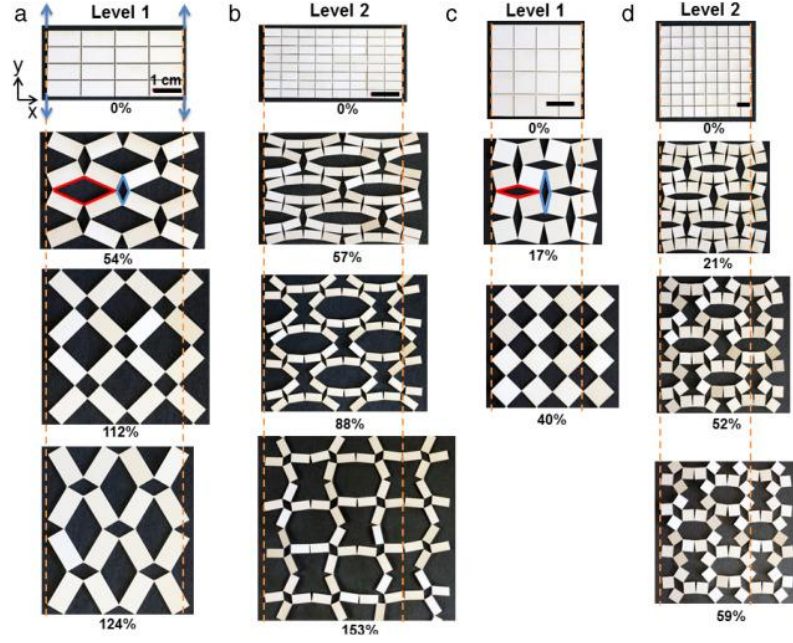


Figure 2.8 (a) A fractal cut pattern featuring square units. (b-d) Examples of square fractal cutting at (b) level-1, (c) level-2, and (d) level-3, with the black lines representing the cut lines. (e) Two motifs of level-1 cutting. (f & g) Deformation of (f) level-1 and (g) level-2 rectangular fractal cut kirigami structures after being stretched in the y-direction [84].

To forecast the tensile characteristics and Poisson's ratio of kirigami metamaterials, a geometric model was created. The nominal stresses in the x and y dimensions for level-1 structures are represented as ε_x^{Lvl-1} and ε_y^{Lvl-1} , along with the Poisson's ratio ν^{Lvl-1} , can be expressed as follows [84]:

$$\varepsilon_x^{Lvl-1} = \cos\left(\frac{\theta}{2}\right) + \frac{1}{m} \sin\left(\frac{\theta}{2}\right) - 1 \quad (9)$$

$$\varepsilon_y^{Lvl-1} = \cos\left(\frac{\theta}{2}\right) + m \sin\left(\frac{\theta}{2}\right) - 1 \quad (10)$$

$$\nu^{Lvl-1} = -\frac{d\varepsilon_x^{Lvl-1}}{d\varepsilon_y^{Lvl-1}} = -\frac{d\varepsilon_x^{Lvl-1}/d\theta}{d\varepsilon_y^{Lvl-1}/d\theta} = \frac{\cos(\theta/2)/m - \sin(\theta/2)}{m\cos(\theta/2) - \sin(\theta/2)} \quad (11)$$

where $m = a/b$ represents the aspect ratio of the rectangle, with a and b denoting the width and length, respectively. In Equations (9) – (11), θ refers to the expansion angle, as shown in Figures 2.8 (f)–(g). The equation for the level-2 structure is identical to that of the level-1 structure even though the geometric model treats the level-1 cut

structure unit as a rectangle. It is important to remember that the level-1 and level-2 structures' rotation angles θ are unrelated to each other [84].

b. Ribbon Kirigami

The ribbon pattern is another cut-only kirigami design that was first created to improve graphene's ductility. The graphene kirigami tensioning technique was divided into four phases by Qi et al. [86], with the tensile stress applied perpendicular to the length of the ribbon. First, when the tensile deformation is minimal, the ribbon rotates around the hinge, creating out-of-plane distortion without inducing any stress, as the material itself is not stretched. In the second stage, as tensile deformation increases, the material leads to the overall deformation, leading to a rise in stress within the ribbon, with the greatest stress and strain occurring at the hinge. In the third stage, further tensile deformation results in the kirigami structure yielding because of stress accumulation at the hinges. Finally, in the last stage, the structure suffers damage from the tearing of the hinges. This entire process is illustrated in Figures 2.9 (a)–(d) [84].

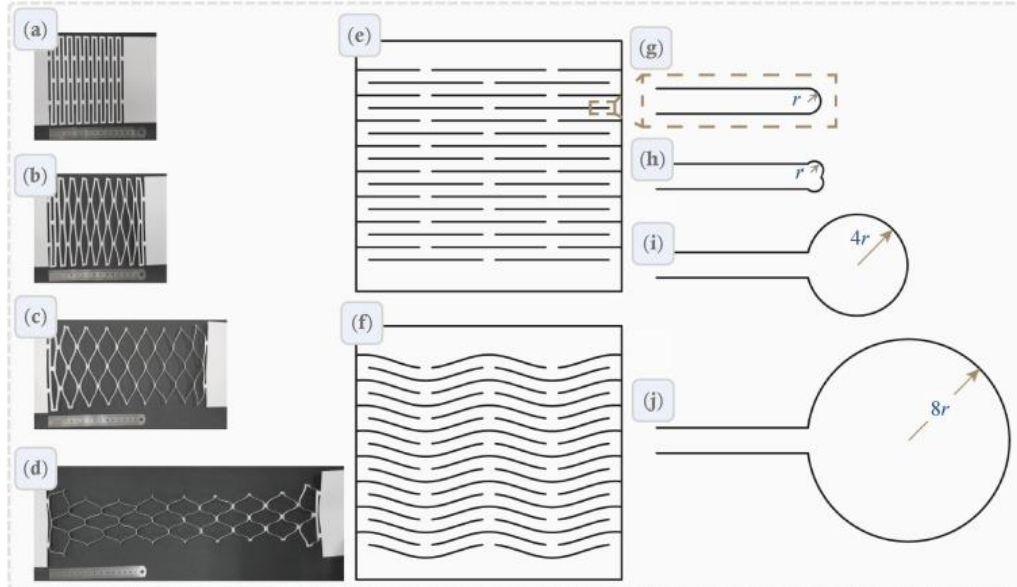


Figure 2.9 Ribbon kirigami. Parts (a)–(d) Illustrate the stretching process of ribbon kirigami. (e) Straight cuts. (f) Curved cuts. Figures (g)–(j) present four types of hinges, which include (g) standard U-shaped cut hinges, (h) dog-bone-shaped cut hinges, (i) $4r$ circular hinges, and (j) $8r$ circular hinges [84].

According to other experimental research [87], kirigami structures made by straight-cutting and curve-cutting have similar stretchability, with the curve-cut kirigami's tensile strain limit slightly increasing. For instance, Figure 2.9 (e) depicts a straight-cut pattern, whereas Figure 2.9 (f) shows a curve-cut pattern. In order to evaluate the effect of the radius on strain energy loss, Chen et al. [87] used circular incisions at both ends of the slit, as seen in Figures 2.9 (i)–(j). When stretching, the existence of these circular gaps reduces plastic deformation at the hinge, resulting in strain energy loss proportional to the circles' radius. Furthermore, Hwang et al. [88] doubled the ultimate tensile strain and increased elasticity by a factor of 30 by making orthogonal small cuts at both ends of the slit. In summary, the ribbon kirigami structure significantly enhances the material's elasticity while being simple to manufacture, making it appropriate for a wide range of uses with different kinds of materials and constructions. Graphene materials were initially used to employ ribbon kirigami [89], [90], [91], but it has been used in a variety of other materials, including carbon nanotubes [92], shape memory alloys [93], monolayer MoS₂ [94], MnO₂ nanowire composites [95], and metallic glasses [96], [97]. Furthermore, the design and construction of energy and health equipment have made extensive use of ribbon kirigami structures.

c. Lattice Kirigami

The kirigami design that incorporates both cutting and folding represents an innovative strategy in the realm of 3D nanomanufacturing. Folding serves as a pivotal mechanism for transforming two-dimensional sheets into three-dimensional structures. In this process, specific sections of the kirigami design are excised, followed by folding to reassemble the missing components, resulting in a cohesive 3D form [98]. Castle et al. [99] introduced the concept of lattice kirigami, which involves intentionally introducing defects into the sheets by cutting and removing (or adding) wedges [100]. This method allows for the creation of dislocations or disclinations that facilitate the formation of intricate 3D configurations. Presently, the majority of research on lattice kirigami is concentrated on honeycomb (triangular) lattice structures [99], [101]. Castle et al. [99] demonstrated this by removing wedges from a hexagonal lattice to create

pairs of 5–7 and 2–4 dislocations, as illustrated in Figures 2.10 (a) and (b). Moreover, they offered climb cut and glide cut concepts, depicted in Figures 2.10 (c) and (d), wherein the kirigami patterns are all derived from 5–7 dislocation pairs. Building upon the bistable characteristics of the 2–4 dislocation pairs, Sussman et al. [101] further advanced this field by introducing a multifunctional lattice kirigami, where the fundamental unit consists of six hexagons encircling an excised hexagon, as shown in Figure 2.10 (e).

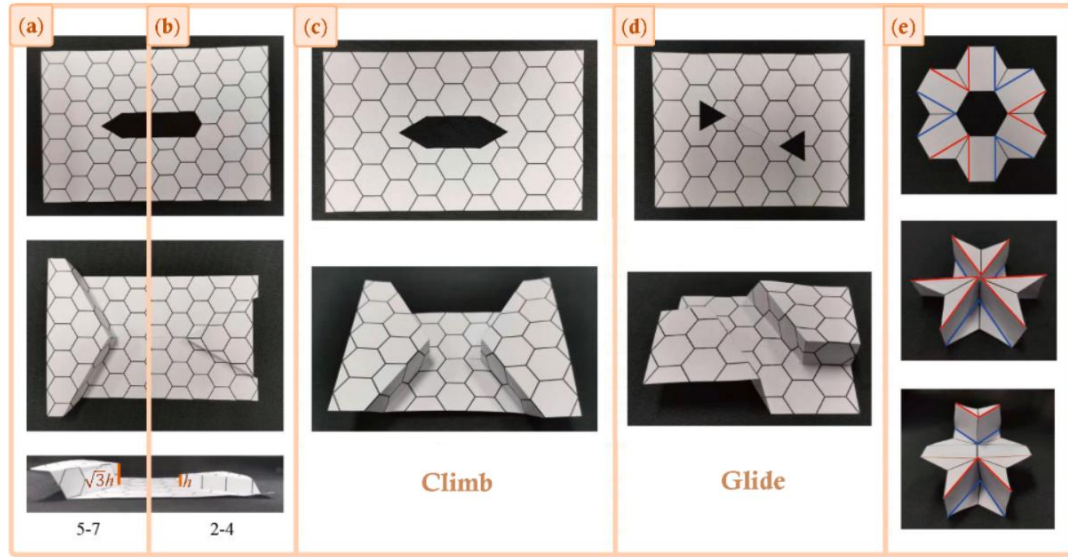


Figure 2.10 Lattice Kirigami: Two methods for wedge block removal: (a) a 5–7 dislocation pair and (b) a 2–4 dislocation pair. (c) Pure Climb Cut: The gap is sealed through folding, with no relative sliding between the slits. (d) Pure Glide Cut: The gap is closed by folding, accompanied by relative sliding between the slits. (e) “Sixon”: Six hexagons encircle a cut hexagon, forming upward or downward steps by folding along the mountain (red) or valley (blue) creases [84].

d. Zigzag Kirigami

The folding configuration of zigzag kirigami is influenced by the traditional origami design known as Miura-ori, which exhibits advantageous traits such as a negative Poisson’s ratio [102] and rigid folding capabilities [103]. Drawing inspiration from Miura-ori, Eidini et al. [104] integrated two single-degree-of-freedom (DOF) zigzag strips that share identical kinematic properties but differ in unit scale, resulting in the development of a novel kirigami metamaterial. Each unit cell within the zigzag

strip features a perforation, where an n-folded version of the smaller Miura strip is equivalent to a large-scale Miura strip. Thus, the BCHn (Basic Cell with Hole) unit cell is the name given to this zigzag kirigami unit cell. The mechanical properties of the zigzag kirigami have been examined, with particular attention focused to the out-of-plane bending and twisting behaviors and the in-plane Poisson's ratio. Figure 2.11 (a) shows the BCHn unit cell's parameter representation. The in-plane Poisson's ratio for the practically infinite BCH2 for the zigzag kirigami configuration with $n = 2$ is as follows [104]:

$$\nu_{\infty} = -\tan^2 \phi \frac{4\lambda \cos \alpha - \cos^2 \phi}{4\lambda \cos \alpha + \cos^2 \phi} \quad (9)$$

where $\lambda = a/b$, and ϕ represents the angle in the xy plane between edge b and the x-axis [104]. Additionally, Eidini et al. [105] introduced a displaced zigzag strip kirigami design inspired by the Miura-ori. The unit cell of the displaced zigzag strip is illustrated in Figure 2.11 (b).

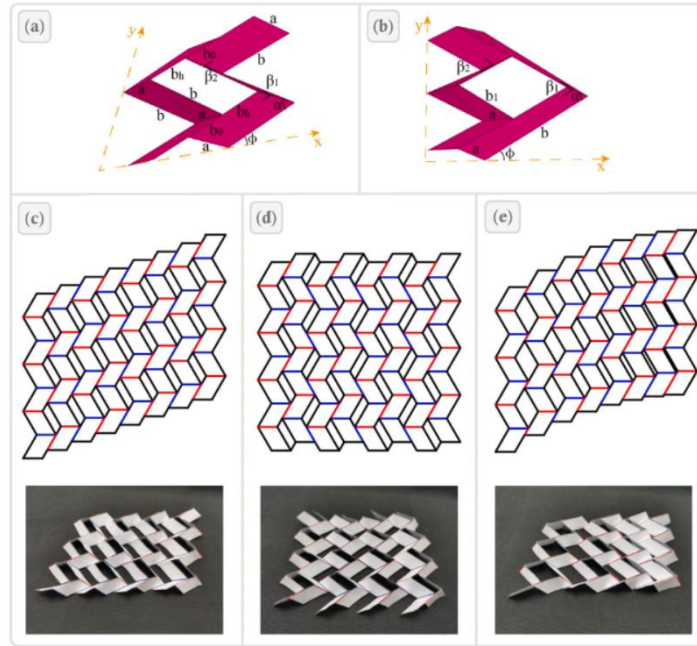


Figure 2.11 Zigzag kirigami. (a) The geometry of the ZCH pattern unit cell. (b) The geometry of the BCH2 pattern unit cell. Adjacent zigzag bars are offset in the same direction to create (c), while two sets of adjacent zigzag bars are displaced upward and downward to produce (d). The distance of the dislocation is varied to form (e) [84].

There are two methods for dislocating zigzag strips. The first involves misaligning two sets of adjacent zigzag strips in opposite directions, resulting in the kirigami structure depicted in Figure 2.12 (d). In the second way, the structure seen in Figure 2.12 (c) is formed by neighboring zigzag strips that are misaligned in the same direction. Furthermore, as shown in Figure 2.12 (e), changes in the geometric parameters of the parallelogram voids produced by the dislocation also affect the zigzag kirigami's pattern and folding. For the roughly infinite ZCH (Zigzag unit Cell with Hole), the in-plane Poisson's ratio is written as follows [105]:

$$\nu_{\infty} = -\tan^2 \phi \frac{a \cos \alpha - b_h \cos^2 \phi}{a \cos \alpha + b_h \cos^2 \phi} \quad (10)$$

The rigid folding, stackability, and negative Poisson's ratio of the Miura-ori are all preserved in the ZCH kirigami. The zigzag kirigami's inclusion of holes reduces density and improves programmability. Compared to the Miura-ori, these characteristics give it a wider range of possible applications.

e. Closed-Loop Kirigami

Through the use of cutting and external inputs, kirigami techniques can enable folding, bending, and twisting at the nanoscale, overcoming the limitations of micro 3D manufacturing. Liu et al. [106] presented a pinwheel-like pattern with notable optical chirality in 2018 that was inspired by kirigami. This nano-kirigami begins by creating four rotationally symmetric slits on a two-dimensional gold film sheet, referred to as closed-loop nano-kirigami, as depicted in Figure 2.12. Following this, the gold film is subjected to irradiation from a globally programmable ion beam. The sputtering of gold atoms and the implantation of gallium atoms induce tensile and compressive stresses in the gold film, respectively. These opposing stresses along the thickness of the gold film cause it to bend towards the direction of irradiation (see Figure 2.12 (b)). Liu et al. [106] developed a comprehensive mechanical model to accurately represent the nano-kirigami structure, demonstrating its predictive capability through experimental validation and numerical simulations. This model features a topology similar to pinwheel patterns, incorporating multiple Fibonacci

spirals (see Figure 2.12 (c)) and a concentric arc structure (see Figure 2.12 (a)). A distinctive aspect of this closed-loop system is that the components within the loop exert mutual influence and constraints when subjected to folding, bending, or twisting. There is encouraging potential for using closed-loop nano-kirigami in mechanical and optical devices, as well as in electromagnetic components.

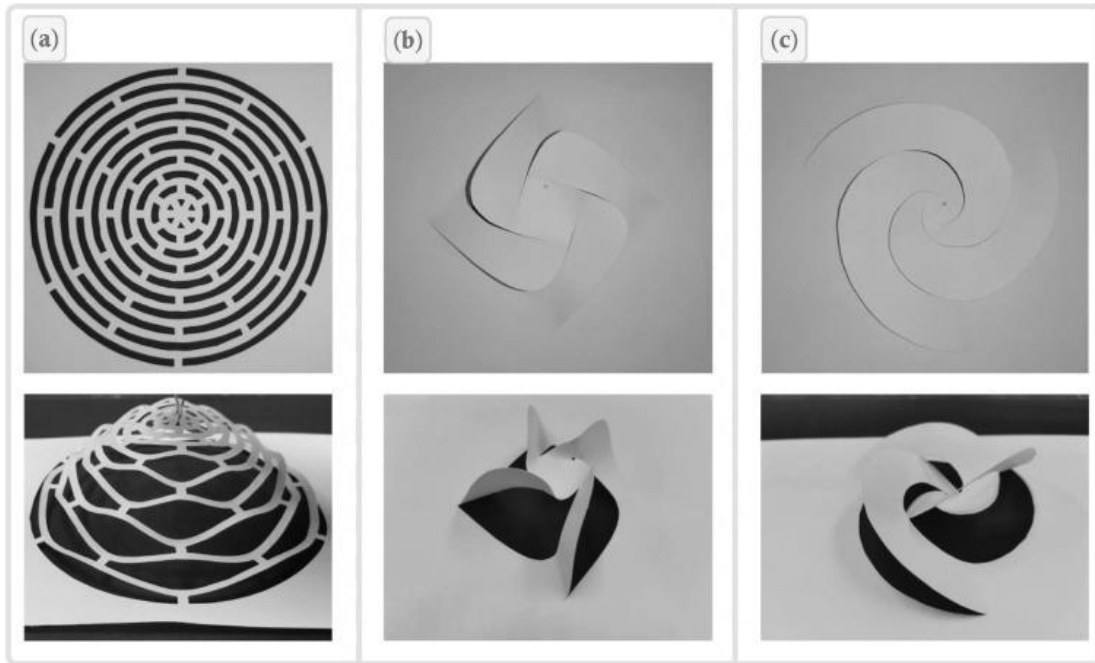


Figure 2.12 Closed-loop kirigami: (a) Structure of a concentrated arc. (b) A pinwheel-like structure with C4 symmetry. (c) Merged several structures of the Fibonacci spiral [84].

Five categories of kirigami patterns were used to summarize the most recent advancements in the discipline. The discontinuous phase transition of the kirigami shell, hinge design, two fractal cutting techniques, ductility of square cutting, and porous square cutting were all covered in relation to the fractal-cut kirigami. One of the kirigami patterns with exceptional ductility and ease of formation is fractal-cut. It is possible to expand the square fractal-cut kirigami sheet to 800% of its initial size [74]. Therefore, the kirigami design has the potential to enhance the voltage output of the raindrop energy harvester by increasing the membrane's stretchability, allowing it to more effectively transfer mechanical energy to the piezoelectric material (PVDF).

The following subsection will provide an overview of the research investigating the effects of using kirigami designs in the context of raindrop energy harvesting.

2.4 Development of a Piezoelectric Raindrop Energy Harvester Using the Kirigami Design

Current research investigates various aspects of the harvester, including the optimization of material selection, the design of flexible membranes, and the integration of structures such as kirigami patterns. These design elements aim to increase the system's efficiency by enhancing the energy capture capability and the piezoelectric response of the materials used. There are several types of research which employ the kirigami pattern in their work. In order to create effective and structurally flexible thin-film energy generators, Hu et al. [107] patterned piezoelectric material. They incorporated interdigitated cuts into polyvinylidene fluoride (PVDF) films to assess their impact on voltage generation and stretchability, as illustrated in Figures 2.13 (a) – (c). The fundamental idea is that significant energy generation can be achieved while extending the strain range of piezoelectric structures using kirigami techniques. The researchers anticipate that the tunability inherent in kirigami designs can be harnessed for the development of multifunctional piezoelectric devices, including applications in the biomedical field.

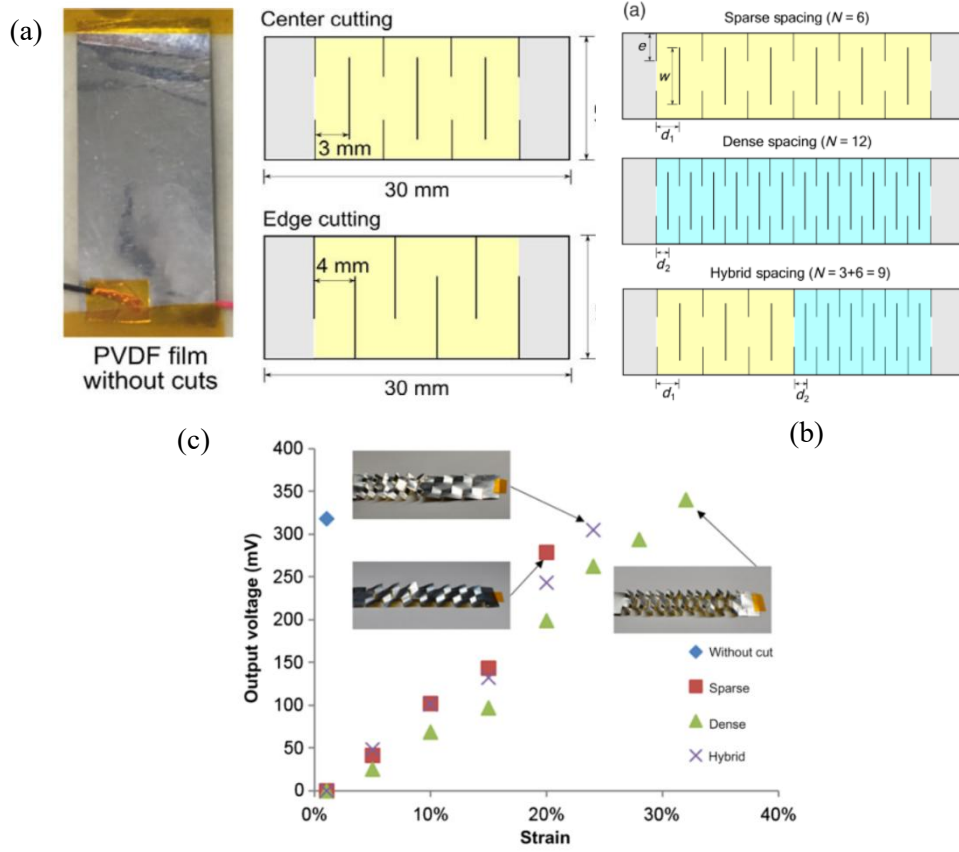


Figure 2.13 (a) Original PVDF film absence of kirigami patterns and cuts (a) Designs for patterns (c) Measured strain and voltage output for various cutting patterns. Inset: stretched kirigami PVDF film in a distorted configuration [107].

All three films are of equal dimensions, measuring 60 mm in length and 15 mm in width. The first sample features cuts spaced 2 mm apart, while the second has cuts spaced 4 mm apart. The third film is a mixture, incorporating 2 mm spacings in one section and 4 mm in another. In the sparse configuration, the film's performance is constrained by stress distribution around the sharp corners, resulting in reduced stress across various areas of the film's surface. Conversely, the denser configuration exhibits increased stress in other regions, which contributes of enhancing generated voltage. Among the tested patterns, the dense design, characterized by the highest an abundance of cuts and sharp corners, yields the greatest voltage production at 333 mV, suggesting a potential correlation between these two factors [107].

Farhangdoust et al. [73] employed finite element analysis to explore the stretchability characteristics of MetaMems (metamaterial-inspired membranes) and to examine their impact on the polarization of PVDF as well as the sensitivity of the sensor. They developed two designs of MetaMems, featuring kirigami and honeycomb geometries, as illustrated in Figure 2.14. Their objective was to create a MetaMems pressure sensor (MPS) that serves as a highly sensitive alternative to conventional pressure sensors (CPS). According to the results of both theoretical studies and numerical simulations, the suggested MetaMems greatly increase the sensitivity of pressure sensors, with sensitivity gains of up to 3.8 times when compared to a comparable traditional sensor that uses a plain membrane.

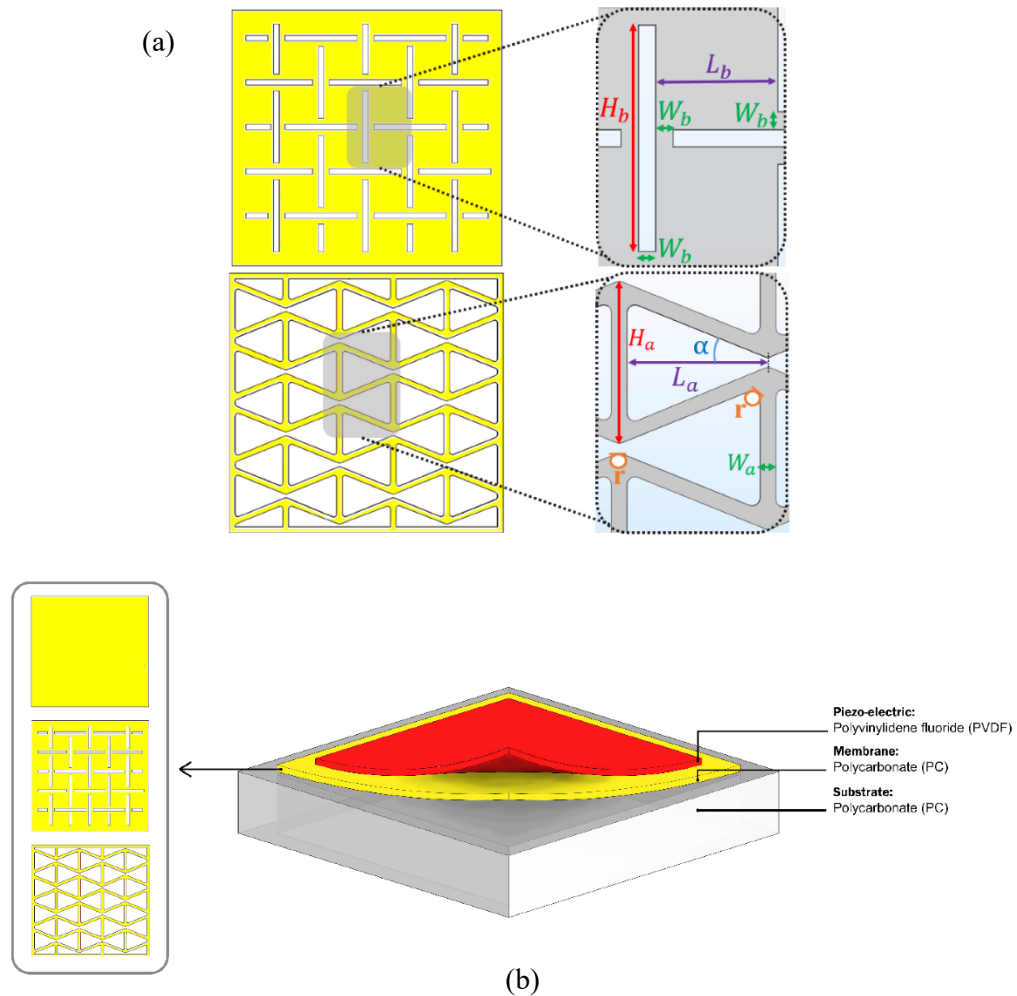


Figure 2.14 (a) Feature of the two MetaMem models; kirigami (top), hexagonal (bottom) (b) Scheme of MetaMems placement in the pressure sensor [73].

When exposed to bending movements, the auxetic hexagonal and kirigami MetaMems pressure sensors (MPSs) sensitivity gains factors increased to 3.8 and 1.3, respectively, in comparison to conventional pressure sensors (CPS). The inherent properties of the auxetic hexagonal and kirigami honeycombs allow for superior stretching capabilities in the MetaMems, resulting in greater flexural deformation compared to the flat membrane. Additionally, Table 2.3 consolidates information regarding the generator materials, research contributions, output power, and authors associated with studies on raindrop energy harvesting. This table aims to provide relevant data for comparative analysis, while further details of each investigation can be found in the respective manuscripts.

Table 2.3 Summary of various raindrop energy harvesting by using piezoelectric material.

Authors	Material	Contribution	Output Voltage	Year of Publication	Ref.
Guigon et al.	PVDF	Carrying out three tests to look at how the output voltage is affected by the water droplet's dimension and the PVDF piezoelectric's thickness.	25 μm thickness generates 3V	2008	[108]
Grinspan et al.	PVDF	Examined the output voltage on various masses of the liquid droplet	92.94 mV at 2.96 m/s velocity	2010	[109]
Morrison et al.	PVDF	Comparing the water droplet and flow form's output voltages	$\approx 2.38 \mu V$	2015	[110]
Wong et al.	PVDF	Comparing the generated voltage of bridge configuration and cantilever configuration	3.5 V & 1V	2015	[44]
Ilyas et al.	PVDF	Using a cantilever design to capture energy from the raindrop's impact	3.75 V	2015	[60]
Chee et al.	PVDF	Considered use of the synchronized drop time of the single water droplet to investigate a multi-harvester array.	1.87 V	2016	[111]
Wong et al.	PVDF	Raindrop energy harvesting experimental of cantilever and bridge transducers through different parameters such as release heights, droplet diameters, and dimensions of PVDF transducer	2.45 V	2017	[112]
Hu et al.	PVDF	Polyvinylidene fluoride (PVDF) films are cut employing kirigami	333 mV	2018	[107]

		to assess the impact on stretchability and voltage generation.			
Kim et al.	PVDF	Developed a high-performance kirigami piezoelectric strain sensor	2.23 V	2022	[113]
Farhangdoust et al.	PVDF	Analyzing the impact of metamembranes to improve piezoelectric metasensor sensitivity	13.74 V	2022	[73]
Harahap et al.	PVDF	Experimental of raindrop energy harvesting by employing 3 level fractal-cut kirigami membranes	70 mV	2024	

2.5 Research Gap and Challenges

This research addresses several critical gaps and challenges in the field of raindrop energy harvesting by employing a 3-level fractal-cut kirigami membrane. Traditional piezoelectric membranes, such as plain PVDF, often exhibit low energy conversion efficiency due to limited deformation and inadequate mechanical adaptability. This study bridges that gap by integrating a kirigami auxetic membrane, enhancing deformation and energy transfer capabilities to optimize energy output. While kirigami patterns have been explored in other applications, their potential for improving energy harvesting systems remains underutilized. This research innovates by introducing a 3-level fractal-cut kirigami design, specifically tailored to increase stretchability and adaptability, resulting in enhanced voltage generation.

This study also tackles significant challenges in achieving voltage enhancement, maintaining structural integrity under repeated impacts, and balancing the kirigami membrane's stretchability with energy efficiency. The design aims to ensure durability and performance while avoiding excessive stress concentrations. Additionally, it addresses the need for environmental adaptability by ensuring consistent functionality under varying rainfall conditions, such as changes in droplet intensity or angle of impact. Finally, the research demonstrates the feasibility of integrating this innovative design with practical applications, including energy storage and powering low-energy devices through effective AC-DC conversion and storage

mechanisms. By addressing these gaps and challenges, the research contributes significantly to advancing the field of raindrop energy harvesting.

CHAPTER 3

METHODOLOGY

SolidWorks simulations will be used to analyze the response of each kirigami auxetic membrane to the mechanical impact of raindrops. Following this, experiments will be conducted by combining various kirigami auxetic membranes (KAM) to assess the efficiency of the energy harvester. The analysis will focus on the amount of power generated relative to the number of raindrops and evaluate how effectively the harvested energy can be stored and utilized.

3.1 Model and Assumption

3.1.1 SolidWorks Simulation

1. Numerical Approach of Raindrop Energy Harvester System

The governing equations for the deformation and deflection caused by waterdrops impacting a layered structure consisting of a substrate, Kirigami Auxetic Membrane (KAM), and piezoelectric material are derived to describe the coupled mechanical and electrical behaviors. Starting with the deformation of the substrate and KAM, the Kirchhoff-Love Plate Theory provides a basis for modelling the bending of thin plates under applied loads [888]. The deformation can be described by the plate bending equation:

$$\frac{\partial^4 w}{\partial x^4} + 2 \frac{\partial^4 w}{\partial x^2 \partial y^2} + \frac{\partial^4 w}{\partial y^4} + \frac{\rho h}{D} \frac{\partial^2 w}{\partial t^2} = \frac{q(x, y, t)}{D} \quad (10)$$

Where $w(x, y, t)$ represents the deflection at a point (x, y) and time t , ρ is the material density, h is the plate thickness, and $q(x, y, t)$ is the external load applied due to raindrop impact. The flexural rigidity D is given by $D = \frac{Eh^3}{12(1-\nu^2)}$, where E is the Young's modulus and ν is the Poisson's ratio. This equation accounts for the dynamic response of the plate under both bending stiffness and inertial effects due to the load. In the piezoelectric layer, mechanical deformation is coupled with electric field effects. The

governing equations are derived from mechanical equilibrium and electric displacement. The mechanical equilibrium in the piezoelectric layer is described by:

$$\frac{\partial \sigma_{xx}}{\partial x} + \frac{\partial \sigma_{xy}}{\partial y} + \frac{\partial \sigma_{xz}}{\partial z} + f_x = \rho \frac{\partial^2 u_x}{\partial t^2} \quad (12)$$

$$\frac{\partial \sigma_{yx}}{\partial x} + \frac{\partial \sigma_{yy}}{\partial y} + \frac{\partial \sigma_{yz}}{\partial z} + f_y = \rho \frac{\partial^2 u_y}{\partial t^2} \quad (13)$$

$$\frac{\partial \sigma_{zx}}{\partial x} + \frac{\partial \sigma_{zy}}{\partial y} + \frac{\partial \sigma_{zz}}{\partial z} + f_z = \rho \frac{\partial^2 u_z}{\partial t^2} \quad (14)$$

Where σ_{ij} are the stress components, u_x, u_y, u_z , are displacements in the x, y, z directions, and f_x, f_y, f_z are body forces. The electric displacement in the piezoelectric layer is governed by:

$$\frac{\partial D_x}{\partial x} + \frac{\partial D_y}{\partial y} + \frac{\partial D_z}{\partial z} = 0 \quad (15)$$

Where the components of the electric displacement vector D_x, D_y, D_z are expressed as:

$$D_x = e_{11} \frac{\partial u_x}{\partial x} + \epsilon_{11} \frac{\partial V}{\partial x} \quad (16)$$

$$D_y = e_{12} \frac{\partial u_y}{\partial y} + \epsilon_{12} \frac{\partial V}{\partial y} \quad (17)$$

$$D_z = e_{13} \frac{\partial u_z}{\partial z} + \epsilon_{13} \frac{\partial V}{\partial z} \quad (18)$$

Here, e_{ij} are the piezoelectric stress constants, ϵ_{ij} are the permittivity constants, and V is the electric potential. These equations describe the coupled mechanical and electrical behavior, where deformation in the piezoelectric layer generates an electric field due to the direct piezoelectric effect.

2. Initial Condition

In a static SolidWorks simulation for a layered system with the substrate on the top surface, the Kirigami Auxetic Membrane (KAM) in the middle, and the piezoelectric material at the bottom, the initial conditions are established to reflect the

system's equilibrium state before any external forces or loads are applied. Static simulations inherently assume that the system begins in an undeformed and unstressed state unless preloads or specific initial stresses are defined. For this setup, the initial conditions are as follows:

- **Geometry and Material Properties**

The geometry of the system is assumed to be in its natural, undeformed configuration, with each layer perfectly aligned as illustrated in Figure 3.1. The layers are assumed to be perfectly bonded at their interfaces, ensuring continuity in displacement and stress across the substrate-KAM and KAM-piezoelectric interfaces. This means there are no gaps, separations, or sliding at these interfaces.

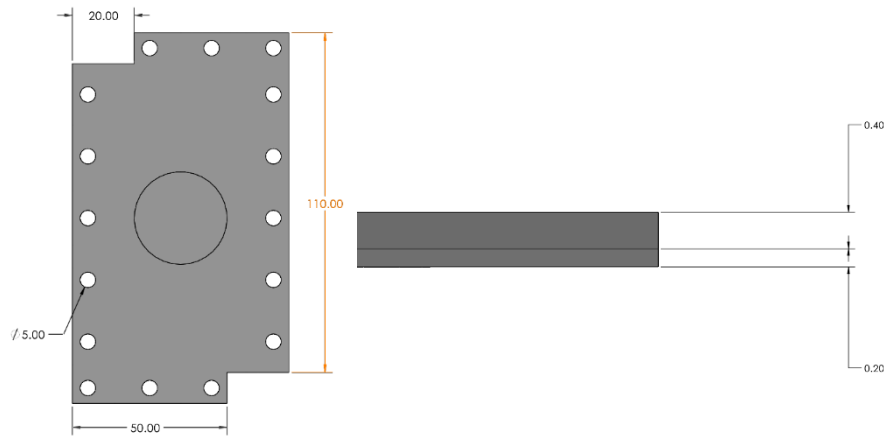


Figure 3.1 Geometry and dimension of the assembled substrate and KAM.

The Polylactic Acid (PLA) material is selected as the constituent material of the substrate and KAM. Using PLA (Polylactic Acid) for 3D printing in real application to create substrate and membrane offers several benefits due to its properties such as, provides sufficient stiffness and strength for structural components, produces parts with a clean and smooth surface, allows for fine detailing, enabling accurate reproduction, etc. The properties of PLA material as an input to the SolidWorks simulation are summarized and in Table 3.1.

Table 3.1 Input PLA material properties on SolidWorks software.

Material	Property	Value	Units
Polylactic Acid (PLA)	Elastic Modulus	4.8	GPa
	Poisson's Ratio	0.35	N/A
	Shear Modulus	2.4	GPa
	Mass Density	1240	kg/m ³
	Tensile Strength	46	MPa
	Yield Strength	26	MPa
	Thermal Conductivity	0.101	W/(m.K)
	Specific Heat	1800	J/(kg.K)

- **External Forces and Loads**

The load in the form of forces, pressure, or moment is introduced during the simulation as static, constant values to evaluate the response of the layered structure. The position of load is placed in the center part of substrate before it is transferred to the piezoelectric material through KAM, because the maximum displacement occurs in the center part of the layers. The illustration of the load placement is shown in Figure 3.2.

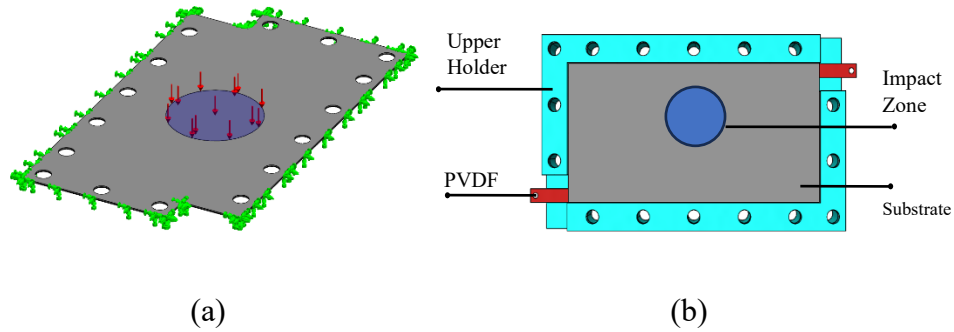


Figure 3.2 (a) Waterdrop impact position in the simulation (b) Waterdrop impact position on the raindrop energy harvester.

- **Displacement and Stress**

At the start of the simulation, all layers are considered to have zero initial displacement and zero stress. This means that the system has no deformation, and the stress state is entirely determined by the applied loads and constraints during the simulation. So, in mathematically:

$$w(x, y, z) = 0 \text{ and } \sigma(x, y, z) = 0$$

Where w is the displacement and σ is the stress tensor.

- **Electrical Conditions in the Piezoelectric Layer**

The piezoelectric material starts with no initial electric potential or charge distribution. The electric potential, V , within the piezoelectric layer is zero everywhere:

$$V(x, y, z) = 0$$

3. Boundary Condition

The boundary conditions for the simulation are critical to accurately model the interactions and constraints of the layered system under the influence of waterdrop impacts. These conditions define how the edges and interfaces of the substrate, Kirigami Auxetic Membrane (KAM), and piezoelectric layer behave under mechanical and electrical influences. For the substrate and KAM, which are modeled as thin plates, the edges are assumed to be fixed as illustrated in Figure 3.3.

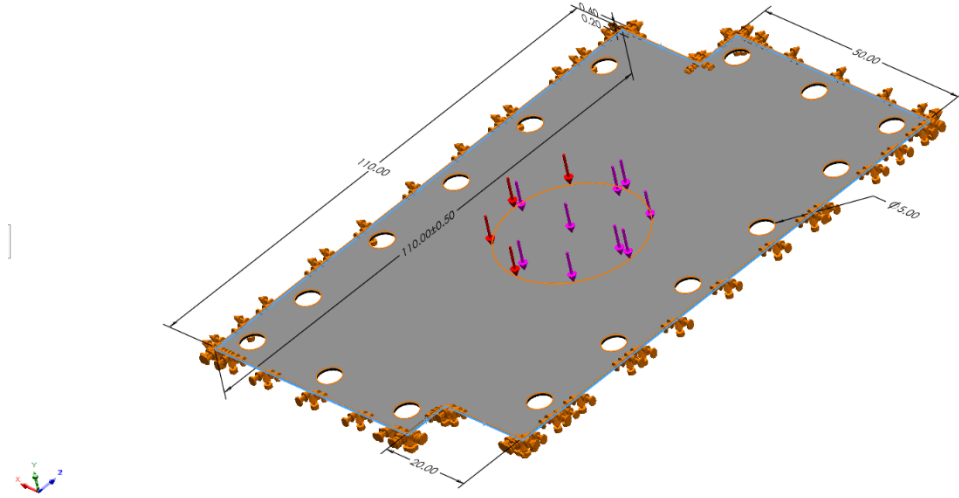


Figure 3.3 Fixed edges of the substrate and KAM geometry.

Fixed edges are described by $w = 0$ (no deflection) and $\frac{\partial w}{\partial n} = 0$ (no slope along the edge). Here, n denotes the direction normal to the edge. These boundary conditions ensure the physical constraints on the deformation of the substrate and KAM under

waterdrop forces. The interface between layers (substrate, KAM, and piezoelectric layer) must maintain continuity in displacement and stress. The displacement continuity condition ensures that:

$$w_{substrate} = w_{KAM} = w_{piezo}$$

Which means that all layers move together without separation. Stress continuity requires that the normal and shear stresses are equal across the interfaces, expressed as:

$$\sigma_{substrate} = \sigma_{KAM} = \sigma_{piezo}$$

At the impact zone, the waterdrop force is modeled as a steady state condition. It implies that the applied load is constant over time, and the system reaches a state of static equilibrium without temporal variations. The load $q(x, y, z)$ from the waterdrop is constant in magnitude and distribution across the impact area. It can be expressed as:

$$q(x, y, z) = \frac{\text{Force of waterdrop}}{\text{Impact Area}} \quad (19)$$

Where force of waterdrop is the total force exerted by the raindrop, derived from its mass and velocity ($F = m \cdot g$), and impact area is the surface area over which the force is distributed (shape of substrate).

4. Meshing Sensitivity Study

For the static SolidWorks simulation, the finite element (FE) mesh and mesh sensitivity study are essential for ensuring the accuracy and reliability of the results. The FE mesh divides the geometry into smaller elements, enabling numerical calculations for stress, deformation, and other responses. For complex layered structures like the substrate, Kirigami Auxetic Membrane (KAM), and piezoelectric layer, a fine mesh is applied to critical areas such as the waterdrop impact zone, interfaces between layers, and thin regions, while a coarser mesh is used in less critical regions to balance accuracy and computational efficiency. The illustration of meshing on the assembled components is shown in Figure 3.4

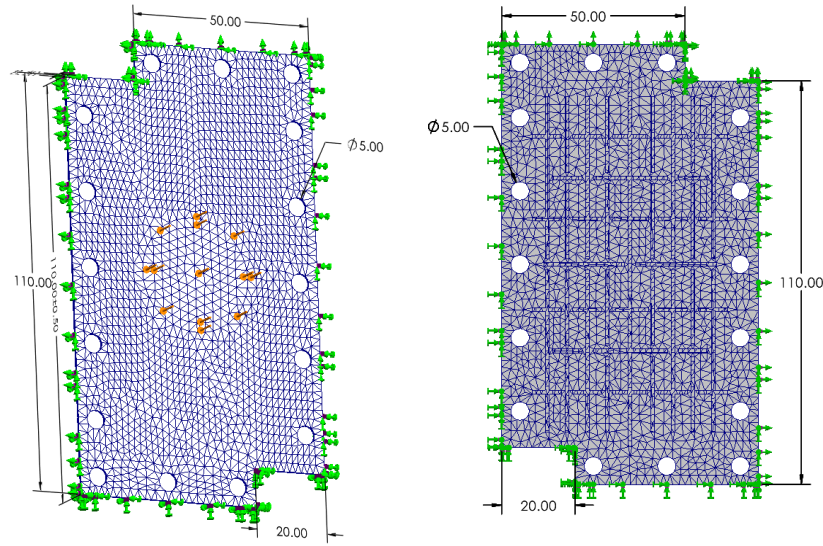


Figure 3.4 Top and bottom view of the substrate and KAM after applying mesh.

In this simulation, standard mesh is selected as a uniform mesh based on global element size, where element size remains consistent across the model unless overridden by local controls. We specify the maximum element size for the mesh 2.40289778 mm, where larger values reduce computational cost but may decrease accuracy, especially in regions with small features or high stress gradients. For minimum element size or the smallest allowable element dimension, it is 0.12014489 mm. This value controls how finely the mesh is refined in areas requiring more detail (sharp edges, small features, or areas with high stress).

3.1.2 Experimental of Raindrop Energy Harvesting

- **Fabrication and Assembly Process**

A custom-designed raindrop energy harvester, integrating a KAM with PVDF, is used for the experiment. The energy harvester configuration, comprising the substrate, KAM, and PVDF, follows the arrangement proposed by Farhangdoust et al. [10]. We put substrate in the top layer, KAM in the middle layer, and piezoelectric material (PVDF) in the bottom layer. The first step of starting this experiment is fabricating the components using 3D printer. The fabrication of a raindrop energy harvester components involves the precise creation of its key components such as substrate and

KAMs using advanced 3D printing technology. This method allows for the accurate production of complex geometries and customized structures, essential for optimizing the harvester's performance. The first step involves designing the raindrop energy harvester's components using computer-aided design (CAD) software. Each component is modelled with specific dimensions and geometric features that are critical to its functionality as illustrated in Figure 3.5.

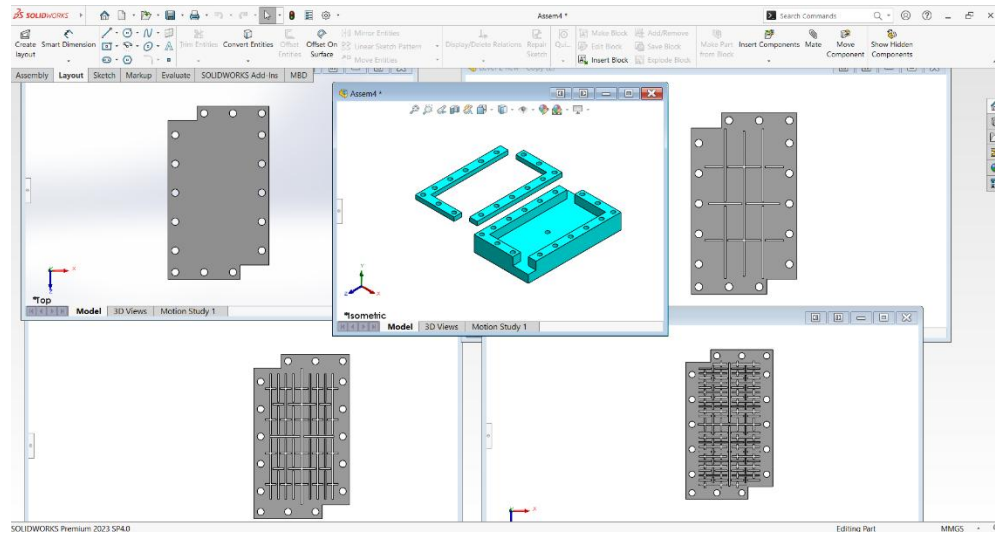


Figure 3.5 The design process of raindrop energy harvester components utilizing CAD software.

Special attention is given to the membrane's design, which involves a kirigami fractal cut to enhance flexibility and energy capture efficiency. Then, polylactic acid (PLA) filament is selected as the constituent material of the substrate and KAMs. The CAD designs are transferred to the 3D printer, which constructs each component layer by layer using PLA filament depicted in Figure 3.6 (a). The printer's precision allows for the accurate formation of the substrate and the complex structures of the KAMs. The printer used to fabricate the components is The Ultimaker S3: Professional 3D printer as shown in Figure 3.6 (b). The Ultimaker S3 is designed to provide professional-grade 3D printing capabilities in a compact and user-friendly package. It offers a balance between performance, reliability, and ease of use, making it appropriate for a variety of uses especially to create the items required as the component of energy harvester in this research. The Ultimaker S3 supports a wide range of filament

materials, including PLA, ABS, PETG, Nylon, TPU, and more, providing users with flexibility in choosing the right material for its specific applications.

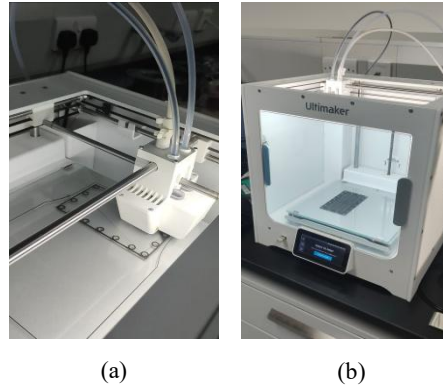


Figure 3.6 (a) Layering process of the raindrop energy harvester components using PLA filament (b) Ultimaker 3D Printer.

The fabrication results of the KAMs, plain membrane, substrate, and supporting structure are displayed in Figure 3.7 (a-b). These components were successfully assembled to form a functional raindrop energy harvester, as illustrated in Figure 3.7 (c). Following the assembly, the system's ability to generate electricity was tested, with voltage output measurements recorded. One such voltage signal, captured using an oscilloscope, is presented in Figure 3.7 (d), showcasing the harvester's response to waterdrop impacts. This demonstrates the system's effectiveness in converting waterdrop mechanical energy into measurable electrical output.

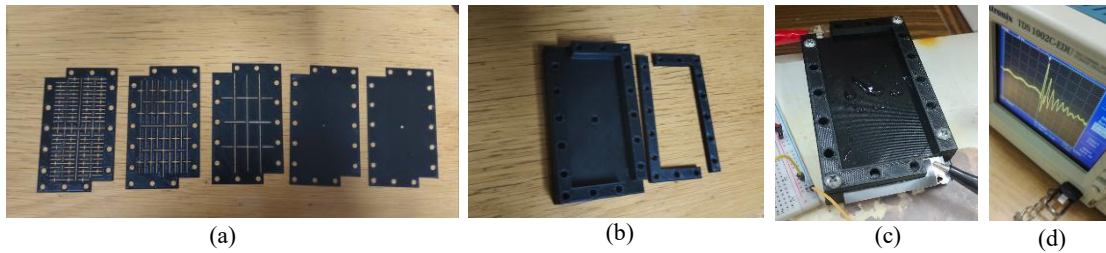


Figure 3.7 (a) Fabrication result of kirigami auxetic membranes, plain membrane, and substrate (b) Bottom holder and upper holder (c) Raindrop energy harvester appearance after whole components are assembled (d) Testing generated voltage of raindrop energy harvester.

- **Experimental Setup**

The experimental setup was carefully designed to simulate real conditions while maintaining a controlled environment for testing the raindrop energy harvester. Kirigami auxetic membrane (middle) and substrate (top) are employed and attached to the PVDF (bottom) to enhance its generated voltage. First, the effect of varying the burette distance from the substrate surface (15 cm, 30 cm, and 40 cm) was tested to observe the response of the generated electricity at different heights. The plain membrane was also tested to compare its sensitivity and deformation transfer capability with other membranes, assessing its effect on the generated voltage. Next, the impact of the raindrop energy harvester's inclination angles (0° , 20° , and 35°) on the generated electricity was examined. Additionally, the efficiency and the effect of the KAM combination will be analyzed to determine the optimal solution for harvesting raindrop energy. Key components of the setup include a burette system, a fabricated raindrop energy harvester, various measurement devices using an oscilloscope for data collection, and an electrical circuit for storing energy. The experimental setup for generating an electric voltage from a raindrop energy harvester device is shown in Figure 3.8.

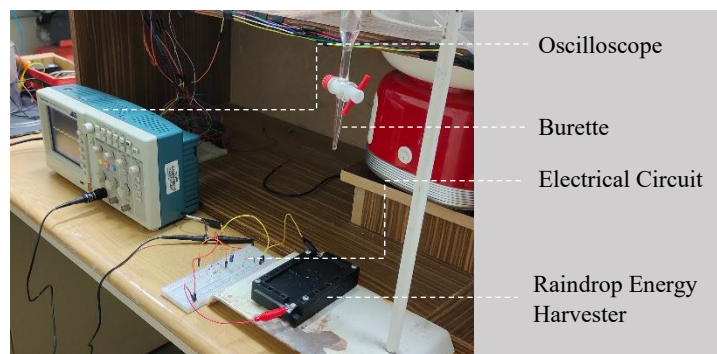


Figure 3.8 The experimental setup of raindrop energy harvesting.

The voltage measurement in this experiment was acquired through the utilization of an oscilloscope Tektronix TDS 1002C-EDU as shown in Figure 3.9, a sophisticated electronic device designed for precise and accurate visualization and analysis of electrical signals.

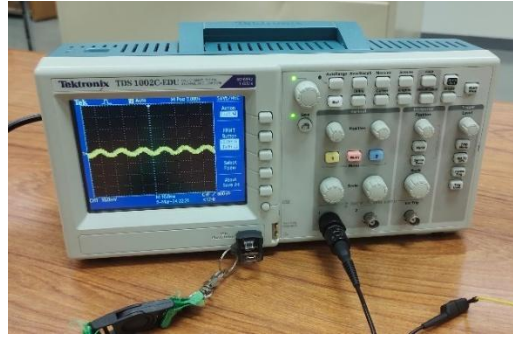


Figure 3.9 Oscilloscope Tektronix TDS 1002C-EDU.

Then, the raindrops were artificially replicated in the laboratory using a burette, which was carefully calibrated to produce droplets of a consistent size and at a controlled, steady rate. This setup allowed for precise replication of natural raindrop impacts, ensuring that experimental conditions remained uniform throughout the testing phase. The constant size and rate of the droplets were critical in evaluating how the harvester responded to waterdrop frequencies, which simulated real-world rainfall scenarios. In this research, a burette with 100 ml volume is utilized as a model for rainfall, with water slowly dripping out of the burette's nozzle to mimic individual raindrops as illustrated in Figure 3.10. The water dripping is exposed to the middle of the substrate surface which has been embedded in the top side of the harvester.

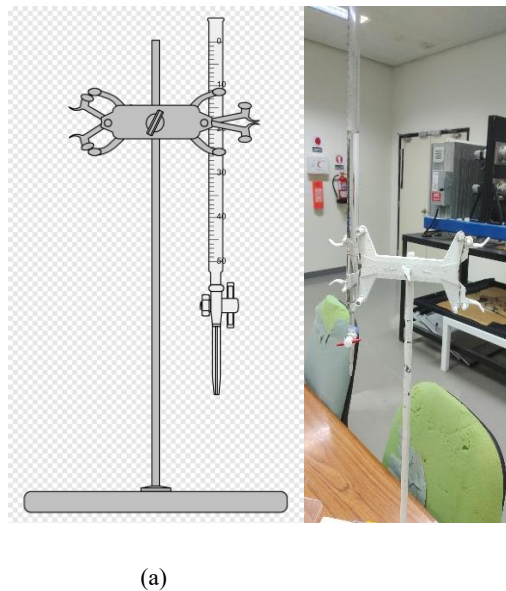


Figure 3.10 (a) Illustration of burette (b) The 100 ml burette used for the experiment.

As illustrated in Figure 3.7 (d), the flow energy generated by the raindrop energy harvester shows that the piezoelectric material (PVDF) produces alternating current (AC) voltage due to the varying excitations from the raindrops. However, most power electronic devices operate on direct current/voltage (DC). Therefore, the field of raindrop energy harvesting necessitates a power electronics circuit (PEC), specifically a rectifier circuit, to facilitate the rectification process (AC-DC conversion) [114]. This process is essential for the effective utilization of the generated voltage. The flowchart of converting produced AC voltage by the piezoelectric into DC voltage is shown in Figure 3.11.

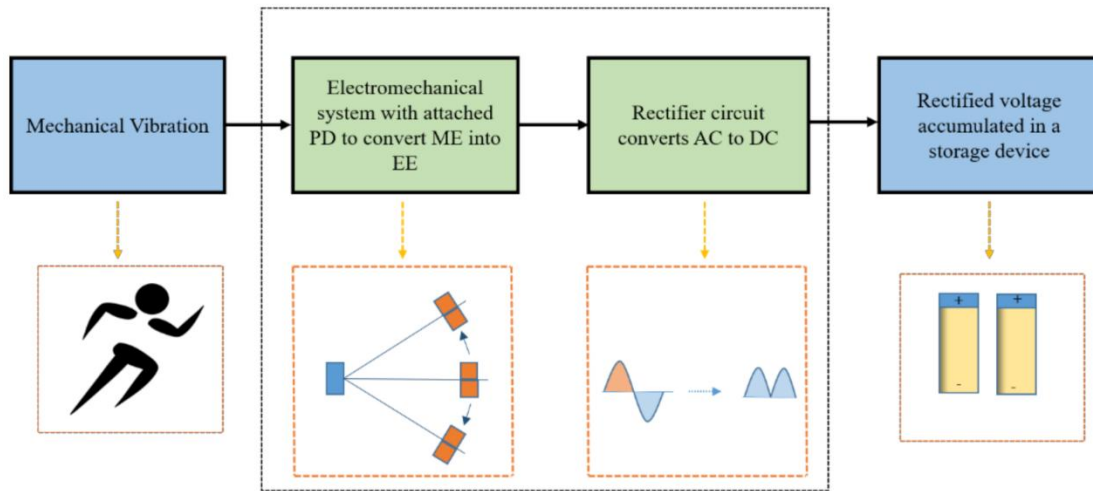


Figure 3.11 A flowchart depicting a standard piezoelectric energy harvesting (PEH) system [115].

A rectifier is an electrical component designed to convert alternating current (AC) into direct current (DC) by permitting current to pass through the device in only one direction. Diodes function like one-way valves in the rectifier, ensuring the unidirectional flow of current. This process is commonly referred to as rectification. Experimentation will be made on a raindrop energy harvester by connecting the harvester to the rectifier circuit to convert the AC generated by the harvester into DC so that the voltage can be accumulated in the capacitor. The scheme and used rectifier for the experiment are illustrated in Figure 3.12 (a) and (b). The electrical circuit is also equipped with an LED as an initial indicator of accumulated electrical energy.

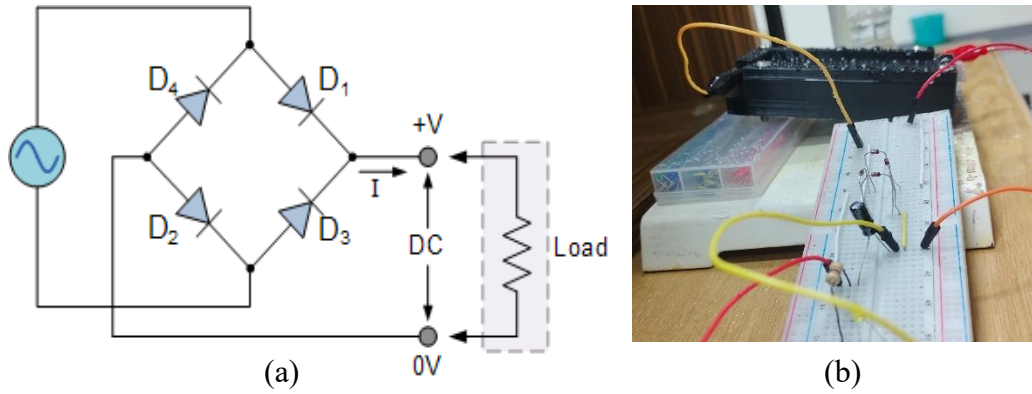


Figure 3.12 (a) The schematic diagram of the rectifier circuit [116] (b) The rectifier circuit used for raindrop energy harvesting.

- **Technical Parameters of the Experiment**

To evaluate the deformation and energy-harvesting performance of the multilayer structure, comprising the substrate, Kirigami Auxetic Membrane (KAM), and piezoelectric layer, a series of experiments were conducted under varying conditions. These experiments focused on understanding the effect of droplet size, impact velocity, and membrane configuration on the overall output voltage and structural response. The technical parameters and scenarios considered in the experiments are summarized in Table 3.2 below.

Table 3.2 Technical Parameters and Experimental Scenarios

Category	Parameter	Value/Description
Material Specification	Substrate	PLA
	Kirigami Auxetic Membranes (KAM)	PLA
	Piezoelectric	PVDF
Thickness	Substrate Thickness	0.4 mm
	KAM Thickness	0.2 mm
	Piezoelectric Thickness	110 μm
Geometric Configuration	Kirigami Fractal Levels	1, 2, and 3 fractal cuts for deformation enhancement
Experimental Parameters	Droplet Diameter	2 mm
	Droplet Impact Velocity	Varying depends on height of the burette to the harvester surface

	Impact Zone	Center of the substrate for maximum deformation
Boundary and Loading Conditions	Boundary Conditions	Fixed edges, locked using bolts in the supporting structure, bonded layers (substrate, KAM, piezoelectric)
	Load Application	Water droplet released at specified heights
Experimental Scenarios	Scenario 1	Varying waterdrops falling height
	Scenario 2	Inclining the raindrop energy harvester to 20° and 35°
	Scenario 3	Combining two different types of membranes
	Scenario 4	Combining similar types of membranes
	Scenario 5	Modifying the sequence of substrate + KAM Type (B+C) known as the most producing voltage
	Scenario 6	Combining three different types of membranes

CHAPTER 4

PROCESS DESIGN AND DEVELOPMENT

This chapter offers an in-depth exploration of the process involved in designing, developing, and integrating a raindrop energy harvester. It begins with a detailed explanation of the fundamental principles by which the energy harvester converts the mechanical force of raindrops into electrical energy. Additionally, this chapter also delves into the innovative integration of this energy harvester with the kirigami auxetic membranes (KAMs).

4.1 Design of Raindrop Energy Harvester

In this study, the energy harvester consists of three primary components: the substrate, the membrane, and the piezoelectric element. The substrate is designed to withstand the impact of water droplets from the backside and is subsequently attached to the kirigami auxetic membrane and the piezoelectric element from the front. The thin layer of substrate that connects to the membrane serves as a diaphragm film, preventing direct pressure from reaching the piezoelectric element from the rear of the sensor [10]. This kind of mechanism was adopted from the concept published by the previous work as illustrated in Figure 4.1 below.

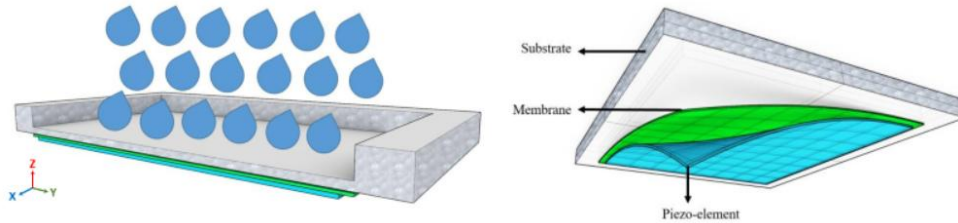


Figure 4.1 The models of raindrops and harvesters in the simulation study [10].

Consequently, the strain response of the kirigami auxetic membrane and the stress response of the piezoelectric element were assessed by subjecting harmonic pressure to the backside of the substrates. Polyvinylidene fluoride (PVDF) was chosen as the preferred piezoelectric element because of its inherent flexibility and compatibility [117]. Polylactic Acid (PLA) was chosen as the material for both the

substrate and the kirigami auxetic membrane. The design of the raindrop energy harvester which contains PVDF as the electricity generator has been shown in Figure 4.2.

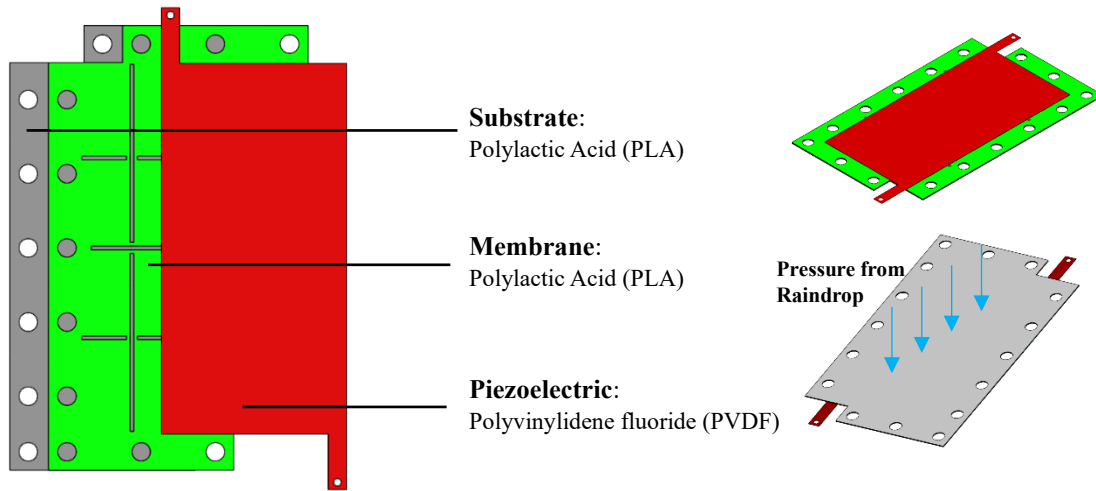


Figure 4.2 Design of raindrop energy harvester.

The substrate, KAM, and PVDF will be supported by a structure made of PLA material. The structure consists of two parts: the bottom and upper holder as shown in Figure 4.3. This structure aims to lock and clamp the substrate, kirigami auxetic membrane, and PVDF together which is placed in the middle so that when the substrate is exposed to the force of waterdrops, the components remain in their position.

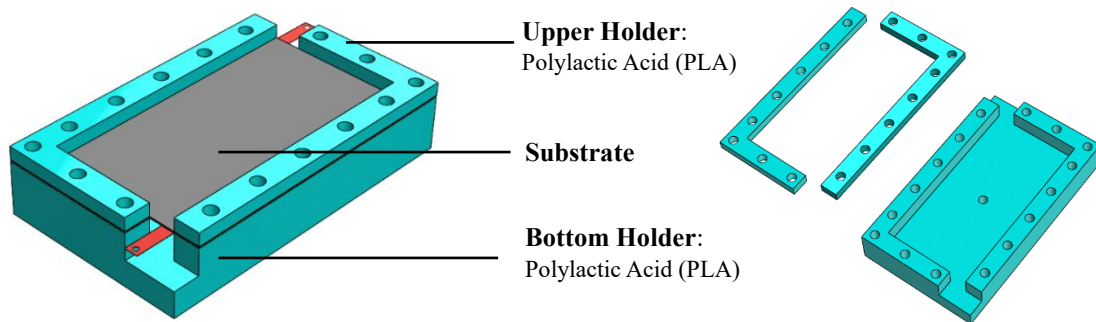


Figure 4.3 Design of supporting structure.

The dimensions and geometric parameters of all the components that make up the raindrop energy harvester are detailed in Table 4.1 below. Then, Figure 4.4 will show a detailed dimension illustration of the raindrop energy harvester components.

Table 4.1 Parameters values used in the raindrop energy harvester model.

Part	Parameter	Value	Unit
Substrate	Width, W_s	70	mm
	Length, L_s	120	mm
	Thickness, t_s	0.4	mm
	Number of Holes, H_m	16	-
	Hole Diameter, D_m	5	mm
Membrane	Width, W_m	70	mm
	Length, L_m	120	mm
	Thickness, t_m	0.2	mm
	Number of Holes, H_m	16	-
	Hole Diameter, D_m	5	mm
PVDF	Width, W_p	50	mm
	Length, L_p	100	mm
	Thickness, t_p	110	μm
Supporting Structure (Bottom Holder)	Width, W_{ss1}	70	mm
	Length, L_{ss1}	120	mm
	Thickness, t_{ss1}	20	mm
Supporting Structure (Upper Holder)	Width, W_{ss2}	70	mm
	Length, L_{ss2}	120	mm
	Thickness, t_{ss2}	5	mm

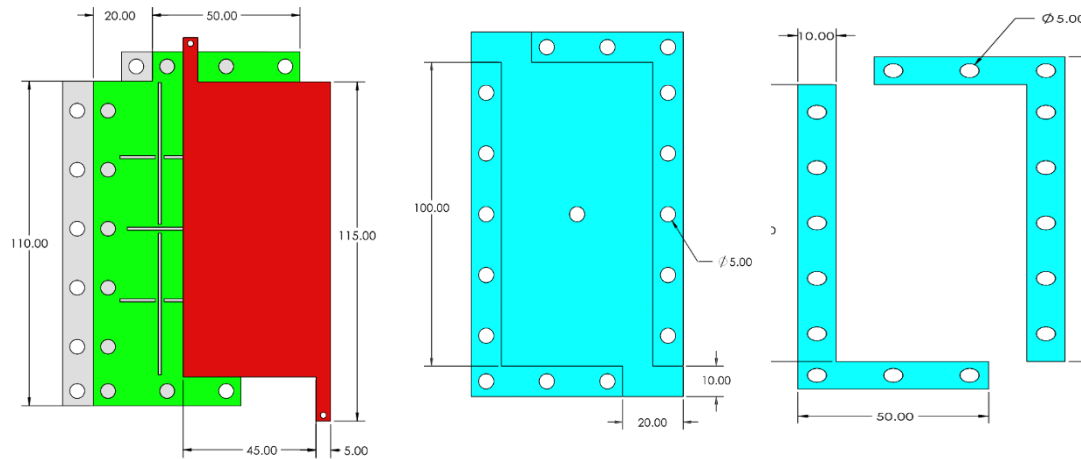


Figure 4.4 Design of raindrop energy harvester components.

Table 4.2 lists the material parameters of the raindrop energy harvester components for the computational study.

Table 4.2 Material Properties of Model.

Material	Parameter	Value	Unit
Polyvinylidene fluoride (PVDF)	Density	1770	kg/m ³
	Young Modulus	2.5	GPa
	Dielectric Constant	~12.5	-
	Reversible Strain	~1%	-
	Energy Efficiency	~1%	-
	Coupling Matrix	15	pC/N
Polylactic Acid (PLA)	Density	1240	kg/m ³
	Poisson's Ration	0.35	-
	Young Modulus	4.8	GPa

All components of the raindrop energy harvester will be fabricated using 3D printing technology involving Fused Deposition Modeling (FDM). This method is widely used for 3D printing materials like PLA and offers several advantages for creating intricate designs such as the kirigami patterns employed in this study.

4.2 Selecting the Piezoelectric Material

Piezoelectric is a smart material and energy provider at a micro-level that will be considered to convert the vibrations caused by a waterdrop's kinetic energy into electricity through a direct piezoelectric effect. In this study, Polyvinylidene fluoride (PVDF) is chosen as the piezoelectric material because of its lightness, eco-friendliness, and flexibility. Vatansever et al. studied raindrop energy harvesting utilizing a cantilever structure. In their research, they compared two types of cantilever piezoelectric transducers, specifically PVDF and PZT. Because the shorter film reacts to the forward strain more quickly, which is essential for higher voltage/power production, the voltage produced by the shorter PVDF sample was higher for the water drop experiment. In conclusion, when exposed to minor impact and moderate mechanical stress, polymer-based piezoelectric materials generate greater peak voltage/power than ceramic piezoelectric materials. However, in high harmonic

pressure on piezoelectric elements, the PZT will appear with the higher-generating voltage due to its higher piezoelectric coefficient in the thickness direction (d_{33}), as summarized in the piezoelectric material properties listed in Table 4.3.

Table 4.3 Comparison of physical properties between piezo ceramic (PZT) and polymer (PVDF) materials [118].

Property	PZT	PVDF
Density (kg/m^3)	7750	1800
Sonic velocity (m/s)	2830	1400
Acoustic impedance (MRayls)	22	3
Compliance ($\times 10^{-9} \text{ m}^2/\text{N}$)	0.02	0.1
Relative permittivity	1800	10
Tan δ (at 1 KHz)	0.02	0.05
d_{33} (pC/N)	410	30
d_{31} (pC/N)	-175	-18
g_{33} (mV m/N)	26	340

The most efficient produced voltage may be achieved by referring to the material utilization as conducted by Vatansever et al. on raindrop energy harvesting, the PVDF was selected for this research which has form and dimension depicted in Figure 4.5.

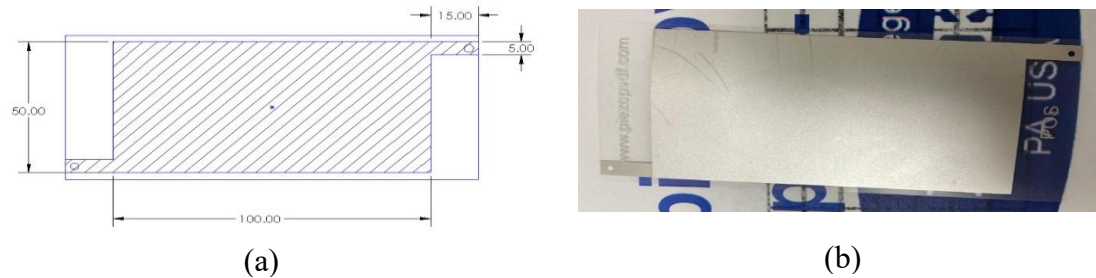


Figure 4.5 (a) Dimension and illustration of the PVDF. (b) PVDF for raindrop energy harvesting.

A commercially available piezoelectric polymer (Polyvinylidene fluoride) by PolyK was used in this research. The PVDF has a rectangular shape with a length of 100 mm, a width of 50 mm, and a thickness of 110 μm . Those dimensions are crucial for determining and adjusting the supporting structure and the kirigami auxetic membrane. The piezo membrane is also protected by a transparent nonconductive coating. Connector wires are soldered onto the two end terminals of the PVDF to

contact the load and measure the generated electricity. This PVDF has specific material properties mentioned in Table 4.2

4.3 Kirigami Auxetic Membranes and Substrate Model

Auxetic refers to a metamaterial concept applicable to any structure that possesses a negative Poisson's ratio (NPR). In this research, the kirigami technique is employed to create these (meta)materials and (meta)structures. The NPR response in auxetic structures is distinctly different, showcasing counterintuitive deformation behavior during strain. When a tensile force is applied to an auxetic structure, it expands transversely, contrary to the behavior of conventional materials. This auxetic design allows structures to expand easily in both longitudinal and transverse directions [14]. Recently, due to the demonstrated improvements in power output associated with negative Poisson's ratio, auxetic types of energy harvesters have garnered increasing interest. One of the auxetic designs is the fractal cut design which means infinitely complex patterns that are self-similar across different scales [84]. This kind of pattern is recognized for its high flexibility in both longitudinal and transverse directions, as it has great potential to provide better stretchability to the membrane and, therefore, enhance the PVDF's polarization [10].

This research will propose three types of kirigami auxetic membranes (KAM), designed by adjusting the shape, dimensions, and materials of the membranes based on the available resources. The next generation of extremely stretchy auxetic membranes for improving the sensitivity of diaphragm-based waterdrop pressure sensors was created by utilizing those KAMs. As one of many references, Farhangdoust et al. [10] created a square shape of a bioinspired membrane and a conventional model equivalent to a plain membrane as depicted in Figure 4.6 with dimensions $12.1 \text{ mm} \times 11.5 \text{ mm}$ to demonstrate the benefits of the bioinspired membrane for power enhancement. Polycarbonate material was selected to fabricate these membranes.

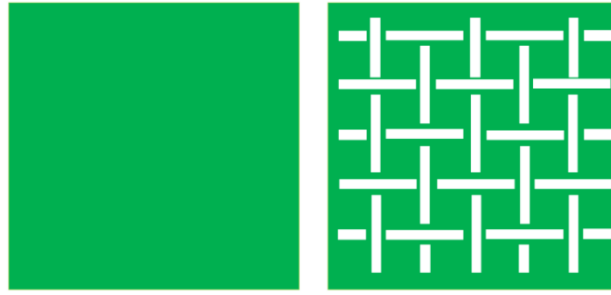


Figure 4.6 Plain membrane (left) and auxetic membrane (right) [10].

Those three KAMs were employed and developed referencing a previously existing design by Farhangdoust et al. to analyze the raindrop pressure sensors through experimental techniques. Additionally, a plain membrane was also tested to facilitate a comparison between the patterned membrane and the unpatterned membrane. The illustration of the kirigami auxetic membranes is shown in Figure 4.7 below.

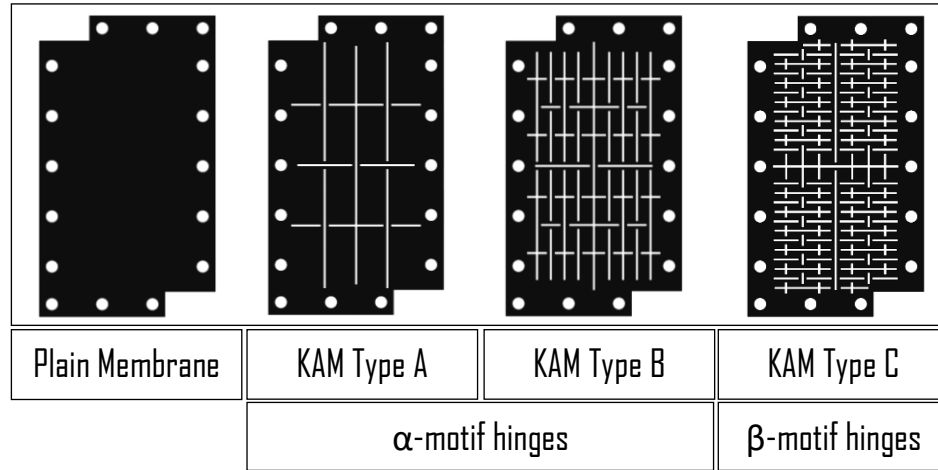


Figure 4.7 Design of the tested plain membrane and kirigami auxetic membrane in the experiment.

The shape and dimensions of the membrane are designed to align with the PVDF membrane, ensuring that the energy collected by the harvester can be clearly observed and measured. Each kirigami auxetic membrane developed in this study was designated as KAM Type A, KAM Type B, and KAM Type C. The main difference between these membrane types lies in the density of their patterns. Specifically, the pattern density increases progressively from Type A to Type C, with Type A having the

most widely spaced cuts, Type B featuring a moderately dense pattern, and Type C possessing the highest cut density. Additionally, the developed KAM design reveals that KAM Type A and B incorporate the α -motif hinges, while KAM Type C utilize the β -motif hinges as inspired by the kirigami fractal cut pattern illustrated in Figure 4.8. The choice of these distinct hinge motifs is intentional, as the motif hinges of the KAM will generate different stress distribution and direction to the PVDF which will affect the electricity production of the raindrop energy harvester.

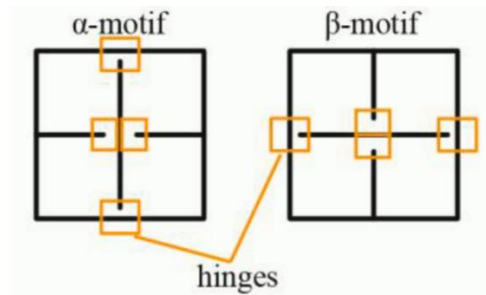


Figure 4.8 Cutting motif of kirigami fractal cut [84].

The detailed dimensions and shapes of the proposed KAMs are presented in Figures 4.9 to 4.11.

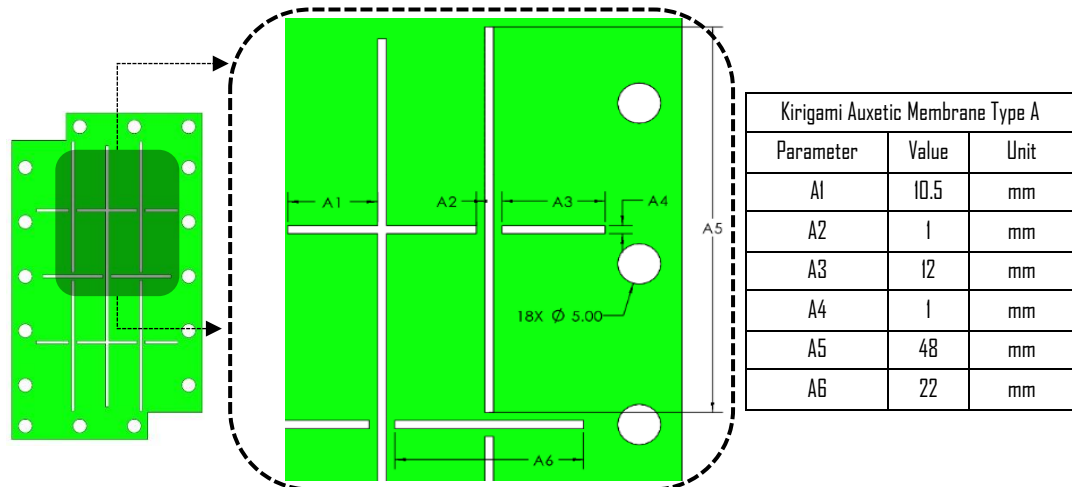


Figure 4.9 Detailed design of KAM Type A.

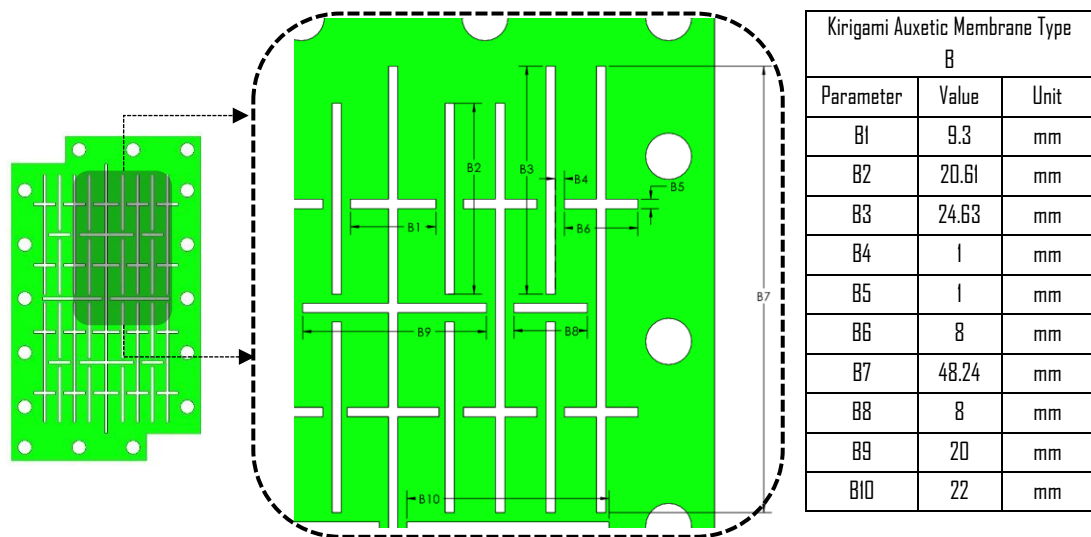


Figure 4.10 Detailed design of KAM Type B.

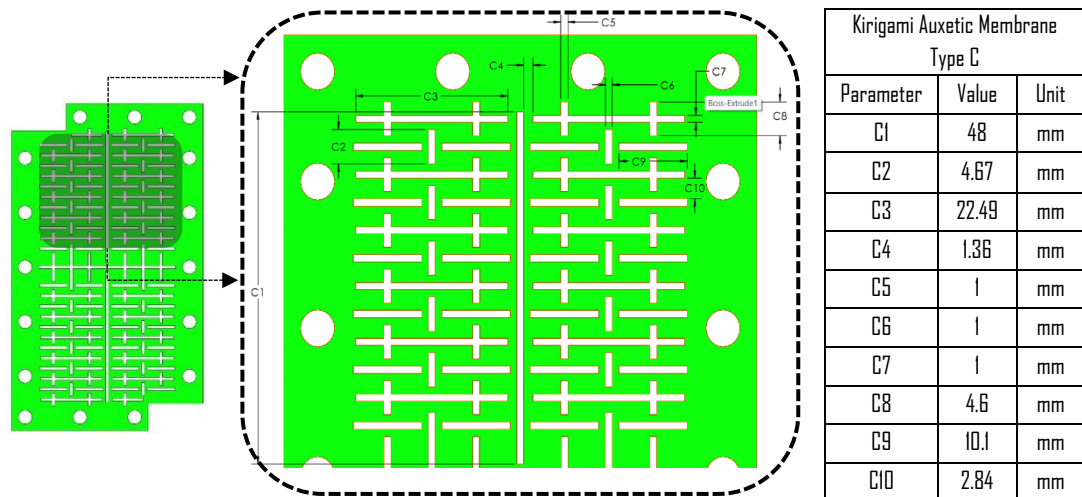


Figure 4.11 Detailed design of KAM Type C.

CHAPTER 5

RESULTS AND DISCUSSIONS

This chapter presents experimental findings supported by SolidWorks simulation software, beginning with an analysis of deflection and stress distribution, followed by detailed discussions on the velocity and kinetic energy of water drops. It includes a comparative study of the electric potential (voltage) generated by energy harvester-attached kirigami auxetic membranes, examining the effects of height, inclination, and membrane combinations. Finally, the impact of the single and multiple waterdrops on the energy transfer rate to a capacitor as energy storage is analyzed.

5.1 Velocity and Kinetic Energy of Waterdrop

For raindrop energy harvesting (REH), the amount of stress tensor to produce electrical potential is highly dependent on the waterdrops condition. The electrical energy output of REH devices is determined by the velocity, mass, and mechanism of droplet impact with which the droplet collides with the harvesting device. The velocity of the waterdrops would theoretically be able to be analyzed as free-falling velocity. Thus, the velocity of waterdrops can be obtained by using the Equation 2.

$$v = \sqrt{2gh} \quad (5.2)$$

Where g is the gravity (9.81 m/s^2), h is the distance of the initial point of water drop to the surface (m), and v is the velocity of free fall waterdrop (m/s). During the experiment, the h value is substituted as the distance of the burette to the membrane surface. By measuring the change in the height of the burette relative to the membrane surface, we derived the relationship between velocity and height that velocity is directly proportional to the square root of the height as shown in Figure 5.1. The burette height increment ranges from 15 cm to 500 cm for this analysis. In the experiment, however, the burette height will be adjusted to 15 cm, 30 cm, and 40 cm (maximum height) to observe the electric potential of the raindrop energy harvester, which will be discussed in the following subsection.

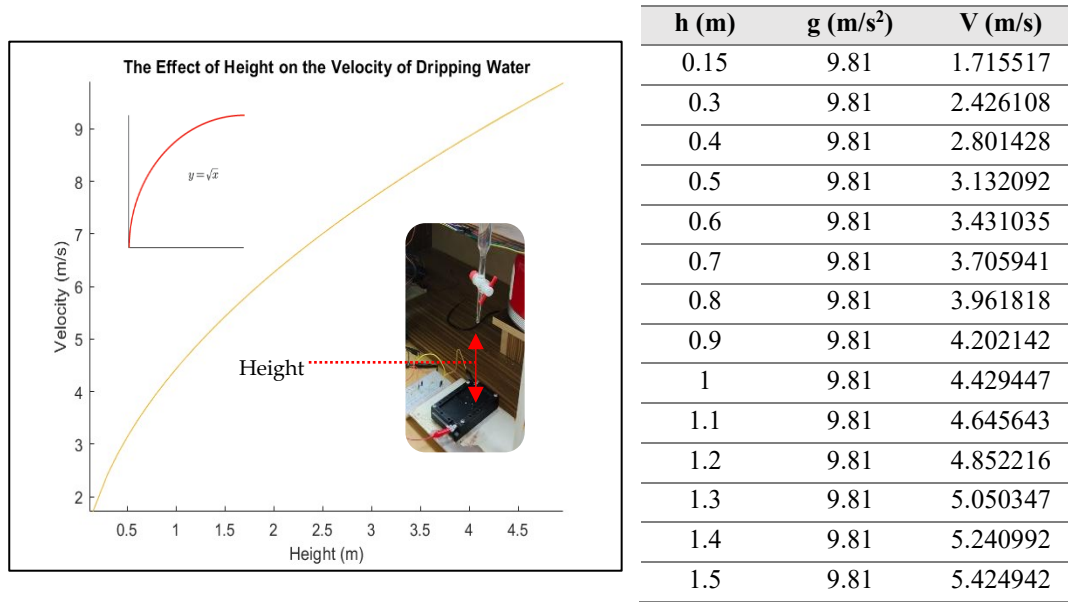


Figure 5.1 Waterdrop velocity analysis by varying the height of the burette.

Further, this study aimed to examine the transformation of kinetic energy from water droplets using a raindrop energy harvester device to convert the device's vibrational or mechanical energy into electrical energy. As the droplet descended from rest, it accelerated along a trajectory, progressively gaining velocity. The droplet's kinetic energy is then related to its velocity and size, as illustrated in Equation 5.3.

$$E_{KE} = \frac{1}{2} \rho_w \left(\frac{4}{3} \pi \left(\frac{d}{2} \right)^3 \right) v^2 \quad (5.3)$$

Where ρ_w is the density of water (kg/m³), d is the diameter of the waterdrop (mm), and v is the velocity of the waterdrop (m/s). The analysis of the kinetic energy correlation to the velocity is depicted in Figure 5.2. According to this equation, the kinetic energy of a waterdrop increases with the square of its velocity. Therefore, even a small increase in the velocity of the waterdrop results in a significant increase in its kinetic energy. This relationship is crucial for understanding how variations in waterdrop velocity can impact the overall energy harvesting efficiency of the raindrop energy harvesting system.

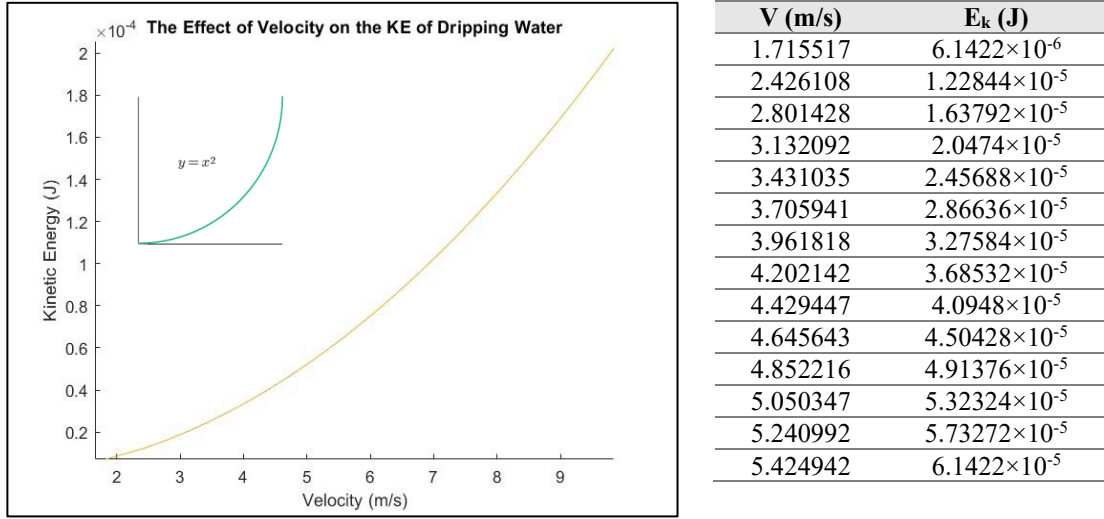


Figure 5.2 Analysis of kinetic energy correlation to the waterdrop velocity.

5.2 Deflection of the Designed Kirigami Auxetic Membranes

Once the water droplets interact with the raindrop energy harvester, deflection occurs to the substrate and kirigami auxetic membrane due to the mechanical force of the waterdrops. This deflection will transfer stress to the PVDF then converted into electricity. Deflection refers to the measure of movement, strain, stretch, or deformation experienced by an object when subjected to external forces. In this experiment, examining the deflection of kirigami auxetic membranes provides critical insights into their dynamic responses. Each kirigami auxetic membrane including plain, KAM Type A, KAM Type B, and KAM Type C will be examined using SolidWorks to obtain their deflection when an amount of equal waterdrop force is exposed to each membrane through a substrate as a receiver. When assessing the deflection response caused by waterdrops, it is important to consider the amount of external force applied. First, the mass of each water droplet is necessary to be analyzed by using Equation 5.1.

$$m = \frac{4}{3}\pi \left(\frac{d}{2}\right)^2 \rho \quad (5.1)$$

Where m is waterdrop mass, $d = 2$ mm stands for diameter of waterdrop (standard laboratory burette typically ranges from 2 to 4 millimeters, assumed 2 mm for this

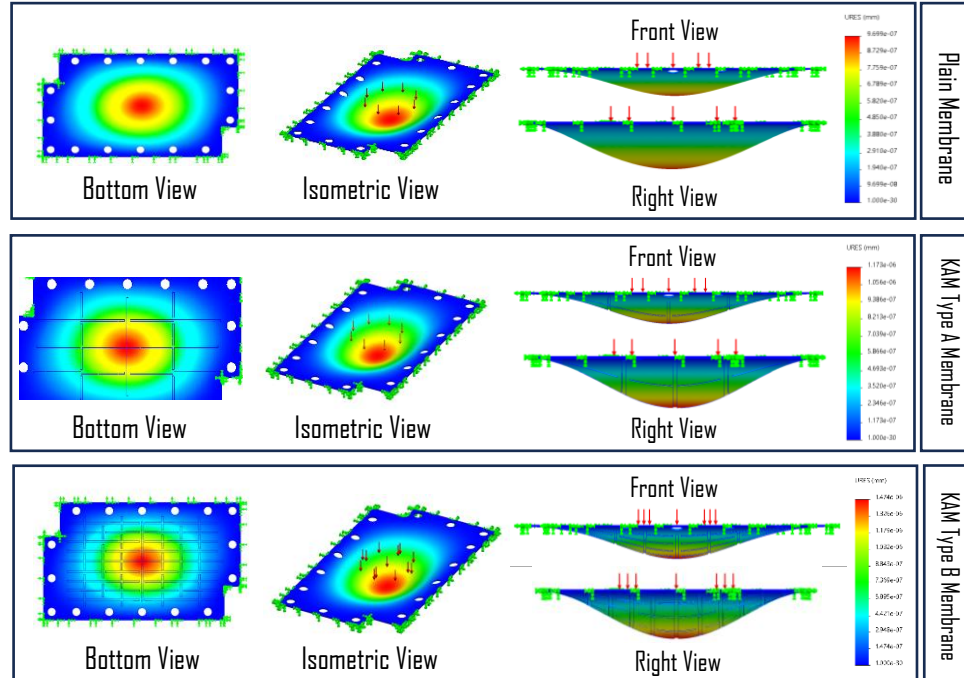
experiment), and $\rho = 998 \text{ kg/m}^3$ is water density. The obtained mass of each one of the waterdrops with those parameters is $m \approx 4.19 \times 10^{-6} \text{ kg}$. The next step is acquiring the force F exerted by the waterdrop that can be estimated using Equation 5.2.

$$F = m \cdot a \quad (5.2)$$

From Equation 5.2, the force exerted by the waterdrop is determined to be $F \approx 4.11 \times 10^{-5} \text{ N}$. For the final step, the amount of pressure can be calculated by considering the force distributed over the contact area of four proposed membranes (0.005 m^2) using Equation 5.3.

$$P = \frac{F}{A} \quad (5.3)$$

Thus, it was obtained that one waterdrop can give $8.22 \times 10^{-3} \text{ Pa}$ excitation pressure. This constant selected pressure in the simulation helps to accurately measure the resulting deflection on the surface being studied. Pictures of the deflection after exposing waterdrops are shown in Figure 5.3 below.



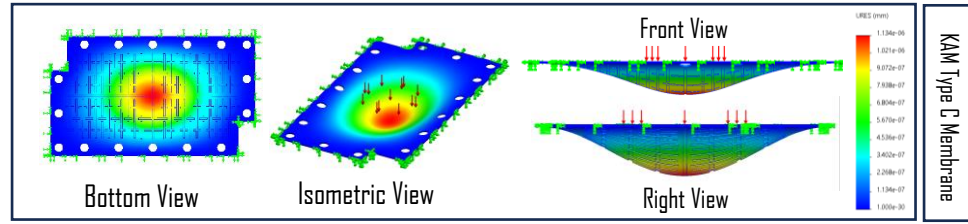


Figure 5.3 Deflection appearance of plain, KAM Type A, KAM Type B, and KAM Type C membrane.

The deflection data provides insight into the mechanical behavior and sensitivity of each membrane type. Sensitivity, in this context, refers to the magnitude of the deflection response to the applied force. Higher deflection indicates higher sensitivity, meaning the membrane is more responsive to external forces. As tested in those simulations above, the KAM Type C and KAM Type B are the most sensitive membrane which has an almost similar deflection of 1.49 nm and 1.47 nm after receiving waterdrop force in the center of the substrate. On the other hand, the plain membrane's structure is likely more rigid and less adaptable to external forces, resulting in the smallest deflection of all membranes with 0.96 nm and followed by KAM Type A as the second lowest with 1.13 nm. This phenomenon occurs because the KAM Type C and B have a more Negative Poisson's Ratio which allows them to deform more significantly than plain and KAM Type A membranes under applied stress. Thus, three proposed kirigami auxetic patterns help the flexibility of the membrane to boost the piezo-element's stretchability and deliver more strain energy to the piezo-element. In addition, the comparison of deflection by taking five nodes in the most impacted zone of the membranes (center) is shown in Figure 5.4.

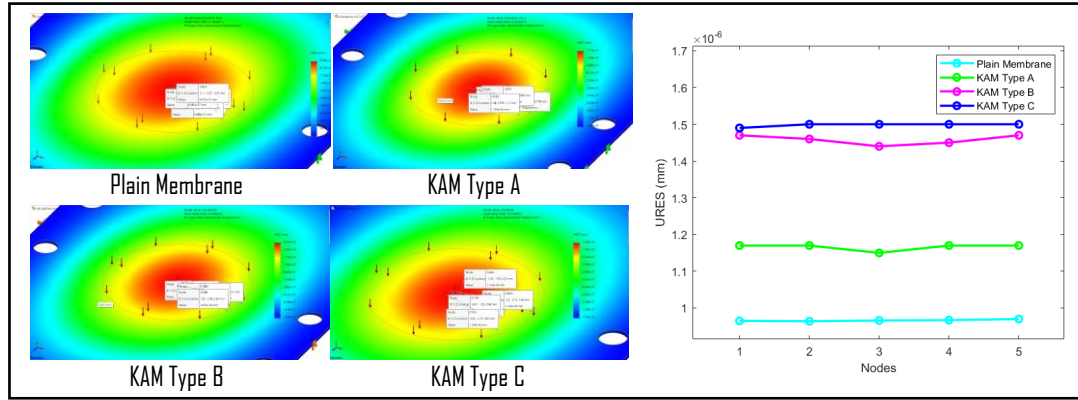


Figure 5.4 The deflection magnitude of each membrane is compared by selecting five random nodes in the red zone produced by the SolidWorks simulation.

In Figure 5.5, we analyze the stress distribution across the kirigami auxetic membrane. As observed in this figure, most of the center area of the three proposed KAM surfaces experience a higher level of stress compared to the plain membrane. The peak stress of 4.68, 7.2 Pa, 9.1 Pa, and 8.7 Pa were observed in the plain, KAM Type A, KAM Type B, and KAM Type C membranes respectively. Then, the membrane will transfer the stress of the applied waterdrop pressure over the PVDF. Therefore, we need to examine the raindrop energy harvester's performance as a unity device along with substrate and membrane to understand stress distribution on the PVDF voltage increase.

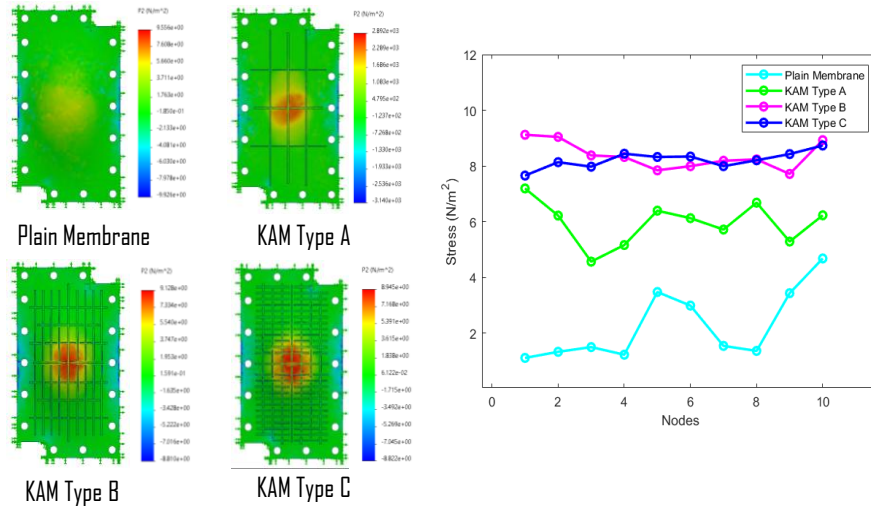


Figure 5.5 Membrane stress distribution by taking ten different nodes in the waterdrop impacted zone.

5.3 Impact of Waterdrop Falling Height Induced by Burette on Electric Potential Generation

The height from which a waterdrop falls significantly impacts the electric potential generated in raindrop energy harvesting systems. This effect is primarily due to the changes in the kinetic energy of the waterdrop as it falls. As the falling height increases, the velocity of the waterdrop increases due to gravity, leading to a higher kinetic energy upon impact. During this experiment, three KAMs are attached to the raindrop energy harvester device alternately. The initial voltage peak recorded by the oscilloscope was identified as the maximum voltage generated when waterdrops impacted the surface of the raindrop energy harvester, as referenced in previous research and illustrated in Figure 5.6 [112]. Different falling heights were tested at 15, 30, and 40 cm, and a thorough analysis of how the height of falling water drops affects electrical output performance was conducted, as illustrated in Figure 5.7. As the falling height increased, the electric potential demonstrated a corresponding increase, which was consistent with the changes in instantaneous velocity and kinetic energy of the water droplet impacting the surface of the energy harvester embedded with the kirigami auxetic membrane.

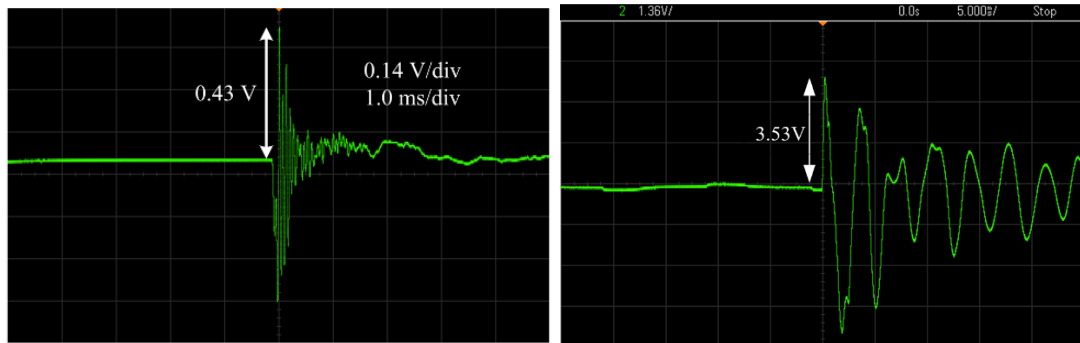


Figure 5.6 The voltage measurement method using the oscilloscope [112].

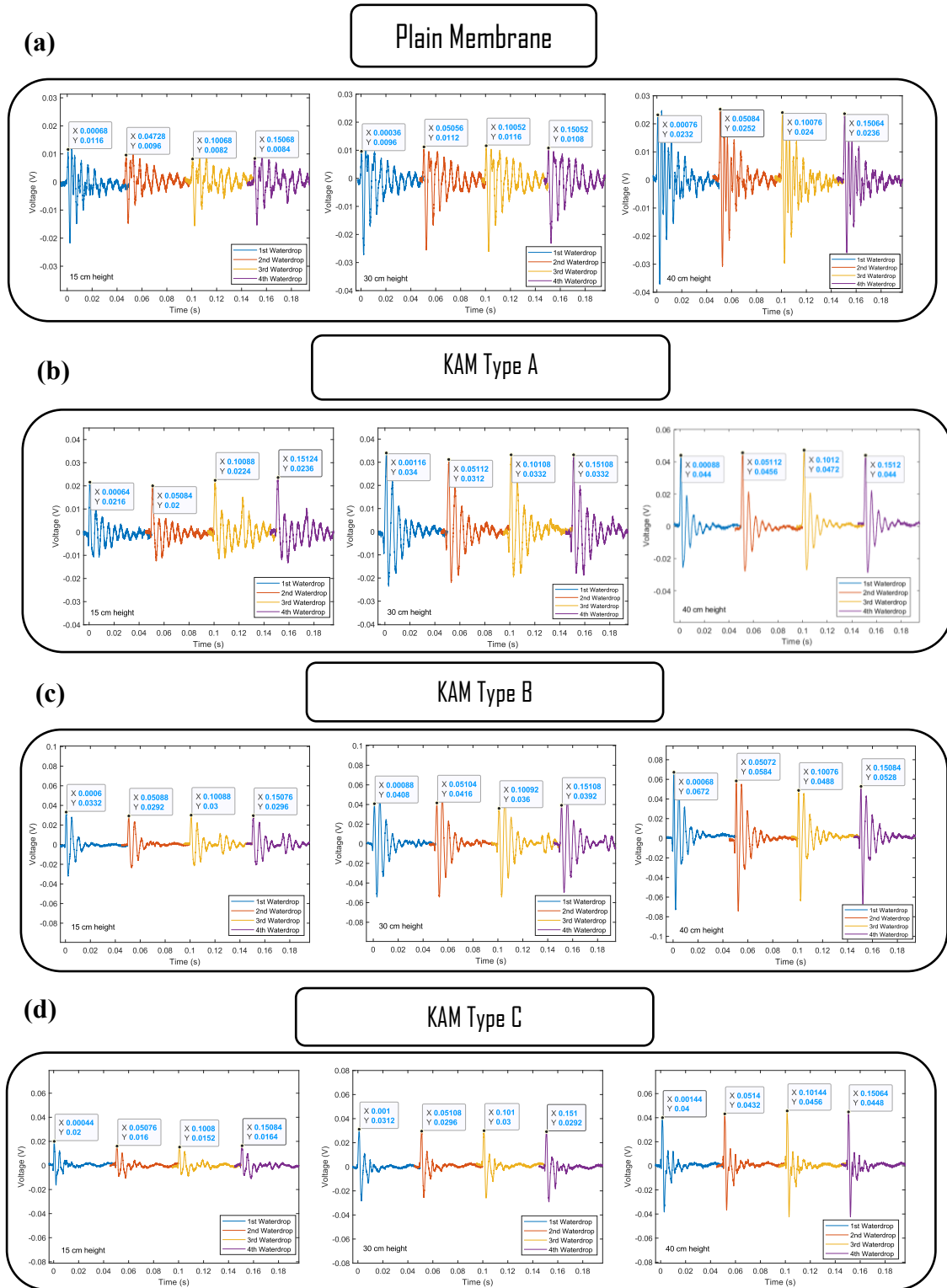
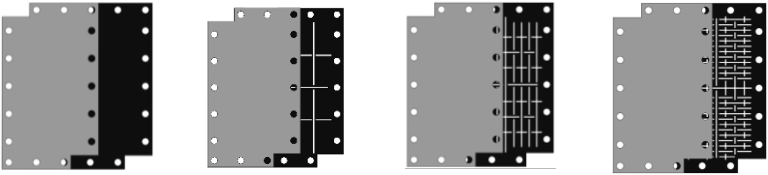


Figure 5.7 The electric potential of the raindrop energy harvester when varying the waterdrop falling height at 15, 30, and 40 cm when impinging four waterdrops and embedding (a) plain membrane (b) KAM Type A (c) KAM Type B (d) KAM Type C.

Figure 5.6 shows the voltage obtained from the experimental waterdrop impact tests for different heights of the burette and changing the KAM attached to the raindrop energy harvester for each attempt. Four different types of membranes consisting of plain, KAM Type A, B, and C membranes are tested in this experiment. The water droplet always impinges the central substrate and four water droplet impacts are measured. The experiment shows that the voltage generated by the harvester rises when the height of the burette is varied from 15 cm to 30 cm, and then to 40 cm as shown in Table 5.1.

Table 5.1 The effect of water droplets on the electrical output generated by the raindrop energy harvester which attached four different types of membranes at different falling heights.

				
Plain Membrane KAM Type A KAM Type B KAM Type C				
Height	Average Generated Voltage (mV)			
	Plain Membrane	KAM Type A	KAM Type B	KAM Type C
15 cm	9.5	21.9	30.8	15.8
30 cm	10.9	32.9	39.4	30
40 cm	24	45.2	55.8	43.4

With the increase in falling height, the electric potential showed a trend of increase, indicating a direct relationship between the height from which the object falls and the amount of electric potential generated. This trend suggests that as the gravitational potential energy of the object increases with greater height, it is converted more effectively into electric potential energy upon impact [119]. However, the produced electricity of the harvester by embedding KAM Type C is not parallel with its position as the most distributing waterdrop stress to the PVDF. The mismatch between stress distribution and electricity generation is primarily a geometric design issue related to how the auxetic pattern deforms and interacts with the PVDF. KAM Type C might be effective at distributing waterdrop stress, but its pattern geometry

might not be ideal for maximizing strain transfer to the PVDF because KAM Type C adopts beta (β) kirigami cutting mode which results in more lateral stretching instead of following the longitudinal (d_{31}) operation mode of piezoelectric. This condition leads to lower piezoelectric output despite high mechanical stress.

In natural settings, raindrops can travel distances of several tenths of a meter before striking an object on the ground, resulting in significantly higher kinetic energies that are challenging to replicate in a laboratory environment. Acquired from the experiment in the laboratory, KAM Type A, B, and C can enhance the voltage generation compared to the plain membrane. There is a significant increase when KAM is present in the raindrop energy harvester. At a maximum height of 40 cm, KAM Type A increases the generated voltage by 88.3%, reaching 45.2 mV; KAM Type B achieves a 132.5% increase, generating 55.8 mV; and KAM Type C boosts the voltage by 80.83%, producing 43.4 mV. In comparison, the plain membrane generates only 24 mV. KAM Type B is the most effective in all levels of height, likely due to its specific design features that better capture and convert the energy from falling water drops. KAM Type B generates 30.8 mV at a height of 15 cm, 39.4 mV at 30 cm, and 55.8 mV at 40 cm. Thus, the data suggests that the structural modifications in the membranes play a crucial role in improving energy conversion efficiency. The summarization and comparison of the average voltage generated by each membrane at different water drop heights is presented in Figure 5.8.

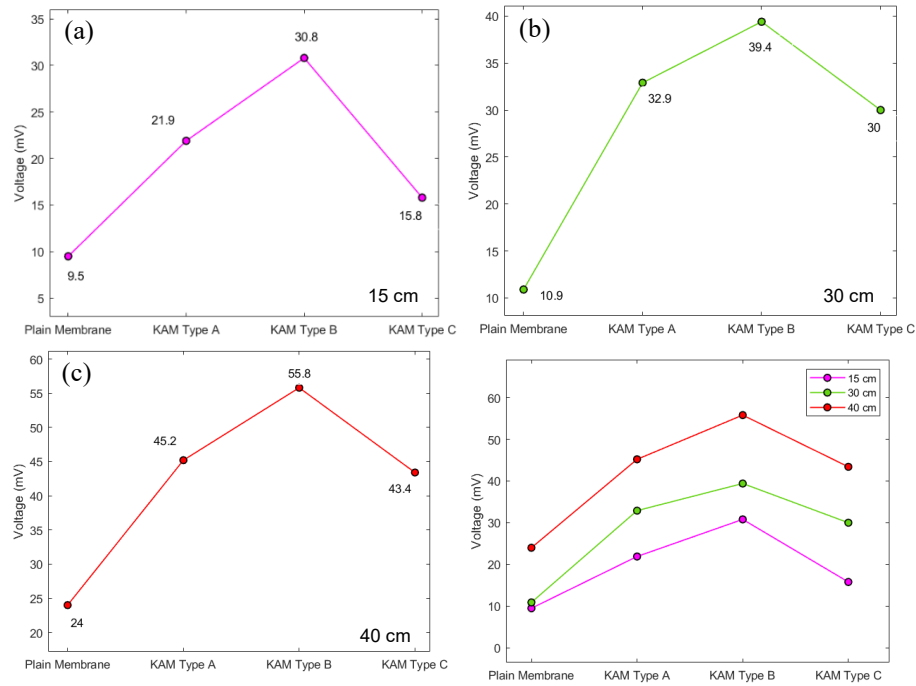


Figure 5.8 The comparison of the generated voltage by the raindrop energy harvester at waterdrop falling heights (a) 15 cm (b) 30 cm (c) 40 cm and (d) The combined graph showing the generated voltage at waterdrop falling heights of 15 cm, 30 cm, and 40 cm.

5.4 Impact of Raindrop Energy Harvester Inclination on Electric Potential Generation

Another parameter influencing the raindrop energy harvester interaction is the inclination of the harvester. The raindrop energy harvester can adopt different inclinations by considering waterdrop dynamics, water accumulation, and structural considerations. Figure 5.9 shows the voltage of the harvester at an inclination of 0° (horizontal), 20° , and 35° in downward orientation when water is dropping on a central position. Then, the value of the average generated voltage when the harvester was inclined will be shown in Table 5.2. The inclination of a raindrop energy harvester is a critical parameter that influences the impact dynamics, force distribution, and overall efficiency of energy capture. Properly optimizing the inclination based on specific environmental conditions can significantly enhance the performance of the harvester.

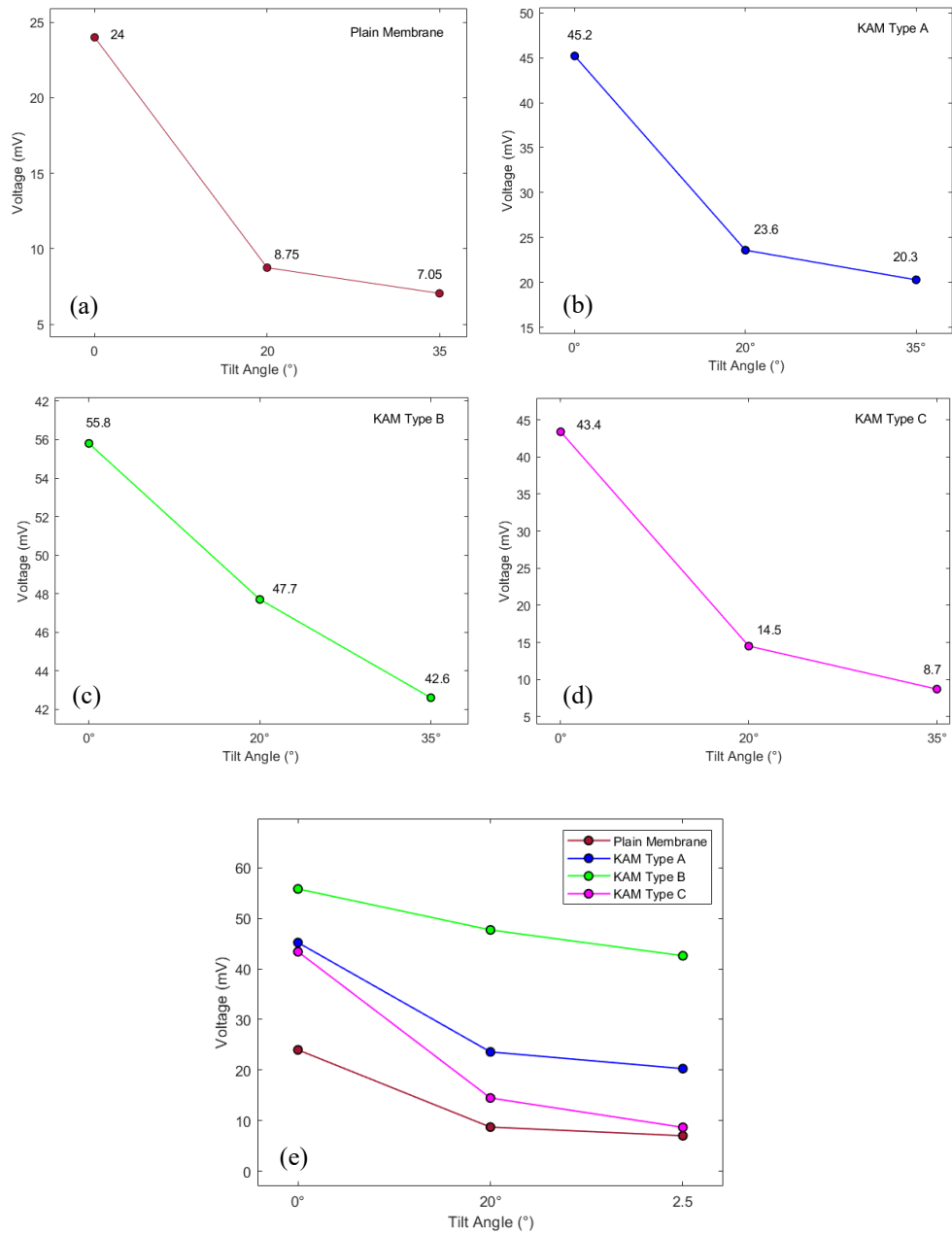


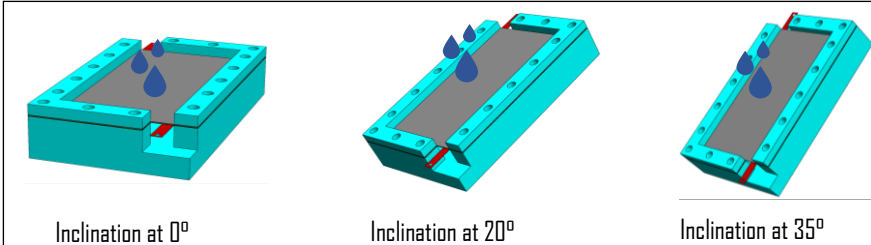
Figure 5.9 The comparison of the generated voltage by the inclined raindrop energy harvester at 0°, 20°, and 35° when the harvester attached (a) plain membrane (b) KAM Type A (c) KAM Type B (d) KAM Type C, and (e) The combined graph showing the generated voltage by the raindrop energy harvester when it is attached different membrane and inclined at 0°, 20°, and 35°.

For all types of membranes at the maximum distance of 40 cm, the optimal inclination for generating the highest voltage is at 0° which the result is similar to the waterdrop height analysis conducted before. As the inclination increases to 20° and

35°, the generated voltage generally decreases. For example, when the raindrop energy harvester is equipped with KAM Type B, it generates a voltage of 55.8 mV, which decreases to 47.7 mV and 42.6 mV as the inclination is adjusted to 20° and 35°, respectively. A huge gap in inclination angle was taken to capture an obvious response in the voltage generated by the harvester while ensuring that the waterdrops continue to fall perpendicularly onto the substrate surface.

In its application, the inclination will be applied to optimize the performance of the harvester based on specific environmental conditions. For example, wind can cause raindrops to fall at an angle rather than vertically. The direction and speed of the wind can change the trajectory of the raindrops, making them hit the harvester's surface at varying angles. When wind is present, the harvester might need to be inclined differently to align with the predominant direction of the wind-driven rain. When the raindrop energy harvester is inclined while the waterdrops continue to fall perpendicularly, several mechanical factors change, specifically affecting the stress distribution and reducing the contact angle between the membrane and the PVDF layer. The reduced contact angle leads to stress concentration at specific points, where only a certain part of the membrane is in full contact with the PVDF. These areas may experience higher localized pressure, but the rest of the membrane may not transfer significant stress to the PVDF. This unequal distribution of stress across the membrane leads to lower overall energy conversion of the harvester. Adjusting the angle to match the rain's trajectory can improve the efficiency of energy capture. In this analysis, it was found that minimizing the inclination of the harvester is advantageous for optimal energy harvesting when waterdrops fall perpendicularly.

Table 5.2 The effect of water droplet impacts on the electrical output of a raindrop energy harvester equipped with a plain membrane, KAM Type A, KAM Type B, and KAM Type C, at inclination angles of 0° (horizontal), 20°, and 35°.

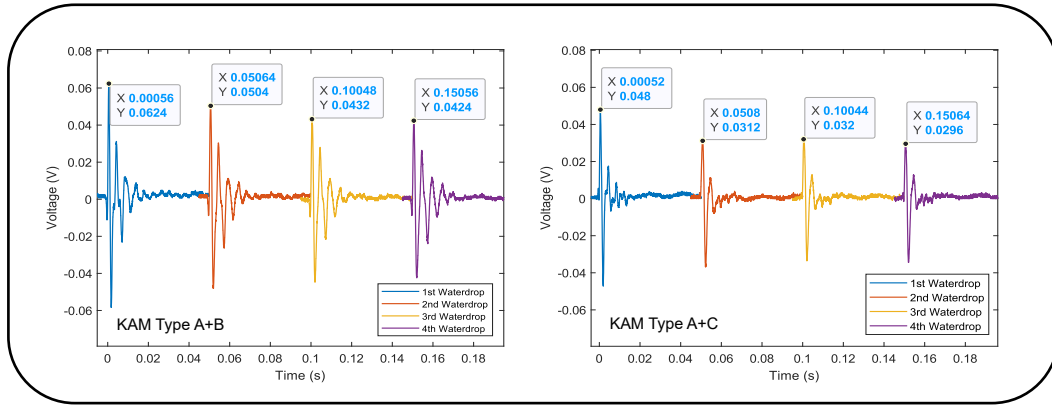
				
Inclination at 0° Inclination at 20° Inclination at 35°				
Inclination	Average Generated Voltage (mV)			
	Plain Membrane	KAM Type A	KAM Type B	KAM Type C
0°	24	45.2	55.8	43.4
20°	8.75	23.6	47.7	14.5
35°	7.05	20.3	42.6	8.7

5.5 Impact of Combining Two Different Types of Membranes on Electric Potential Generation

In the pursuit of optimizing energy capture from raindrop energy harvesters, the integration of diverse membrane designs offers a promising avenue for enhancing performance. By leveraging the unique patterning of each KAM type, it is possible to address the limitations observed when using a single KAM configuration. This subsection aims to identify synergistic effects and optimal combinations that maximize efficiency, paving the way for more effective and adaptable energy harvesting solutions. In total, six combinations of KAM will be tested, all with the waterdrop released from a height of 40 cm above the substrate surface. The sequence of the harvester structure in this experiment starts with the substrate on the top surface, followed by the KAM, which refers to the designated name of the combination. The recorded voltage signal acquired from the oscilloscope for examining two combinations of KAM is depicted in Figure 5.10.

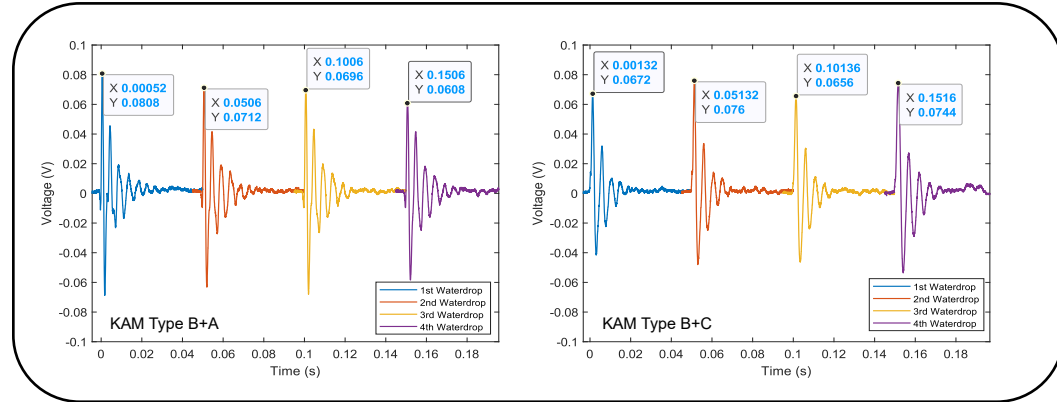
(a)

Combination of KAM Type (A+B) and (A+C)



(b)

Combination of KAM Type (B+A) and (B+C)



(c)

Combination of KAM Type (C+A) and (C+B)

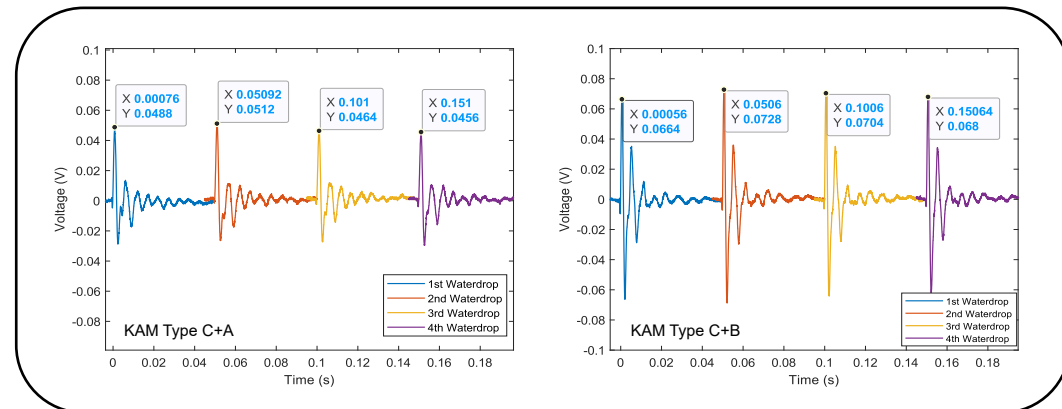
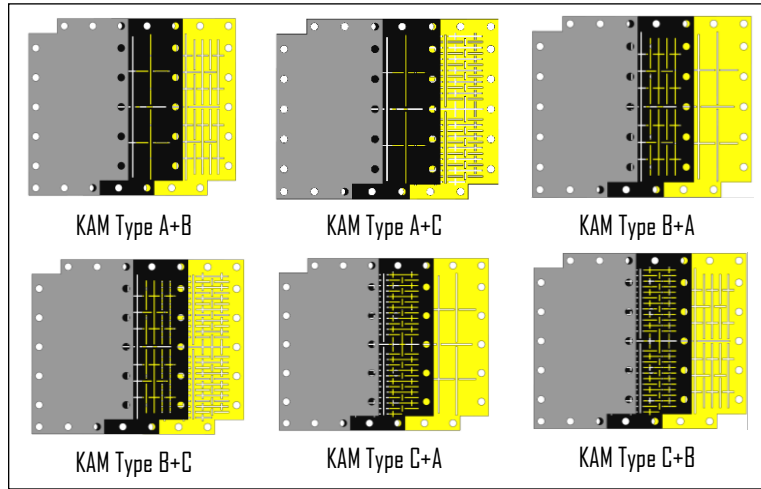


Figure 5.10 The electric potential of the raindrop energy harvester when impinged four waterdrops by employing two combinations of KAM (a) Combination of KAM Type (A+B) and (A+C) (b) Combination of KAM Type (B+A) and (B+C) (c) Combination of KAM Type (C+A) and (C+B).

Examining the KAM Type A, B, and C combination aims to identify the most effective pairings that improve overall efficiency and generated voltage. The results shown in Figure 5.9 indicate that specific combinations of KAM Type B with KAM Type C have higher average voltages at 70.8 mV when the waterdrop is exposed to the harvester surface, suggesting a synergistic interaction that could inform future design strategies for more efficient raindrop energy harvesters. KAM Type B, when paired with either Type A or Type C, consistently produced high average voltages (70.6 mV and 70.8 mV, respectively). Comparing the pair of KAM Type B+C to the single KAM Type B which only can afford 55.8 mV, the combination of KAM Type B+C can increase the electric potential by up to 26.83%. These insights underscore the importance of strategic membrane combinations in optimizing the performance of raindrop energy harvesters, pointing to the potential benefits of leveraging the unique properties of different kirigami designs. The whole electric potential generated by the raindrop energy harvester when employing a combination of two KAMs is summarized in Table 5.3.

Table 5.3 The voltage generated by the raindrop energy harvester employs two combinations of KAM when four water droplets are exposed to the harvester surface.



The Pairing of Membranes	1st Waterdrop	2nd Waterdrop	3rd Waterdrop	4th Waterdrop	Average Generated Voltage (mV)
KAM Type A+B	62.4	50.4	43.2	42.4	49.6
KAM Type A+C	48	31.2	32	29.6	35.2

KAM Type B+A	80.8	71.2	69.6	60.8	70.6
KAM Type B+C	67.2	76	65.6	74.4	70.8
KAM Type C+A	48.8	51.2	46.4	45.6	48
KAM Type C+B	66.4	72.8	70.4	68	69.4

5.6 Impact of Combining Similar Type of Membranes on Electric Potential Generation

Combining similar types of membranes, particularly in the context of kirigami auxetic membranes, can have a substantial impact on the voltage generated by these systems. This approach was evaluated during the experiment to assess the energy harvester's response when using similar types of membranes, effectively increasing the membrane's thickness. The voltage generated by the raindrop energy harvester when a similar type of KAM is attached has been obtained as shown in Figure 5.11.

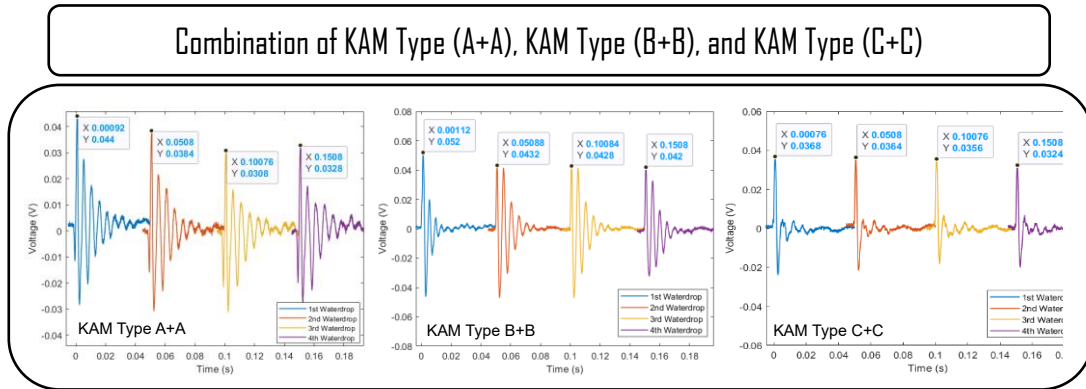


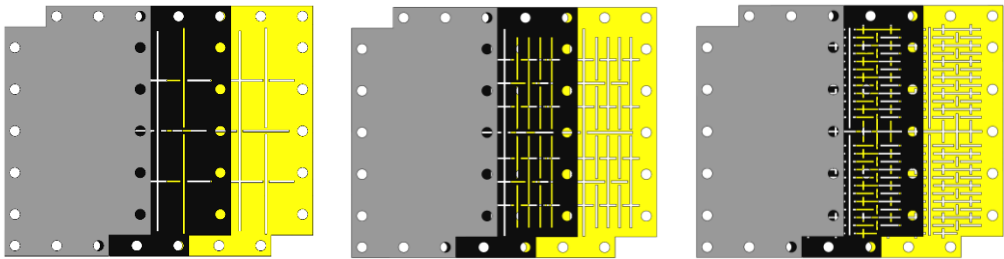
Figure 5.11 The electric potential of raindrop energy harvester when impinged four waterdrops by employing similar types of KAM Type (A+A), KAM Type (B+B), and KAM Type (C+C).

From Figure 5.11, combining similar types of KAMs results in a decrease in voltage generation. This reduction in voltage is attributed to the increased membrane thickness when similar KAMs are used together in the energy harvester. As the membrane thickness increases, the stretchability transferred from the membrane to the PVDF decreases, leading to lower generated voltage. Increasing the thickness of a material generally leads to a decrease in its stretchability due to it will improve the

rigidity of the material. Thicker materials tend to be more rigid and less flexible. The additional thickness provides more resistance to deformation because there is a greater amount of material that needs to be stretched. This increased rigidity reduces the overall ability of the material to elongate under stress.

The experimental results demonstrated a significant decrease in voltage generation when combining similar types of KAMs in raindrop energy harvesting applications. Specifically, the average voltage generated by the KAM Type (A+A) combination was 36.5 mV, which represents a 19.25% decrease compared to the 45.2 mV generated by a single KAM Type A membrane. Similarly, the KAM Type (B+B) combination produced an average voltage of 45 mV, showing a 20.95% decrease from the 56.8 mV generated by a single Type B membrane. The KAM Type (C+C) combination had an average voltage of 35.3 mV, indicating an 18.66% decrease from the 43.4 mV generated by a single KAM Type C membrane. These findings suggest that the increased thickness resulting from combining similar membranes negatively impacts their stretchability and efficiency, thereby reducing the overall voltage output in the range of 18 – 20%. The result of the generated voltage when applying a similar type of membrane during the experiment is summarized in Table 5.4.

Table 5.4 The voltage generated by the raindrop energy harvester employing similar type of KAMs when four water droplets are exposed to the harvester surface.

					
KAM Type (A+A) KAM Type (B+B) KAM Type (C+C)					
The Pairing of Membranes	1st Waterdrop	2nd Waterdrop	3rd Waterdrop	4th Waterdrop	Average Generated Voltage (mV)
KAM Type A+A	44	38.4	30.8	32.8	36.5
KAM Type B+B	52	53.6	60	57.6	45

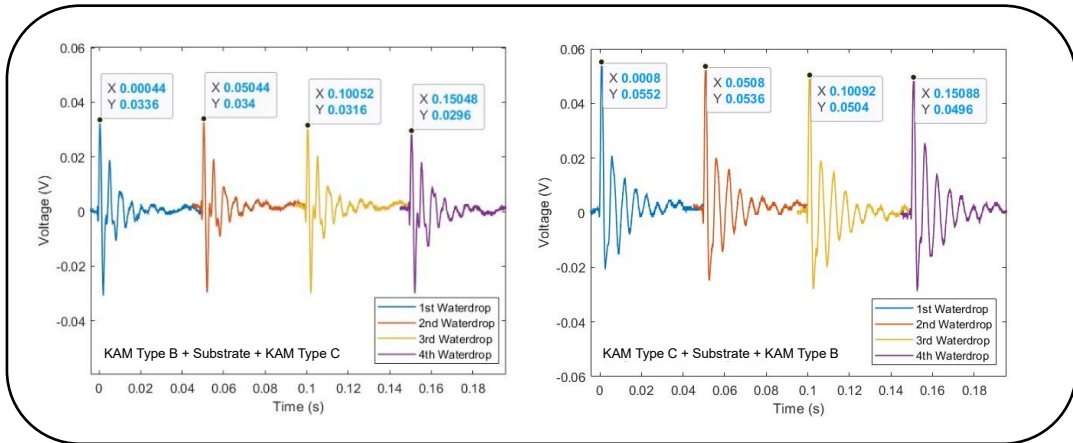
KAM Type C+C	36.8	36.4	35.6	32.4	35.3
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5.7 Impact of Modifying the Sequence of Substrate and the Kirigami Auxetic Membrane Type (B+C) on Electric Potential Generation

Modifying the sequence of the substrate and KAM expected can have a significant impact on the voltage generated in energy harvesting systems. The arrangement and layering of these materials influence how mechanical energy from waterdrops is transferred and converted into electrical energy. By altering the sequence in which the substrate and KAM are positioned, the stress distribution, stretchability, and interaction between the layers can change, potentially enhancing or reducing the efficiency of voltage generation. In this experiment, the sequence of the most effective voltage generation achieved using the combination of two KAMs arranged as Substrate + KAM Type B + KAM Type C will be changed and modified to obtain the response of the energy harvester on converting mechanical energy from waterdrops into electrical energy. The result of the experiment is shown in Figure 5.12.

(a)

Combination of (KAM Type B + Substrate + KAM Type C) and (KAM Type C + Substrate + KAM Type B)



(b) Combination of (KAM Type B + KAM Type C + Substrate) and (KAM Type C + KAM Type B + Substrate)

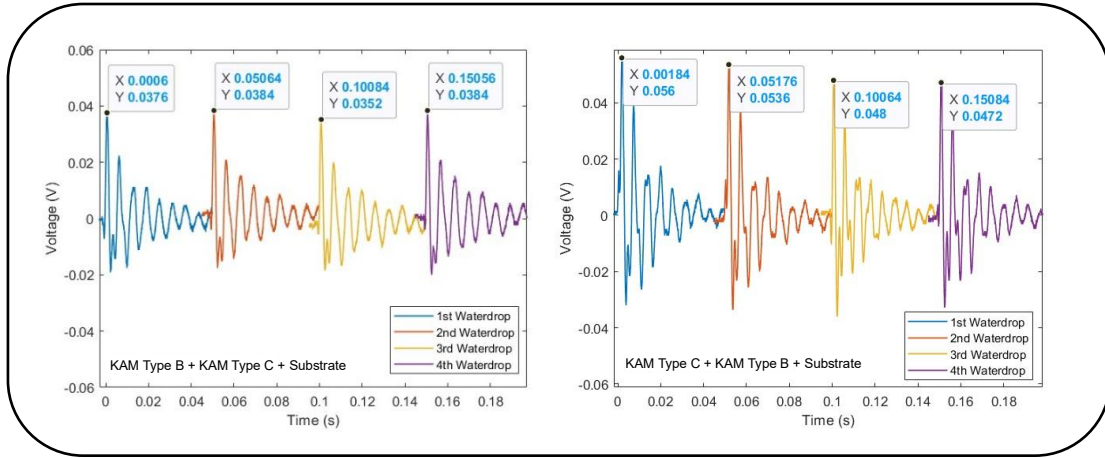


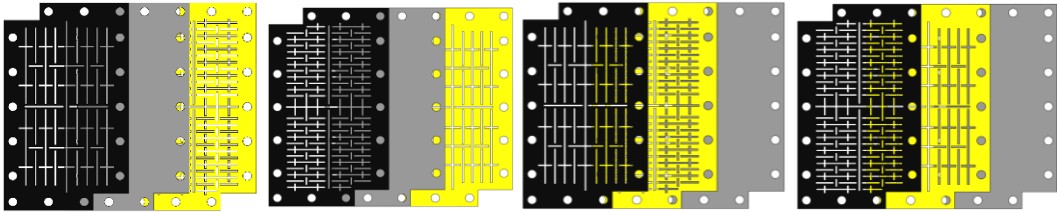
Figure 5.12 The electric potential of the raindrop energy harvester when impinged four waterdrops by employing and sequence modifying of two combinations of KAMs and substrate (a) Combination of (KAM Type B + Substrate + KAM Type C) and (KAM Type C + Substrate + KAM Type B) (b) Combination of (KAM Type B + KAM Type C + Substrate) and (KAM Type C + KAM Type B + Substrate).

Across all the sequence modifications tested in the experiment, a consistent decreasing trend in voltage generation was observed. Despite varying the arrangement of substrates and KAM, the results uniformly showed a decline in output, suggesting that these sequence changes did not favourably impact the energy conversion efficiency. This condition may be attributed to the placement of a thick, unpatterned substrate either in the middle or at the lowest position (before the PVDF membrane) within the KAM and substrate sequence. A thick, unpatterned substrate tends to be more rigid, which limits the overall flexibility and stretchability of the combined layers. This rigidity can hinder the ability of the system to effectively transfer mechanical energy from the KAM to the PVDF, resulting in lower energy conversion efficiency. The thickness and lack of patterning in the substrate also increase the material's resistance to deformation. This can reduce the amplitude of membrane movement in response to external forces like waterdrops, which are critical for generating higher voltages.

The sequences KAM Type B + Substrate + KAM Type C and KAM Type B + KAM Type C + Substrate exhibit lower average voltages of 32.2 mV and 37.4 mV

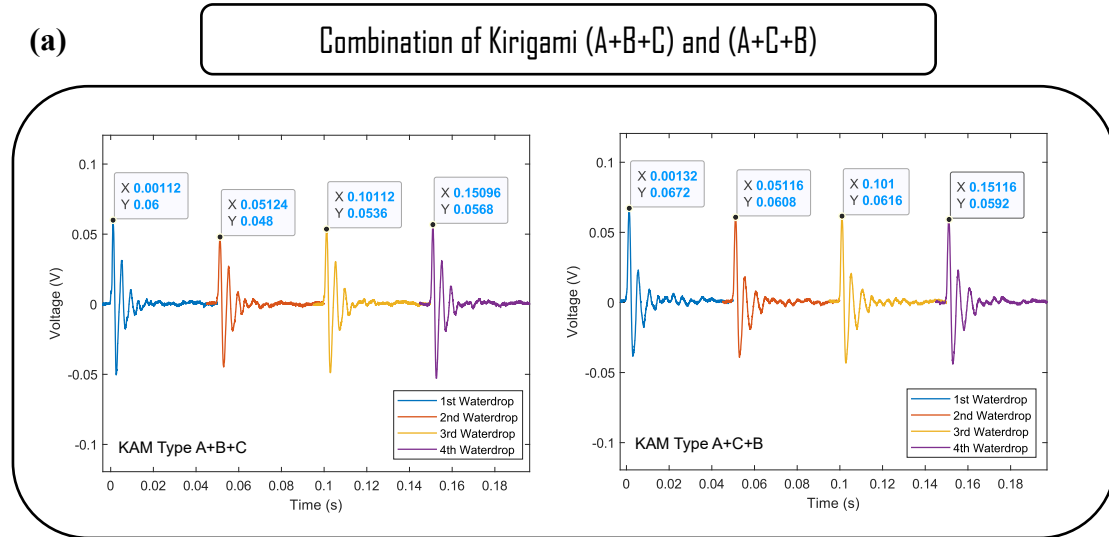
respectively. This indicates that these specific sequences might impede effective energy transfer due to suboptimal mechanical coupling or stress distribution. In contrast, the sequences KAM Type C + Substrate + KAM Type B and KAM Type C + KAM Type B + Substrate generate higher voltages of 52.2 V and 51.2 V. While placing KAM Type C first shows some improvement, the presence of the substrate still introduces inefficiencies. So, any modification involving the insertion of a substrate between the KAM layers or after them reduces the voltage generation compared to the original KAM Type B+C combination with the substrate placed on the top side which can afford 70.8 mV voltage. The original sequence without moving substrate position remains the most efficient configuration for generating voltage in this system. The summarization of the generated voltage by modifying the sequence of the original combination is shown in Table 5.5.

Table 5.5 The voltage generated by the raindrop energy harvester employing the sequence modified of two combinations of KAMs and substrate when four water droplets are exposed to the harvester surface.

					
KAM Type B + Substrate + KAM Type C KAM Type C + Substrate + KAM Type B KAM Type B + KAM Type C + Substrate KAM Type C + KAM Type B + Substrate					
The Pairing of Membranes	1st Waterdrop	2nd Waterdrop	3rd Waterdrop	4th Waterdrop	Average Generated Voltage (mV)
KAM Type B + Substrate + KAM Type C	36	34	31.6	29.6	32.2
KAM Type C + Substrate + KAM Type B	55.2	53.6	50.4	49.6	52.2
KAM Type B + KAM Type C + Substrate	37.6	38.4	35.2	38.4	37.4
KAM Type C + KAM Type B + Substrate	56	53.6	48	47.2	51.2

5.8 Impact of Combining Three Different Types of Membranes on Electric Potential Generation

The other effort to optimize energy capture from raindrop energy harvesters was made by examining the impact of integrating three distinct types of membranes to achieve optimum generated voltage. Similar to the combination of two types of membranes, by leveraging the unique properties and synergistic interactions of these membranes, this attempt aims to enhance the efficiency, durability, and adaptability of energy harvesting systems. This exploration seeks to provide insights into how such combinations can revolutionize the field of renewable energy, paving the way for more effective and sustainable solutions. Six combinations will be tested, each with the waterdrop released from a height of 40 cm above the surface as well. The harvester structure begins with the substrate on the top surface, followed by the KAM as specified by the designated combination name. The result of the generated voltage by the harvester is shown in Figure 5.13 below.



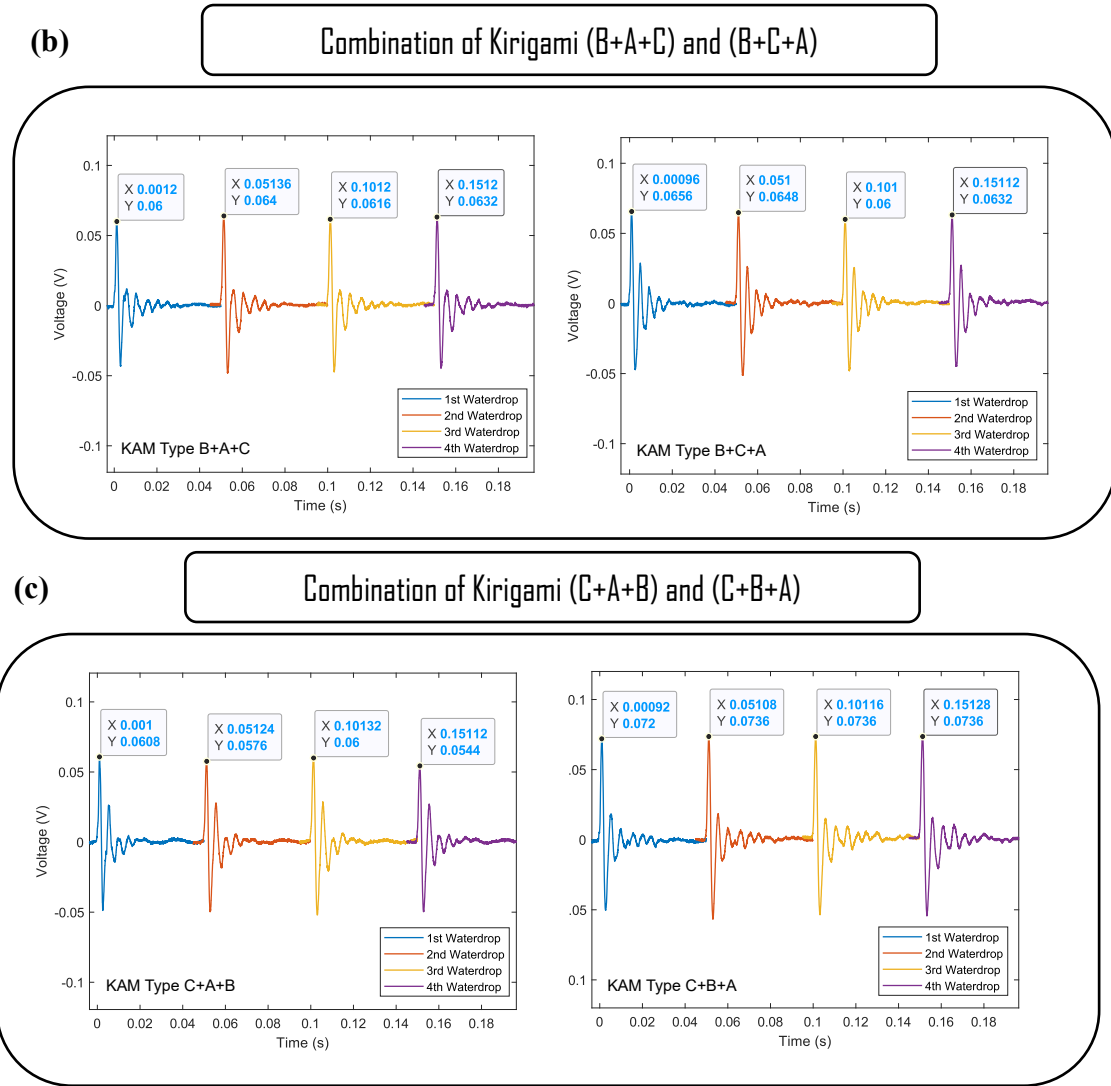
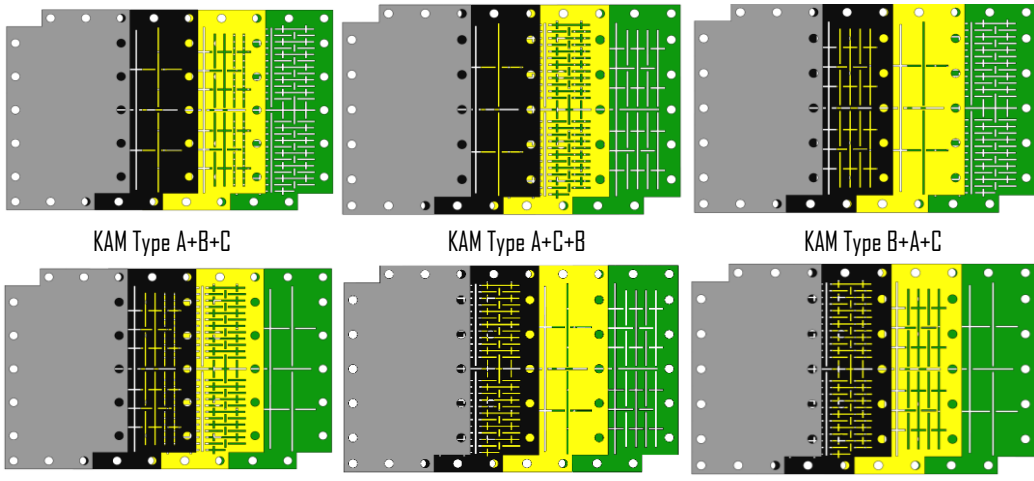


Figure 5.13 The electric potential of raindrop energy harvester when impinged four waterdrops by employing three combinations of KAM (a) Combination KAM Type (A+B+C) and (A+C+B) (b) Combination of KAM Type (B+A+C) and (B+C+A) (c) Combination of KAM Type (C+A+B) and (C+B+A).

The combination of KAM Type C+B+A produced the highest average voltage of 73.2 mV. This suggests that this sequence of membranes is particularly effective at maximizing voltage generation. The combination of KAM Type C+B+A also demonstrated consistent voltage potentials across all four impinged waterdrops to the raindrop energy harvester, with values of 72 mV, 73.6 mV, 73.6 mV, and 73.6 V sequentially. This consistency indicates reliable performance and stability when the harvester is equipped with three combinations of membranes. Each KAM (Type C, B,

and A) may have different mechanical deformation properties, such as varying flexibility, stiffness, and strain distribution. When these membranes are combined in a sequence, they lead to a more balanced and efficient stress distribution, maximizing the piezoelectric response. Compared to the combination of KAM B+C in two combinations of membranes, KAM Type C+B+A generates approximately 3.39% more voltage. Thus, the combination KAM Type C+B+A emerged as the most effective configuration, generating the highest and most consistent average voltage. The summarization of the generated voltage recorded by the oscilloscope for three combinations of membranes is shown in Table 5.6.

Table 5.6 The voltage generated by the raindrop energy harvester employing three combinations of KAM when four water droplets are exposed to the harvester surface.

					
KAM Type A+B+C KAM Type A+C+B KAM Type B+A+C KAM Type B+C+A KAM Type C+A+B KAM Type C+B+A					
The Pairing of Membranes	1st Waterdrop	2nd Waterdrop	3rd Waterdrop	4th Waterdrop	Average Generated Voltage (mV)
KAM Type A+B+C	60	48	53.6	56.8	54.6
KAM Type A+C+B	67.2	60.8	61.6	59.2	62.2
KAM Type B+A+C	60	64	61.6	63.2	62.2
KAM Type B+C+A	65.6	64.8	60	63.2	63.4
KAM Type C+A+B	60.8	57.6	60	54.4	58.2
KAM Type C+B+A					

KAM Type C+B+A	72	73.6	73.6	73.6	73.2
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Then, the comparison of the equipped kirigami auxetic membrane's impact on the voltage generation such as a single KAM, two combinations of KAMs, and three combinations of KAMs are illustrated in Figure 5.14. All of those generated voltages were measured at the maximum distance level of the burette to the raindrop energy harvester surface (40 cm).

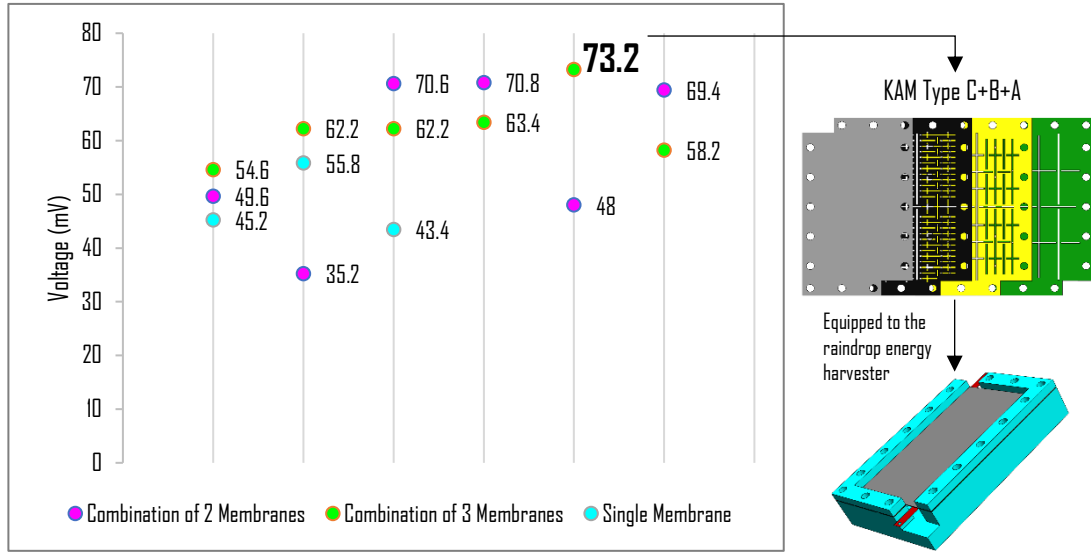


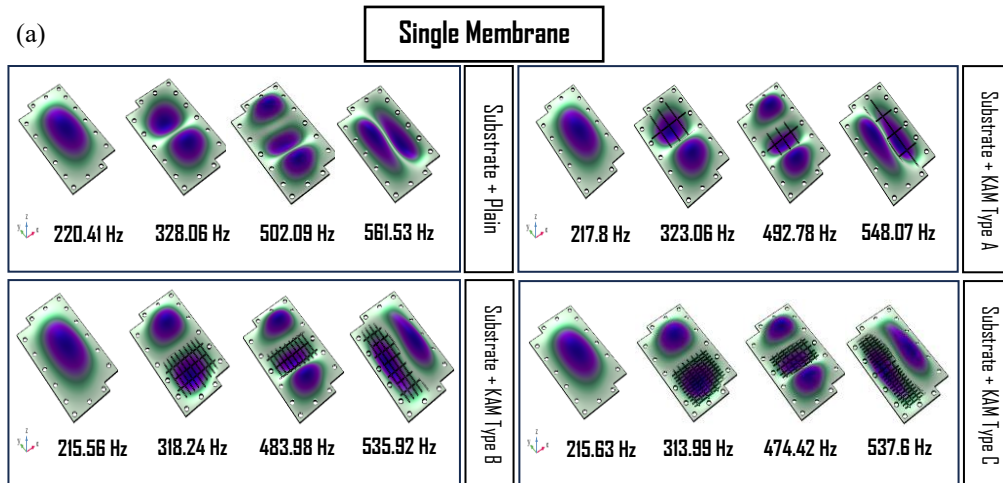
Figure 5.14 The generated voltage comparison of the raindrop energy harvester when employing single and combined kirigami auxetic membranes (KAMs).

Based on the provided chart comparing the PVDF-generated voltage across different KAM configurations, the combination of three membranes shows a noticeable advantage in generating the highest voltage across all scenarios, suggesting a synergistic effect when kirigami auxetic membranes (KAM) type C, B, and A are combined, it can generate 73.2 mV as the highest recorded voltage.

5.9 Energy Harvester Efficiency Analysis of Membrane Utilization

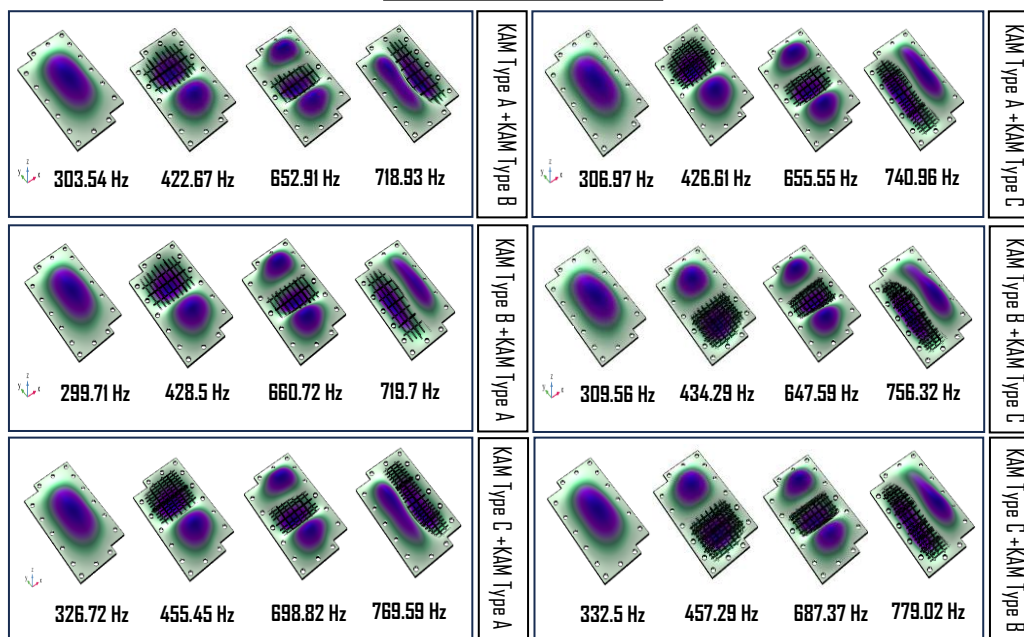
"Efficiency, often referred to as energy conversion efficiency, typically denotes the ratio of output energy to input energy within a system. To ensure consistency, the

efficiency of the piezoelectric energy harvester can be defined similarly, as the ratio of output electrical energy E_{out} to input mechanical energy E_{in} , expressed as $\eta = E_{out}/E_{in}$. This section examines the efficiency of the energy harvester when the full range of membrane combinations is applied to the system as discussed in the previous section. The electrical power and the harvester's energy conversion efficiency may then be determined using the data that was produced. At first, the finite element analysis of each combination is examined. The sensitivity enhancement of the suggested combination was examined using finite element analysis (FEA) to obtain the first natural frequency of the membrane combination and to calculate the efficiency of the raindrop energy harvester. The COMSOL Multiphysics software's three-dimensional geometric module was used to model all of the membrane designs whether single or combined that were suggested in the preceding section. Table 3.1 was used to input the PLA material and mechanical properties into the software. Figure 5.15 shows the FEA results for whole models of the substrate and membranes.



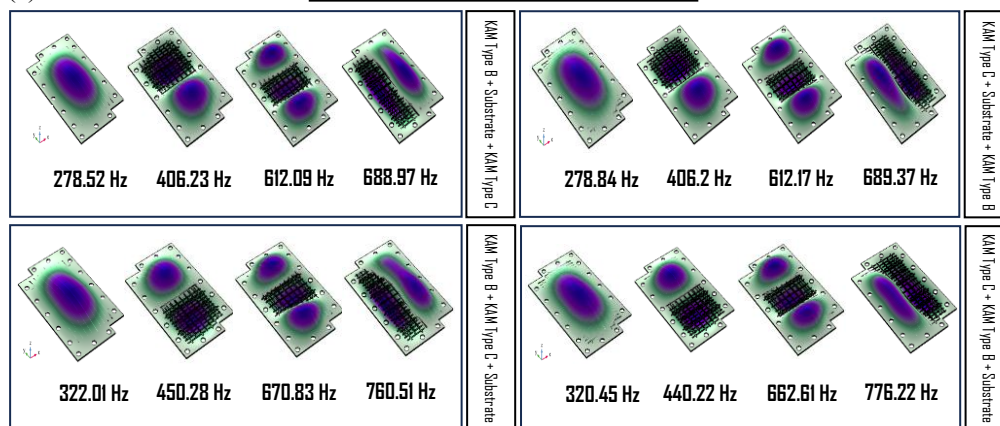
(b)

Combination of two KAMs



(c)

Modifying the Sequence of two KAMs



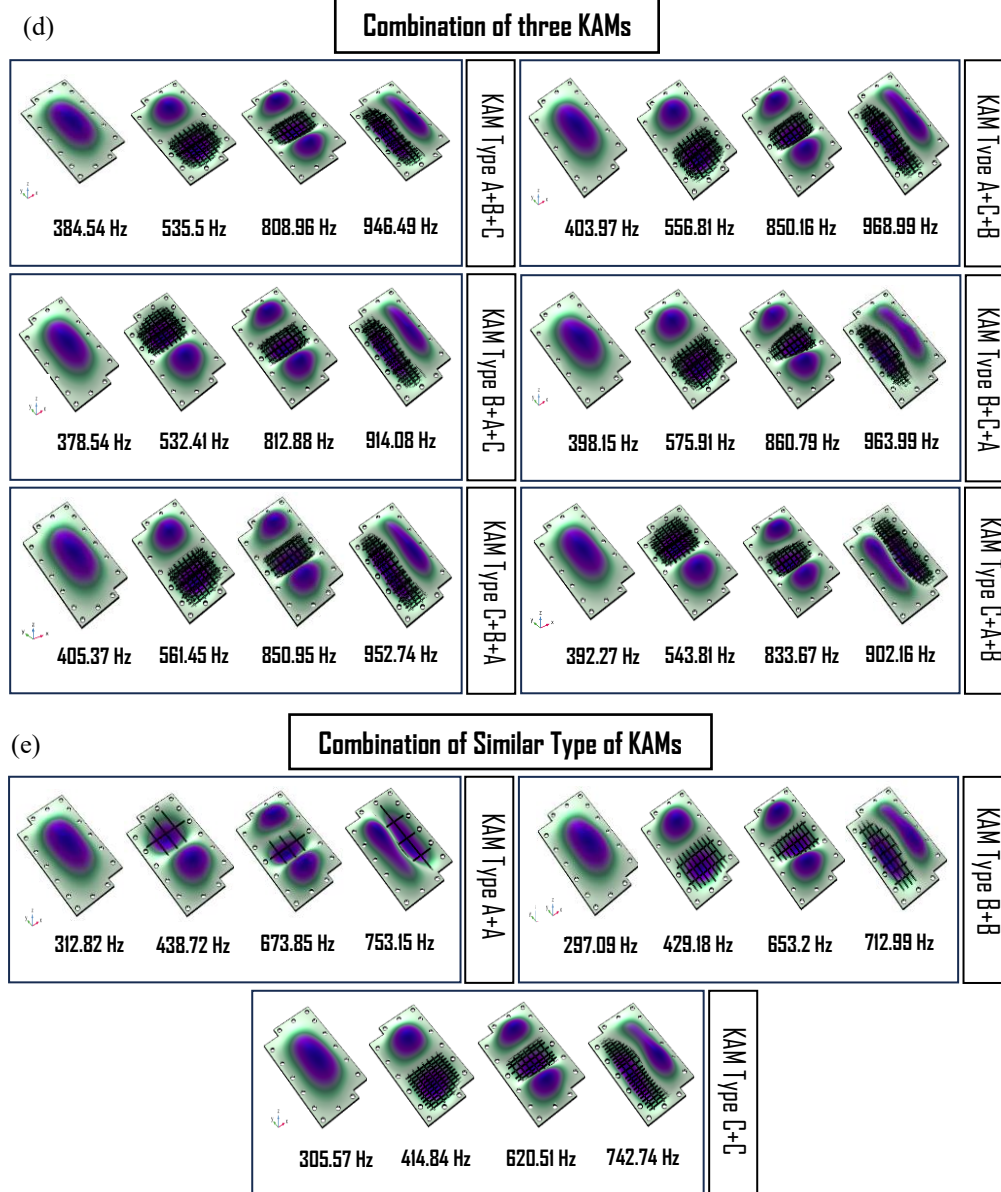


Figure 5.15 Mode shapes and natural frequency of the harvester when employing (a) Single membrane (b) Combination of two KAMs (c) Modifying the sequence of two KAMs (d) Combination of three KAMs (e) Combination of similar type of KAMs.

The COMSOL Multiphysics software's eigenfrequency analysis was used to determine the initial natural frequencies of each attempt and mode shapes. As shown in that Figure, the first natural frequency of each combination tested during the experiment takes place as shown in Table 5.7. It is noticeable that membrane design

and sequencing affect the resonance frequency, which varies between 215.56 (Hz) to 405.37 (Hz).

Table 5.7 The first natural frequency of attempt during the experiment.

Combination	First Natural Frequency of Each Attempt (Hz)
Substrate + Plain	220.41
Substrate + KAM Type A	217.8
Substrate + KAM Type B	215.56
Substrate + KAM Type C	215.63
KAM Type A + KAM Type B	303.54
KAM Type A + KAM Type C	306.97
KAM Type B + KAM Type A	299.71
KAM Type B + KAM Type C	309.56
KAM Type C + KAM Type A	326.72
KAM Type C + KAM Type B	332.5
KAM Type B+ Substrate +KAM Type C	278.52
KAM Type C+ Substrate +KAM Type B	278.84
KAM Type B+ KAM Type C+ Substrate	322.01
KAM Type C+ KAM Type B+ Substrate	320.45
KAM Type A+B+C	384.54
KAM Type A+C+B	403.97
KAM Type B+A+C	378.54
KAM Type B+C+A	398.15
KAM Type C+B+A	405.37
KAM Type C+A+B	392.27
KAM Type A+A	312.82
KAM Type B+B	297.09
KAM Type C+C	305.57

To determine the efficiency of the energy harvester, it is essential to first determine the initial energy of a single water droplet. Referring to Figure 5.3, the velocity of a droplet after falling from a height of 40 cm from the burette to the harvester surface is measured at 2.8 m/s. Assuming the droplet has a diameter of 2 mm, the kinetic energy of the impact, calculated using Equation 5.3, is found to be 1.6×10^{-5} Joules. After having obtained the energy of a water droplet, then the electrical power is calculated as shown in Equation 5.4 [120].

$$W_{el} = \frac{1}{2R_{opt}} \int_0^{t_{max}} V^2 dt \quad (5.4)$$

Where the W_{el} (Joule) is the electrical power generated by the harvester, R_{opt} (Ω) is the optimal resistance which refers to the specific electrical resistance that maximizes the efficiency of a device designed to convert the kinetic energy of waterdrops into electrical energy. If the resistance is too high or too low compared to the optimal value, the amount of energy harvested will be less because the mechanical energy from the waterdrops is not fully converted into electrical energy. The t_{max} (s) refers to the maximum time duration over which the voltage is integrated, and V (Volt) is the average voltage generated by the energy harvester. The optimal resistance is necessary to be determined before calculating the generated electrical power by utilizing Equation 5.5 below [120]. In raindrop energy harvester application, the natural frequency of the substrate-KAM-piezo system will dictate the conditions under which the system is most effective. By incorporating the first natural frequency into the R_{opt} equation, we can ensure that our electrical load is tuned to the mechanical response of the system, thereby optimizing energy harvesting efficiency.

$$R_{opt} = \frac{1}{\omega C_p} \quad (5.5)$$

The first mode frequency of the energy harvester is represented as ω (Hz) as shown in Table 5.7, and C_p (F) is internal capacitance which indicates the ability of the device to store electrical energy generated by the deformation of the material when impacted by a waterdrop. The internal capacitance can be determined by using Equation 5.6.

$$C_p = \frac{\epsilon_r \epsilon_0 A}{d} \quad (5.6)$$

The internal capacitance is affected by several factors such as the relative permittivity or dielectric constant of PVDF (ϵ_r), the relative permittivity of free space (ϵ_0) which has a constant value of approximately 8.854×10^{-12} F/m [121], the area of the PVDF material exposed to the electric field (A) measured in m^2 , and the thickness of the PVDF material (d) in meters. The value of $\epsilon_r = 12.5$, $A = 5 \times 10^{-3} m^2$, and $d = 110 \times 10^{-6} m$ is obtained from PVDF material properties in Tables 4.1 and 4.2. Thus, the value of C_p can be determined:

$$C_p = \frac{\varepsilon_r \varepsilon_0 A}{d} = 5.028 \times 10^{-9} F$$

On the other hand, the optimal resistance (R_{opt}), electrical power (W_{el}), and efficiency of energy harvester are able to be calculated by utilizing the known parameters which have been summarized in Table 5.8.

Table 5.8 The calculation result of optimal resistance, electrical power, and energy harvester efficiency of each membrane and substrate combination.

Combination	ω_r (Hz)	C_p (F)	R_{opt} (Ω)	Avg. Voltage (mV)	t (s)	W_{el} (J)	$W_{droplet}$ (J)	η (%)	Number
Subs. + Plain	220.41	5.028×10^{-9}	902273.293	24	0.05	1.596×10^{-11}	0.000016	9.9748×10^{-5}	1
Subs. + KAM Type A	217.8	5.028×10^{-9}	913085.659	36.5	0.05	3.65×10^{-11}	0.000016	0.00022798	2
Subs. + KAM Type B	215.56	5.028×10^{-9}	922574.023	55.8	0.05	8.44×10^{-11}	0.000016	0.00052734	3
Subs. + KAM Type C	215.63	5.028×10^{-9}	922274.528	43.4	0.05	5.12×10^{-11}	0.000016	0.00031911	4
KAM Type A+ KAM Type B	303.54	5.028×10^{-9}	655169.192	49.6	0.05	9.39×10^{-11}	0.000016	0.00058672	5
KAM Type A+KAM Type C	306.97	5.028×10^{-9}	647848.508	35.2	0.05	4.78×10^{-11}	0.000016	0.00029884	6
KAM Type B+KAM Type A	299.71	5.028×10^{-9}	663541.612	70.6	0.05	1.88×10^{-10}	0.000016	0.00117371	7
KAM Type B+KAM Type C	309.56	5.028×10^{-9}	642428.145	70.8	0.05	1.95×10^{-10}	0.000016	0.00121916	8
KAM Type C+KAM Type A	326.72	5.028×10^{-9}	608686.51	48	0.05	9.46×10^{-11}	0.000016	0.00059144	9
KAM Type C+KAM Type B	332.5	5.028×10^{-9}	598105.433	69.4	0.05	2.01×10^{-10}	0.000016	0.00125823	10
KAM Type B+ Subs.+ KAM Type C	278.52	5.028×10^{-9}	714024.33	32.2	0.05	3.63×10^{-11}	0.000016	0.00022689	20
KAM Type C+ Subs.+ KAM Type B	278.84	5.028×10^{-9}	713204.908	52.2	0.05	9.55×10^{-11}	0.000016	0.00059696	21
KAM Type B+KAM Type C+ Subs.	322.01	5.028×10^{-9}	617589.691	37.4	0.05	5.66×10^{-11}	0.000016	0.00035389	22
KAM Type C+KAM Type B+ Subs.	320.45	5.028×10^{-9}	620596.213	51.2	0.05	1.06×10^{-10}	0.000016	0.00066001	23
KAM Type A+B+C	484.54	5.028×10^{-9}	410430.628	54.6	0.05	1.82×10^{-10}	0.000016	0.00113492	11
KAM Type A+C+B	403.97	5.028×10^{-9}	492289.171	62.2	0.05	1.96×10^{-10}	0.000016	0.00122795	12
KAM Type B+A+C	378.54	5.028×10^{-9}	525360.745	62.2	0.05	1.84×10^{-10}	0.000016	0.00115065	13
KAM Type B+C+A	398.15	5.028×10^{-9}	499485.261	63.4	0.05	2.01×10^{-10}	0.000016	0.00125741	14
KAM Type C+B+A	405.37	5.028×10^{-9}	490588.984	73.2	0.05	2.73×10^{-10}	0.000016	0.00170657	15
KAM Type C+A+B	392.27	5.028×10^{-9}	506972.383	58.2	0.05	1.67×10^{-10}	0.000016	0.00104395	16
KAM Type A+A	312.82	5.028×10^{-9}	635733.19	36.5	0.05	5.24×10^{-11}	0.000016	0.00032744	17
KAM Type B+B	297.09	5.028×10^{-9}	669393.303	45	0.05	7.56×10^{-11}	0.000016	0.00047268	18
KAM Type C+C	305.57	5.028×10^{-9}	650816.692	35.3	0.05	4.79×10^{-11}	0.000016	0.00029916	19

Several factors contribute to the low efficiency of the energy harvester, including the limited mechanical energy input. Waterdrop impacts provide only small amounts of mechanical energy due to the small droplet diameter and low falling height, both of which reduce the energy available for conversion [122]. Then, the frequency of the mechanical impact (waterdrop) may not match the natural resonant frequency of the PVDF material. It can lead to less efficient conversion. The KAMs design and

placement also can give an enhancement effect on the efficiency of the energy harvester. The data presented in Table 5.8 illustrates the efficiency variations in energy harvesting using different combinations of KAMs. The combination of KAM Type C+B+A demonstrated the highest efficiency conversion, achieving 0.00170657%. This is due to the fact that the raindrop energy harvester equipped with the KAM Type C+B+A configuration generates the highest voltage at 73.2 mV compared to other configurations, while the mechanical energy from the waterdrops remains constant. The summarization of the efficiency of each combination is illustrated in Figure 5.16. When the plain membrane is used in the raindrop energy harvester, it achieves an efficiency of $9.9748 \times 10^{-5} \%$. In contrast, equipping the harvester with the KAM Type C+B+A significantly improves efficiency to 0.00170657%, representing a 1600% increase. In a previous study by Filipi et al., their raindrop energy harvester achieved a mean efficiency of 0.017% under dry surface conditions, which is ten times higher than our harvester's performance.

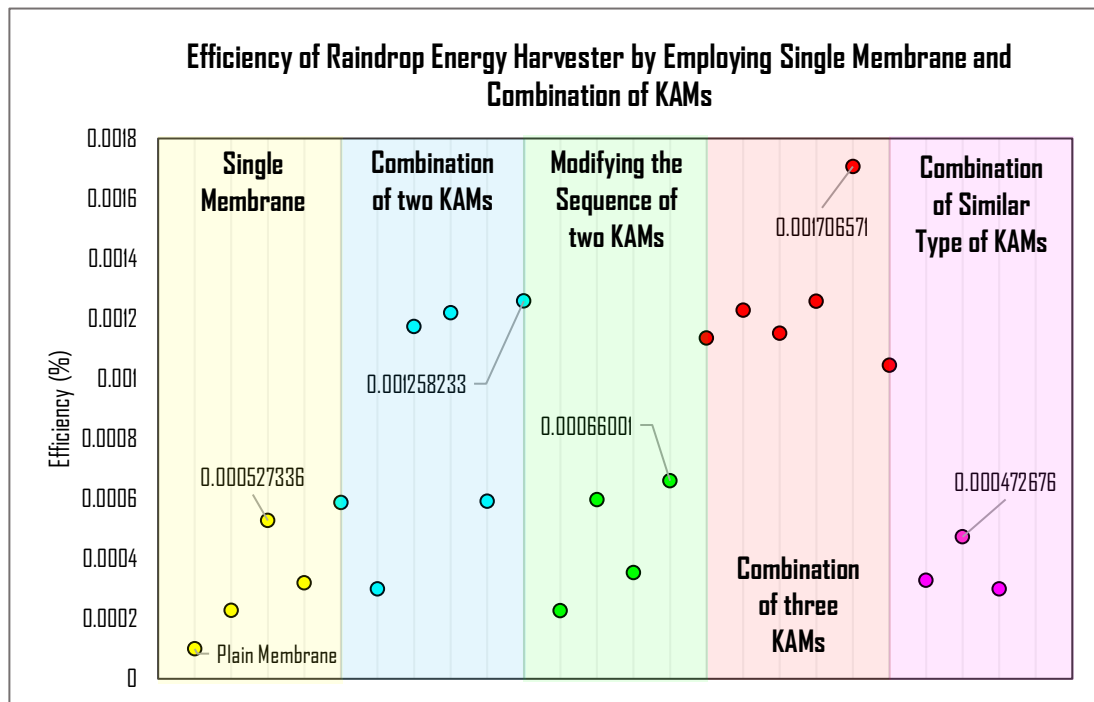


Figure 5.16 The efficiency the raindrop energy harvester by equipping single membrane and combination of KAMs.

The efficiency of the raindrop energy harvester obtained in this research might appear low, even after incorporating kirigami auxetic membranes, when compared to existing research on raindrop energy harvesting using piezoelectric materials. This is due to certain limitations encountered during the experiment, such as:

- **Low Energy Density of Raindrops:** Raindrops have inherently low kinetic energy due to their small mass and limited velocity (the maximum height of the burette to the harvester surface is only 40 cm), even at terminal velocity. Consequently, the total energy available for harvesting is minimal compared to larger renewable sources like solar or wind. With multiple instances of rain available to be harvested, the efficiency and electrical power generated are expected to increase.
- **Experimental Constraints:** Laboratory conditions often differ from real-world environments. Factors like controlled droplet size, uniform impact, and limited exposure time might not fully demonstrate the practical harvesting potential.

However, this outcome should be viewed within the broader context of scientific contribution, novelty, and potential application scope such as:

- **Pioneering Novelty:** This study is the first to experimentally employ a kirigami auxetic membrane (KAM) to enhance raindrop energy harvester performance where the previous research employing auxetic structure for enhancement purpose used simulation approach. The unique design using a 3-level fractal-cut kirigami membrane represents a groundbreaking innovation in the field.
- **Proving the Enhancement of Energy Transfer:** By introducing the kirigami auxetic membrane, the study aims to improve deformation characteristics, enhance strain distribution, and optimize energy transfer to the piezoelectric layer.
- **Scalability and Future Applications:** While the efficiency of a single harvester is low, deploying arrays of harvesters across large surfaces (e.g.,

rooftops, roads, or umbrellas) could scale up energy collection for low-power applications like IoT sensors or weather stations.

- **Practical Applications for Micro-Power Devices:** Even with low efficiency, the harvested energy can power micro-devices, such as environmental monitoring sensors, eliminating the need for traditional batteries in remote or off-grid areas.
- **Addressing Efficiency Limitations:** Identifying the challenges and inefficiencies in this initial design lays the groundwork for future optimization. Modifications in material properties, membrane geometry, or piezoelectric configurations can improve efficiency over time.

5.10 Effects of Single, Multiple, and Continuous Waterdrops on The Generated Voltage

This subsection will examine the process of capturing and storing electrical energy generated by the raindrop energy harvester, with variations in the number of waterdrops dripped from the burette onto the substrate surface. As the most efficient combination, KAM Type C+B+A was taken for acquiring data in this experiment. The water was varied between single drops and multiple/continuous drops. The height of the burette to the substrate surface remains at the maximum level of 40 cm. Then, the stopcock of the burette is opened gradually to expose more water drops to the surface. This resulted in an irregular waterdrop flow rate from the burette, caused by the manual adjustment of the stopcock, which could not be precisely controlled. The number of water droplets is determined by calculating the volume of a single droplet and dividing it by the water flow rate. In the initial test, the data showed that three droplets hit the substrate surface every second, with a flow rate of 4.5 ml/min which is equal to 0.075 ml/s. Therefore, the volume of each droplet can be calculated using the following formula:

$$\text{Volume per droplet} = \frac{0.075 \text{ ml/s}}{3 \text{ droplets/s}} = 0.025 \text{ ml/droplet} \quad (5.7)$$

In total, thirteen attempts were tested by increasing the waterdrops flow rate gradually which can be classified into single drop, multiple drops, and continuous drop. Utilizing volume per droplet, the number of waterdrops of all attempts can be determined as shown in Table 5.9. The water droplets flowing from the burette to the surface exhibit single-drop behavior when the flow rate reaches approximately 3 droplets per second. As the flow rate increases, the liquid still forms separate droplets, but they appear more frequently. This results in a quick succession of drops without merging into a continuous stream. The droplets are still distinct, but the spacing between them is shorter. This flowing is classified as multiple drops which occurs at 6 – 20 droplets per second. Then, at high flow rates, droplets lose their distinct form and merge into a near-continuous stream. This behavior is common when the flow rate exceeds the point where surface tension can re-form distinct droplets, causing the liquid to flow continuously. This waterdrop flow rate is continuous drops which have more than 20 droplets per second.

Table 5.9 Number of waterdrops dripping from the burette by considering the waterdrops flow rate and volume of a water droplet.

Waterdrops Flow Rate (ml/s)	Volume of one droplet (ml/droplet)	Number of Waterdrops (droplets/s)	Type of Waterdrops
0.075	0.025	3	Single drop
0.222222	0.025	9	Multiple drops
0.25	0.025	10	
0.303030	0.025	12	
0.333333	0.025	13	
0.344828	0.025	14	
0.357143	0.025	14	
0.370370	0.025	15	
0.421053	0.025	17	
0.454545	0.025	18	
0.5	0.025	20	Continuous drop
0.555556	0.025	22	
1.111111	0.025	44	

The effect of the number of water droplets on the generated voltage was then analyzed, and the findings are presented in Figure 5.17. Based on the graph, it demonstrates a clear positive correlation between the number of droplets and the voltage transfer rate. The data is provided in the form of mV/s to see the potential transferred voltage to the storage when it is installed to the circuit. After allowing water droplets to contact the substrate surface for 60 seconds, the accumulated voltage can be measured using an oscilloscope. By dividing this total voltage by the duration of water exposure, the transferred voltage can be calculated. As the number of waterdrops increases, the voltage transfer rate also increases. For the maximum capability of the burette to generate ≈ 1.11 ml/s or 44 waterdrops, the energy harvester is able to transfer 1.578 mV/s to the storage which means, the storage (capacitor) requires less time to be charged when the number of droplets increased.

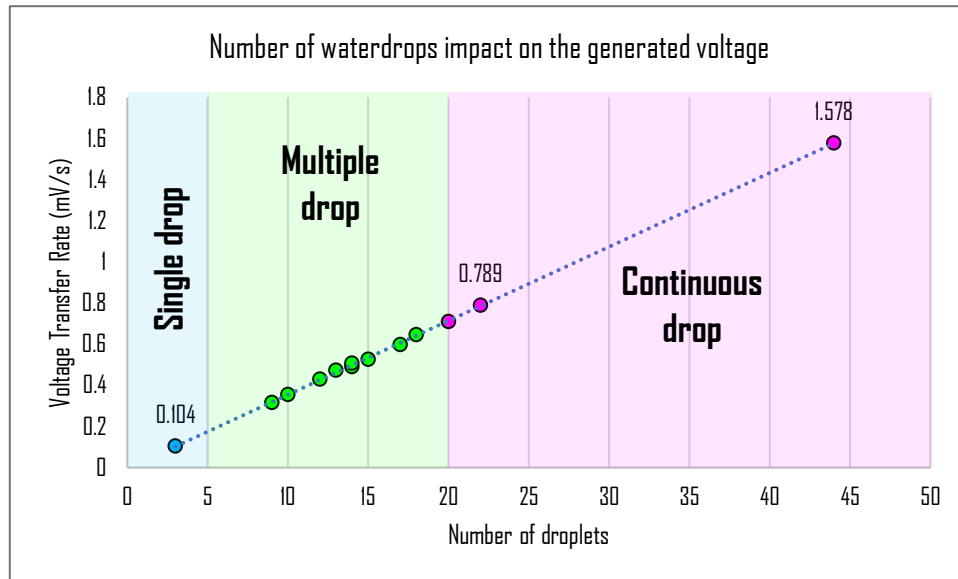


Figure 5.17 The relationship between the number of water droplets and the voltage generated by the raindrop energy harvester, equipped with the KAM Type C+B+A.

In practical applications of piezoelectric materials, they are typically connected to digital devices that require a DC voltage supply. Consequently, the capacitor charging application discussed in this research also necessitates a full-wave bridge rectifier with coupling capacitance to smooth out the DC voltage. In this scenario, the

small yellow LED bulb requires 125 mV to 150 mV to flash. When the energy harvester is connected to an electrical circuit comprising a capacitor, resistor, rectifier, and bulb as illustrated in Figure 5.18, the duration of energy transfer to the capacitor is observed, as shown in Figure 5.19. For a slow charging rate where the generated voltage is low, the effect of the resistors is minor because the piezoelectric voltage is low compared to what the resistors can drop. Thus, the effect of the resistor can be neglected in this case.

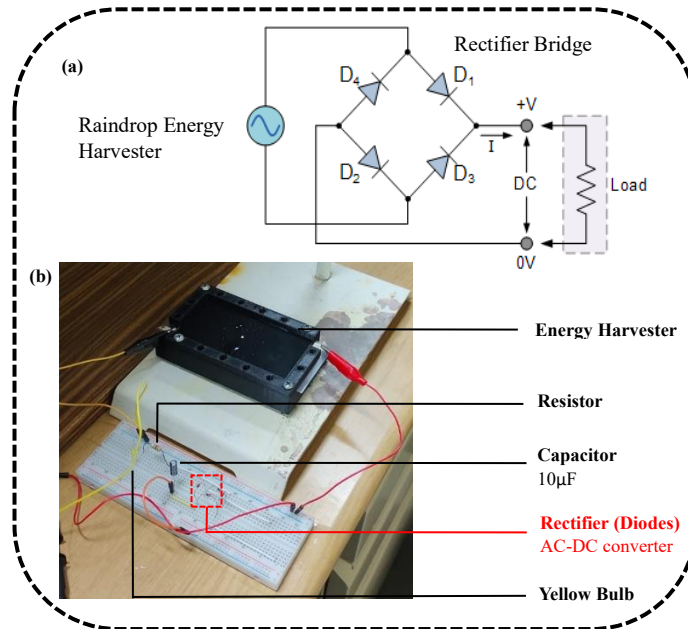


Figure 5.18 (a) Schematic diagram of rectifier (AC-DC converter) circuit (b) Experimental setup of the rectifier circuit connected to the raindrop energy harvester.

From Figure 5.19, it shows that the duration of the energy transfer process decreases as the voltage transfer rate increases. The inverse relationship indicates that faster voltage transfer reduces the time needed, which is critical for applications requiring quick energy delivery or charging. For example, when the energy harvester produces 1.578 mV/s under exposure to 44 water droplets per second, it can transfer energy to the capacitor in 79.2 seconds to reach 125 mV. Conversely, at a lower rate of 0.104 mV/s with 3 droplets per second, the energy transfer process is significantly slower requiring 1200 seconds.

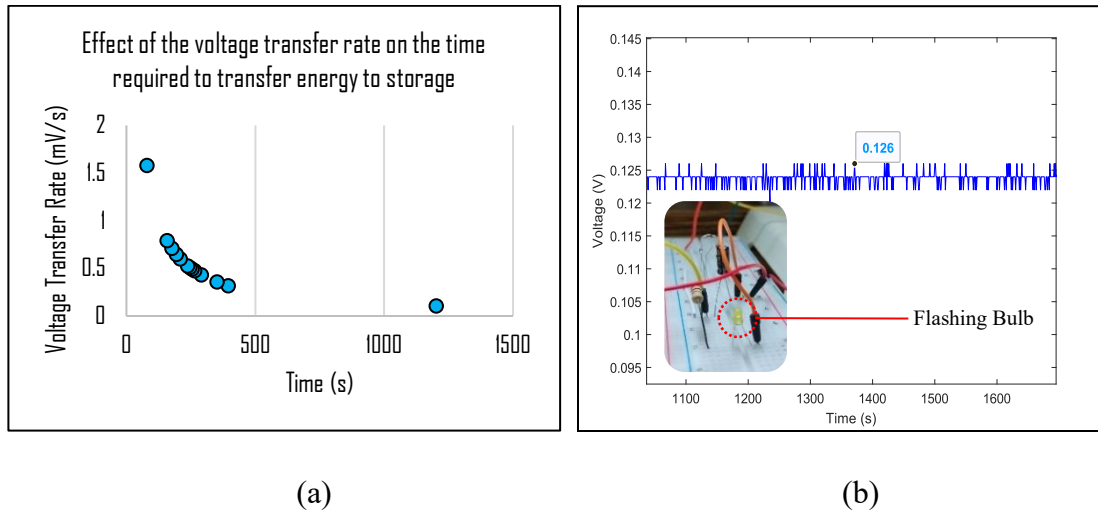


Figure 5.19 (a) The required time for the energy harvester after generating voltage to charge the capacitor to 125 mV, sufficient to flash the yellow LED bulb. (b) The illustration shows the LED bulb lighting up after receiving current from the capacitor.

This comparison underscores the importance of optimizing the voltage transfer rate. This optimization can be reached by adjusting the water flow rate, the height of water dripping to the surface, the inclination of the harvester, and consideration of the combination and utilization of KAM. By doing those things, the energy harvester can significantly improve the energy efficiency and transfer rate making it feasible to provide power for sensing, lighting, signage, and digital displays, especially in heavy-rain regions.

CHAPTER 6

CONCLUSION AND RECOMMENDATION

6.1 Conclusions

This research proposes three types of kirigami auxetic membranes (KAM) to harness electrical power from waterdrop impacts, with the objective of enhancing the generated electricity of raindrop energy harvester. The proposed KAM is comprised of a complex of kirigami patterns named KAM Type A, B, and C which represent the density of the pattern and are created by using the fractal cut method. Fractals are incredibly intricate patterns that repeat a basic process and are self-similar at various scales. The simulation results showed that KAM Type B and C will experience the biggest deflection after receiving waterdrop pressure at 1.47 nm and 1.49 nm. This deflection occurs alongside the stress distribution to the PVDF, with KAM Types B and C capable of transferring 8.7 Pa and 9.1 Pa. In other words, the KAM Type B and C will transfer more stress deformation to the PVDF layer, and therefore the electricity output will be enhanced.

Then, the raindrop energy harvester enhancement equipped with a single and combination of KAMs was studied and compared to the harvester equipped plain membrane when the substrate was under waterdrop pressure. From the experiment, the results showed that by combining the KAMs with C+B+A configuration will enhance the electricity output with a power multiplication up to 3 at 73.2 mV compared to plain membrane that only can generate 24 mV. The KAM polarizes the PVDF better than a plain membrane because of its higher ability to stretch the PVDF even more they are combined. According to efficiency analysis, the combination of KAM Type C+B+A also appears as the most efficient configuration with 0.00170657% which is a proof of concept for performance improvement. Testing to store the electricity to the power storage, the raindrop energy harvester equipped KAM Type C+B+A can provide 1.578 mV/s at the maximum number of waterdrops exposed to the substrate and requires 79.2 seconds to light up a small LED bulb. Therefore, the proposed KAM installed to the

raindrop energy harvester could be used for harnessing energy from raindrop to run low power device such as light.

6.2 Recommendations

The future work for developing the raindrop energy harvesting system includes the using of syringe pump for the representation of raindrops which make the researcher can control the flow rate, number of droplets, and diameter of the waterdrops to produce a more precise measurement. The new pattern and dimension of the kirigami auxetic membranes (KAM) need to be examined further to optimize the enhancement of electricity produced. Additionally, harvesting real rainfall energy should be considered to evaluate the raindrop energy harvester's performance across varying rainfall intensities, including light, medium, and heavy rain.

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