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SURVEY

Underwater Thermal Energy Harvesting: Frameworks, Challenges, Applications, and Future Investigation

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ABSTRACT This paper studies the latest and state-of-the-art underwater thermal energy harvesting algorithms and techniques designed in the latest decade (2014-2024). The techniques are classified based on their unique operations for energy harvesting. This classification includes thermal energy harvesting using a phase change material (PCM), thermoelectric generator (TEG) and multi-source harvesting. Every class of techniques is described by its operation using a schematic diagram and a mathematical model to fully understand its working principle. Moreover, every individual technique is also described in terms of its operation, amount of harvested energy/power and the aspect(s) where margin of further improvement exists. Also, a comparative analysis of the classified algorithms is performed with each other as well as with other underwater energy harvesting techniques (solar, piezoelectric, wave) to highlight their effectiveness and feasibility in a diverse set of underwater and various other applications. The classified techniques are also compared in terms of harvested output to indicate their harvesting efficiency. Furthermore, the publications made in the latest decade in terms of thermal energy harvesting using PCM, TEG and multi-source methods are also graphically depicted. Such a description of the studied techniques and classified methods is unique from the already existing underwater energy harvesting reviews in literature where an in-depth and thorough analysis is absent, rather only marginal description is given. The harvesting results indicate that hybrid (multi-source) and PCM methods have the greatest amount of harvested power and energy, respectively. Finally, the research challenges in underwater thermal energy harvesting are specified and areas of further research are highlighted for future investigation.

INDEX TERMS Multi-source, phase change material, temperature gradient, thermoelectric generator, underwater thermal energy harvesting.

I. INTRODUCTION

Underwater wireless sensor networks are used to acquire information about the aquatic environment, which is performed by deployment of nodes and data collection strategies [1]. While collecting data, some sensor networks utilize mobile devices to cover a wide area of the network and ensure a large amount of data collection [2]. Researchers have always investigated strategies to cope with the challenges associated with the exploration and study of the underwater environment [3]. One of the challenges associated with the underwater environment is that the involved devices

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operate with limited battery power, which restricts the lifetime of the devices [4]. This necessitates the design and development of strategies to address the issue of limited battery power [5], [6].

Energy harvesting in the underwater environment has the inherent capability of providing extra power to the limited battery power of operating devices. This, in effect, not only enhances the battery lifetime of the harvesting devices but also ensures their battery-less operation when a sufficient amount of energy is harvested [7], [8]. This harvested energy originates from a number of sources. These sources, for instance, include piezoelectric [9], solar [10], kinetic energy of water flow, waves, tides and vibrations [7], [11], wind on water surface [12], marine life, motion of autonomous underwater vehicles (AUVs) and their paths tracking [13] and thermal energy due to temperature variations [14].

Underwater thermal energy is harvested from temperature variations in different parts of the underwater environment [15]. The temperature variations are usually input to a thermoelectric generator (TEG) [100] or a phase change material (PCM) [15]. The TEG is a semiconductor device in which the charge carriers are excited by the temperature variations to constitute an electric current and, therefore, generate electric power. The PCM is usually used with an underwater vehicle that dives from water surface (where PCM is usually in the liquid phase) and as it moves down the water surface, the pressure increases and the PCM solidifies [16]. When the vehicle moves upward and comes back to water surface, the solid PCM changes to liquid phase due to decreasing pressure and this causes its volume to expand that (usually) drives an electric motor to generate power. The thermal energy harvested in the underwater environment is of critical significance in that it is more stable in response to day-light cycle than solar radiations [17]. Also, it does not require acoustic vibrations and wave motion as needed in the piezoelectric and wave energy harvesting methods [18], [19], respectively. Moreover, thermal energy is easy to integrate with underwater vehicles and floating devices [15].

The underwater thermal energy harvesting can be used along with other underwater harvesting methods to power devices for a diverse set of applications. These applications, for instance, include path planning and navigation for underwater ships and autonomous vehicles [20], [21], [22], water quality monitoring [23], [24], [25], precious materials detection [26], [27], [28], seismic monitoring [29], [30], [31], debris detection of crashed planes [32], [33], [34], underwater research investigation [35], [36], [37], Tsunami detection [38], [39], [40], coastal areas monitoring [41], [42], [43], military surveillance and warfare [44], [45], [46], hidden mines detection [47], [48], [49] and prediction of general underwater environment characteristics with time [50], [51], [52], to mention a few.

Underwater thermal energy harvesting has been addressed in literature. The authors in [14] provide a review of various underwater energy harvesting techniques: solar, thermal, piezoelectric, wave, marine life and hybrid. They highlight the extent of the harvested energy by the addressed techniques. However, it lacks an in-depth and thorough investigation of the way energy is harvested and its limitations and future investigations for each harvesting method. Although, the authors in [53] provide a review of underwater energy harvesting techniques, the harvested energy is limited mostly to low power devices operating in the milliwatt power range. In addition, for devices operating at high power, only the solar radiations and inductive power transfer techniques are considered. However, the former technique struggles in the absence of sunlight in deep water and the later technique requires the presence of certain conditions for optimal performance. Moreover, it does not incorporate the underwater thermal energy harvesting that can drive devices requiring high power consumption such as an AUV [14].

To overcome the aforementioned limitations of the available underwater energy harvesting studies, this paper provides a thorough and in-depth study of the underwater thermal energy harvesting techniques developed in the latest decade (2014-2024). The energy harvesting techniques are classified into TEG, PCM and multi-source harvesting methods. Every energy harvesting class of algorithms is described by its mathematical model and schematic diagram of operation for the best understanding. The working principle, harvested amount of power/energy and the demerit(s) of each studied individual algorithm are described that further provides an insight to operation understanding and margin of improvement in subsequent investigation. The applications of the harvested energy in various underwater applications are also given. Moreover, the description of the classified algorithms in terms of energy harvesting in various applications for the latest decade is also given by publication count that provides an insight to their future trends in various applications. In addition, a comparative analysis of the classified underwater thermal energy harvesting techniques is also given that provides a foundation for improvement in further research. Finally, research challenges associated with the underwater thermal energy harvesting are highlighted and directions for future investigation are specified. The real world implementation of this work is threefold. First, the proposed work can be used by researchers to choose one of the described harvesting methods for powering underwater devices depending upon the power requirement, which has been shown by the power harvesting capability of each method. Second, it can be used to overcome the shortcomings of the described energy/power harvesting algorithms in future investigation, which will further enhance the harvesting output in practical implementation. Third, the given directions for future investigation can be utilized by researchers to propose, design, model and implement new strategies for an overall enhanced harvested output.

The rest of this paper is organized as follows. Section II classifies and describes the underwater thermal energy harvesting techniques. The comparison of the energy harvesting

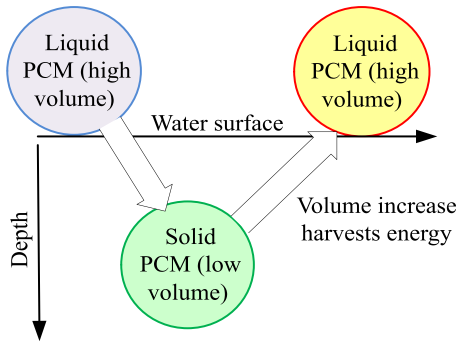

FIGURE 1. Schematic diagram of energy harvesting by PCM.

extent of the classified techniques is performed in Section III while Section IV performs a comparative analysis with other energy harvesting techniques. The challenges of underwater thermal energy are addressed in Section V while the conclusions are drawn in Section VI. Finally, Section VII highlights the future research directions.

II. UNDERWATER THERMAL ENERGY HARVESTING TECHNIQUES

This section classifies the underwater thermal energy harvesting methods based on the use of a phase change material, thermoelectric generator or multi-source harvesting. Each of the classified categories is discussed in detail in the following lines and the algorithms in each category are analyzed based on harvesting methods, harvested output and merits/achievements and demerits.

A. THERMAL ENERGY HARVESTING USING A PHASE CHANGE MATERIAL

The concept of using a PCM for thermal energy harvesting was first given as a patent [54], [55]. A PCM material releases or absorbs energy when it changes phase [56]. The phase change occurs due to temperature variations and this property can be utilized to harvest and store energy [57], [58], [59]. Underwater temperature variations are used to harvest energy from the PCM materials to drive autonomous underwater vehicles and other devices utilizing them [60].

As shown in Figure 1, the PCM changes state from liquid to solid (towards low temperature) and vice versa that causes the released pressure (expanded volume) to drive a generator (or a mechanical device) and harvest electrical energy. A PCM state transition takes place between the liquid and solid phases. The material is moved from the liquid phase at a higher temperature to the solid phase at a lower temperature (within water) by some underwater device such as an underwater autonomous vehicle. It is then allowed to transform itself from solid to liquid phase by moving towards water surface. This process releases the pressure (expanded volume) to drive a connected device such as an electric generator to harvest energy. The state transformation of the PCM material in liquid form is generally modeled as [16]:

$$\Delta V = C(T) \log \frac{(1+\Delta P)}{B(T)}, \tag{1}$$

where $\Delta V = V_1(T) - V_2(T, P)$, $\Delta P = P_2 - P_1$, V_1 is the volume of the PCM material in cubic meters at atmospheric pressure level P_1 in MPa (MegaPascal), and V_2 is its specific volume at pressure P_2. The empirical parameters B and C are measured in units of MPa and m^3/kg (cubic meter per kilogram), respectively and vary with temperature T, which is measured in $^\circ C$ (degree Celsius). Considering Pentadecane as a liquid PCM, these parameters are computed for the temperature range of greater than 10 $^\circ C$ and less than 35 $^\circ C$ as [61]:

$$\begin{aligned} B(T) &= 762.8 - 4.805 \times (T - 79.4) \\ &\quad + 0.0116 \times (T - 79.4)^2, \qquad (2) \\ B(T) &= 0.2058 \times V_1(T) \qquad (3) \end{aligned}$$

where $V_1(T)$ is modeled in [62] as:

$$\begin{aligned} V_1(T) = [&1.0307 \times 10^3 - 1.2596 \\ &\times (T + 273.15) + \quad 1.8186 \times 10^{-3} \\ &+ (T + 273.15)^2 - 1.9555 \times 10^{-6} \\ &\times (T + 273.15)^2]^{-1}. \end{aligned} \tag{4}$$

The rest of this section describes the methods of underwater thermal energy harvesting using a PCM.

The authors in [63] harvest energy using a new thermal buoyancy engine with a turbine. The engine provides more kinetic energy to the turbine that converts it into electrical energy and does not increase the mass of the involved PCM. The process of energy conversion from the engine to the turbine is optimized with parameters of the turbine for enhanced harvesting. The various parameters of a designed thermal engine, such as the thickness of the wall, thermal resistance and the materials used to harvest energy, are described in [64] to achieve an optimal energy harvesting. The mathematical model of the engine is provided with miniaturized conversion of thermal to electrical energy. A non-linear model linking the pressure and rate of phase change is given in [65]. Factors that affect the system pressure and storage capability are analyzed as well. The authors in [66] adjust the height to radius ratio of a proposed heat exchanger in an ocean thermal engine. It consists of several circular regions that divide the inner region of the exchanger. With these strategies, the heat transfer process is enhanced that reduces the melting time of the PCM by 34% resulting in an enhanced harvesting efficiency. An analysis of the PCM is performed in [67] for thermal to electrical energy conversion. First, temperature variations are stored in the form of potential energy in an accumulator and then electric motor, generator and other components are used to transform it into electrical energy. The parameters affecting the harvesting efficiency are also thoroughly analyzed and the prototype is tested. The authors in [68] study various parameters of the phase change materials and the external factors affecting its harvesting efficiency. They conclude that the melting time of the phase change material in the thermal engine reduces by reducing the temperature of the outer wall of the engine. In addition, the melting of the PCM is also affected by the distribution of velocity in the liquid phase. The process of heat to electrical energy conversion is modeled in [69] as a quasi-static process for a volumetric pump. In addition, the effect of various parameters on the efficiency of the pump is analyzed and a model of the heat exchanger is presented with various performance parameters.

The authors in [70] argue that the traditional gliders use PCM materials that do not effectively change phase with the motion of the glider due to low thermal conductivity. This reduces the thermal energy conversion efficiency. To deal with this problem, vertical speed and drift time are computed for the energy conversion process during melting process of the PCM (higher to lower temperature) while speed and functional depth are included during the solidification process. Energy is harvested in [71] in harvesting and sampling intervals of eight hours duration and making a glider to dive over a depth of 500 meters for a trial duration of 1.5 years. The authors use a phase change material that expands with a temperature difference during the movement of the float from a colder to a warmer location. This process expands the tube containing the PCM that causes its internal oil to act upon an under pressure piston. This oil is collected in the piston, heated and pressurized to run a hydraulic motor that generates power in generator connected with it. For enhanced harvested output, a gearbox mechanism is used to speed up the motor rotation. The authors in [72] propose a quasi-static model of the volumetric pump used in the thermal glider. It consists of a PCM that converts thermal energy into mechanical energy that is then governed by a hydraulic accumulator to convert and save in the form of electrical energy. The range and energy storage system of the harvested thermal energy is improved in [73]. It first uses the PCM material to harvest energy and then utilizes it to control the buoyancy of the engine instead of an electrical pump.

A PCM material is used in [74] to control and optimize the buoyancy characteristics and parameters driven by the ocean thermal energy to ensure optimal storage and expenditure of the consumed energy. The counterweight, hydrodynamic and heat transfer characteristics of a PCM-based float are analyzed in [75] and modifications are made in the existing designs to obtain optimal power harvesting results. The time of heat transfer from sea to the harvesting device is optimized and reduced in [76] that enhances the time in which the energy is harvested. Multiple air chambers are utilized and air flow is introduced in [77] along with adjusting buoyancy of the harvesting device by adding PCM between the chambers and shell of the harvesting device as well as utilizing miniaturization of the devices collecting energy. Also, the overall structure of the harvesting buoy is also optimized for optimal energy harvesting results. The authors in [78] design a hybrid PCM that involves buoyancy regulation and storage to drive unmanned underwater vehicles in long missions, such as a mission comprising of 3000 km in one deployment. It develops a basic model of a hydraulic-to-electric conversion that is validated by experimental investigation to power vehicles.

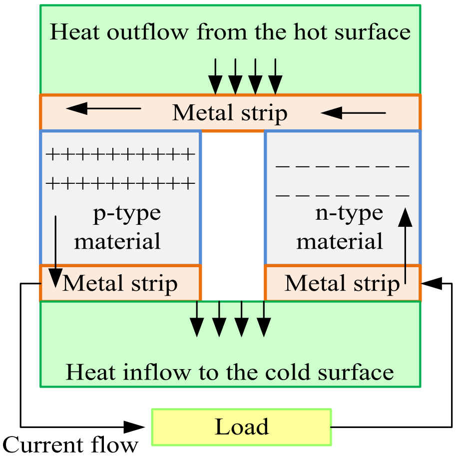

FIGURE 2. Schematic diagram of energy harvesting by TEG.

B. ENERGY HARVESTING USING A THERMOELECTRIC GENERATOR

In 1821, Thomas Johann Seebeck reported the possibility of creating electric potential energy from the temperature difference across two materials of different nature [79]. This coupled the thermoelectric energy generation with the term Seebeck effect. A thermoelectric generator consists of many thermoelectric modules, whereas a single thermoelectric module consists of serially connected p-type and n-type semiconductor materials of different thermal conductivities.

As shown in Figure 2, a temperature difference ΔT between the two materials generates a voltage difference ΔV across a thermoelectric element. Heat flow from the hotter to the colder surface causes electrons to move from the n-type material towards the p-type material in the circuit and constitute a current. The harvested voltage is modeled as [80]:

$$\Delta V = \alpha \Delta T, \tag{5}$$

where α is the Seebeck co-efficient measured in V/K (Volts per Kelvin). The power P that a single element generates in W (Watts) is represented by [80]:

$$P = \alpha I \Delta T - I^2 R, \tag{6}$$

where I is the current flowing in the element and R is the external load resistance. The maximum generated power is computed as [80]:

$$P = (\alpha I \Delta T)^2. \tag{7}$$

The power generation capability of a TEG is determined by the dimensionless thermoelectric figure of merit Z, which is modeled as:

$$Z = \frac{\alpha^2 \sigma}{k}, \tag{8}$$

where σ is the electrical conductivity in S/m (Siemens per meter) and k is the thermal conductivity in W/m.K (Watts per meter Kelvin). The rest of this section discusses the methods of underwater thermal energy harvesting using a TEG.

A device mounted on an underground water pipe harvests energy from the temperature difference of the pipe and soil and uses it to operate attached sensors and perform data processing and communication [81]. An ionogel material is designed in [82] with properties designed for harvesting thermal energy in a water body and during rain by using the properties such as water-resistance, stability, durability and tolerance. The authors in [83] model a TEG and analyze its heat transfer process and the harvesting capabilities of different harvesting materials. The generator provides better harvesting results when a phase change material is used instead of sea water or stainless steel in the harvesting process. A heat pipe used in [84] harvests energy from the sea floor with a pipe that is then converted into electrical energy by a TEG. The proposed system is tested to power a light emitting diode and also uses a data logger system to monitor the harvested current and voltage. In addition, the heat pipe is kept safe from the deposition of the sea minerals that reduces its efficiency. A Titanium foil with O-rings is applied on the colder side of the TEG in [85] as a sealing element that decreases the thermal resistance and, therefore, increases the harvesting efficiency. Moreover, the surface of the TEG is insulated to further reduce the heat loss and enhance its efficiency. A hydrothermal cap in [86] uses a conduction pipe to harvest thermal energy from the sea and the thermodynamic fluid, which is then converted into electrical energy using a TEG.

A computational fluid dynamic analysis of the TEG is performed in [87]. Analysis of temperature difference between the external sea water and the inner hot hydraulic oil is simulated. Parameters such as inclusion of a heat sink at the hotter side of the system, using oil with high thermal conductivity and temperature in the enclosure are considered. The authors in [88] perform a theoretical analysis for the orientation of heat exchangers of thermal gliders harvesting energy. They conclude that keeping in view the efficiency of the glider and its static stability, the optimal orientation for the heat exchangers is to mount them under the hull. The temperature difference between hot and cold water pipes is transformed into electrical energy in [89] using a cold mini plate. The authors in [90] use an array of large Seebeck material under a ship body below the water line. It gets heat from the exhausted engine or generator of the ship and converts it into electrical power with the help of a TEG. One end of a TEG is heated with solar radiations and the other end is cooled with water from a waterfall to generate the desired temperature difference for electricity generation in [91].

C. MULTI-SOURCE ENERGY HARVESTING STRATEGIES

The multi-source energy harvesting strategies combine multiple underwater energy harvesting methods with thermal energy harvesting to design a hybrid energy system. The most common underwater energy harvesting methods that are combined with thermal harvesting include piezoelectric (wave) and solar radiations at the water surface. To harvest energy from piezoelectric effect, a cantilever beam is usually used, which harvests voltage V in Volts when excited by ocean waves. This voltage is then converted into electrical power by the relationship $P = IV$ or $P = \frac{V^2}{R}$, while the harvested energy equals the amount of harvested power times the time in which the power is harvested. A cantilever beam made up of a macro fiber composite material having length L, width W and height H in meters generates an output voltage that is given by [92]:

$$V = \frac{\sum_{r=1}^{\infty} \times \frac{C_{em}}{C_p} \frac{jm\omega^3 f_r \omega_0}{\omega_r^2 + \omega^2 + 2j\xi\omega_r\omega}}{\sum_{r=1}^{\infty} \frac{C_{em}}{C_p} \times \frac{j\omega C_{em}}{\omega_r^2 - \omega^2 + 2j\xi\omega_r\omega} + \frac{C_{em}}{RC_p} + j\omega}, \tag{9}$$

where C_{em} is the electromechanical coupling co-efficient, C_p is the capacitance of the piezoelectric beam in Farads, j is the imaginary number, ω and ω_r are the excitation and r-th order undamped natural frequencies in radians per second, respectively, ξ is the modal mechanical damping ratio, $f(r)$ is the modal force co-efficient and R is the electric resistance of the beam in Ohms.

In solar radiations, a solar photovoltaic (PV) panel that usually consists of many solar cells connected in series and parallel arrangements generates an output current I, which is given by [93]:

$$I = N_p \times I_{ph} - N_p \times I_d \tag{10}$$

where N_p is the number of solar cells connected in parallel in the PV module, I_{ph} is the photons generated current when solar radiations fall on the PV module and I_d is the diode current flowing through the diode, which is calculated as [93]:

$$I_d = I_0(e^{\frac{qv}{nKT}} - 1) \tag{11}$$

where I_0 is the saturation current, V is the voltage applied to a diode (solar cell), q is the magnitude of the electronic charge that is equal to 1.6×10^{-19} C (Coulombs), T is the temperature in K (Kelvin), n is the ideality factor with a value between 1 and 2 and K is the Boltzman constant that equals 1.38×10^{-23} J/K (Joules/Kelvin). The current and voltages are usually measured in milliAmpere (mA) and milliVolt (mV) units, respectively. The rest of this section discusses the algorithms harvesting power/energy using multi-source methods.

A hybrid scheme combining solar and TEG for energy harvesting is utilized in [94] for a floating node. It harvests 8.375 Wh energy from sunlight and an energy of 0.425 Wh from the thermoelectric generator and uses 6.6216 Wh energy for full day operation. The authors in [95] combine piezoelectric, wave and thermoelectrically harvested energies. Solar radiations are made concentrated and allowed to

TABLE 1. Underwater thermal energy harvesting using a PCM [63], [64], [65], [66], [67], [68], [69], [70], [71], [72], [73], [74], [75], [76], [77], [78], TEG [81], [82], [83], [84], [85], [86], [87], [88], [89], [90], [91] and multi-source [94], [95], [96], [97], [98], [99], [100] harvesting techniques.

Reference	Merit/Achievement	Harvested Output	Depth (km)	Demerit	Year
[63]	Enhanced harvesting due to optimal design of a thermal engine with turbine	24.2 kJ	1	Involves theoretical steps in some process	2023
[64]	Can provide power for operation of a thermal engine up to 27 days and for a long range of 627 km	124 W	1	Operation limited to a certain pressure range	2016
[65]	Able to predict the harvesting output by changing the harvesting parameters as per harvesting requirement	3000 kJ	1	Requires constat tracking of the gliders' path	2016
[66]	Reduced melting time of PCM	x	x	Does not provide information about the harvested extent	2024
[67]	Analysis of factors affecting harvesting efficiency	6696 J	x	Bulky size due to the heavy mass of the phase change material	2019
[68]	Study of parameters affecting PCM harvesting efficiency in a thermal engine	x	x	Outer wall temperature increase requires the depth increase to a significant extent	2023
[69]	Heat conversion analysis of a volumetric pump	x	x	Requires experimental validation	2016
[70]	Analysis of parameters responsible for PCM complete phase change process	x	1	Requires computation of temperature, depth and drift values for complete phase change of PCM	2016
[71]	Designs a mechanical arrangement for PCM enhanced and fast harvesting efficiency	200 W	0.5	Requires sophisticated PCM materials	2016
[72]	Thermodynamic analysis of energy storage of a volumetric pump used in a thermal glider	x	x	Consideration of quasi-static model of the pump imposes certain limitations	2016
[73]	Controlled buoyancy and the resulting harvesting capability of a thermal glider	800 W	1.2	Requires flight and energy storage optimization computation	2015
[74]	Optimization of buoyancy parameters with respect to PCM	x	0.036	Does not provide calculated and harvested output	2021
[75]	Optimization of thermodynamic, physical and route parameters of a float	1.487 Wh	0.7	External underwater characteristics that play role in energy harvesting suffer from variations	2022
[76]	Fast energy harvesting by PCM due to reduced heat transfer time	1740 J	1	Seasonal variations affect the heat transfer time	2023
[77]	Controlled buoyancy using air and size of PCM and energy collection system	22W	2	Harvesting performance is limited to specific PCM	2023
[78]	Enhanced harvesting efficiency of PCM by controlling the hydraulic and electrical components	32 kJ	1	Requires energy harvesting and storage analysis based on dynamics of the involved hydraulics	2023
[81]	Energy harvesting from underground water pipes and soil	21 J	0.0014	Output varies from maximum to complete blackout	2023
[82]	Characteristics study of an ionogel material for energy harvesting	15 mV	x	Diminished harvested extent	2023
[83]	Comparison of PCM and various materials for energy harvesting	6 kJ	1.2	High body mass of the TEG and lacks experiment validation	2018
[84]	Energy harvesting at sea floor	3.9 W	2.765	The heat pipe is prone to bio-fouling	2015
[85]	Significant energy harvesting at ocean floor	22 W	2.765	The required temperature difference in simulation is generally too high to establish	2024

TABLE 1. ***(Continued.)*** **Underwater thermal energy harvesting using a PCM [63], [64], [65], [66], [67], [68], [69], [70], [71], [72], [73], [74], [75], [76], [77], [78], TEG [81], [82], [83], [84], [85], [86], [87], [88], [89], [90], [91] and multi-source [94], [95], [96], [97], [98], [99], [100] harvesting techniques.**

Reference	Merit/Achievement	Harvested Output	Depth (km)	Demerit	Year
[86]	Open degree of freedom to harvest energy with an open choice of thermofluid	0.5 W	0.003	The considered temperature difference is generally too high at the specified depth	2017
[87]	Analyzes the thermodynamic role of the oil used with a TEG for harvesting efficiency	x	x	Requires experimental validation	2016
[88]	Identifies the optimal position of a thermal glider for energy harvesting	x	x	Recommends below the hull orientation for the heat exchanger but it is prone to bio-fouling	2014
[89]	Harvests energy from water pipes	81 mW	x	Requires a constant temperature difference between the pipes	2018
[90]	Involves energy harvesting from a ship exhaust in water	12 W	x	Power harvesting is sensitive to temperature variations	2019
[91]	Temperature difference across a TEG is achieved through water and solar radiations	1.23 W	x	Output is sensitive to solar temperature variations	2016
[94]	Solar and thermal energy combination to power a floating sensor	8.9966 Wh	x	Harvested output due to thermal part is diminished due to very low temperature difference at water surface for the floating device and is, therefore, dependent mainly on the sunlight part that is prone to variations as well	2018
[95]	Combination of piezoelectric, wave and thermoelectric energy harvesting	150 mW	x	Diminished harvested power, complexity of integration of multiple harvesting sources and storing the corresponding harvested energy	2018
[96]	Combines solar radiations and ambient temperature in the day-night cycle to harvest energy	31.8 kW	x	Low temperature difference at night reduces the harvesting efficiency, harvested output varies with the size of the water tank and the sunlight variations	2024
[97]	Harvests energy from solar radiations and temperature difference to power a floating sensor node	8.800 Wh	x	Requires constant sunlight to harvest energy and maintain temperature difference	2016
[98]	Energy harvesting from a water pipe with a magnet and a TEG	1.019 W	x	The turbine inside the water pipe has the capability of harvesting a diminished amount of power owing to the size restriction within the pipe	2018
[99]	Everlasting energy harvesting from solar, thermal and piezoelectric sources	22.3 kJ	x	Lacks experimental validation as the analysis is based on simulations only, also the characteristics of the oil analyzed varies from one liquid to another such as boiling point, extent of volume expansion and specific heat capacity, to mention a few	2022
[100]	Energy harvesting from the heat and motion of marine mammals	x	x	Requires constant tracking of the marine mammals, which not only consumes constant power but is challenging as well, especially in remote geographical locations	2022

TABLE 2. Comparative analysis of the classified thermal and other methods of underwater energy harvesting.

Energy Harvesting Method	Working Principle	Merits	Limitations	Uses in Other Applications
PCM-based Energy Harvesting	A phase change material undergoes phase transition in moving from a higher temperature to a lower temperature (and vice versa) in water. This compresses (solidifies) the material. Then the same material is allowed to move from the lower temperature to a higher temperature that expands its volume that, in turn, drives electrical or mechanical circuits to generate power [16]	Requires a temperature difference between the two underwater points where energy has to be harvested that is generally easily available with variations in water depth. A PCM is independent of the day-night cycle variations effect on energy production as considered in solar energy so the harvested output is mostly stable. Diversity of phase change materials and their composite derivatives helps in using flexible, effective, efficient and productive materials for energy harvesting [101], [102], [103]	Phase change materials vary in types, depending upon the type, they may be costly, toxic, pollutant to environment and require different temperature difference values to harvest energy	Heat management in buildings [104], batteries [105], refrigerated vehicles [106], textiles [107], space shuttles [108], chemical processing [109], display in photonics [110], thermal energy storage [111], electronic packaging [112] and tumor and cancer treatment [113]
TEG-based Energy Harvesting	A TEG is a solid-state semiconductor device that generates a voltage across its p- and n-type materials due to temperature difference. The thermal agitation caused by temperature difference constitutes a flow of charge carriers from one end of the semiconductor device to another. This current is either delivered to the load or stored as electrical energy in a battery or capacitor [79]	Fast operation due to semiconductor material involved in current/power generation than metals that have high thermal resistance as the current flows. They have a variety of current/power generation levels due to availability of various doping concentration of the semiconductor materials involved in current flow, pollution-free operation and are, therefore, good choice for sustainable operation [114]	TEG devices have low energy harvesting efficiency and constantly require a certain and constant temperature difference to maintain the harvested output [114]	Conversion of wasted heat in automobiles, industry and factories into electrical energy, power provision to spacecraft and remote stations [114]
Ocean Kinetic Energy Harvesting	The ocean waves (kinetic energy) are utilized to drive an electrical generator that produces an induced electromotive force to harvest energy [14]. The morphology and operation of the generator is usually manipulated with various techniques to harvest the maximum possible amount of energy	The ocean waves high amplitude results in significant energy harvesting, ubiquitous energy harvesting as its easily available, clean energy with no carbon foot-print, can be harvested using a variety of devices and equipments from a small generator to a large turbine	Locations where the waves motion is not available are not feasible for this type of energy harvesting, variable output power harvesting due to seasonal variations, high maintenance cost	Water desalination, pumping and powering sensor devices [14]
Piezoelectric Harvesting	Uses vibrations and stress of water pressure to stimulate a piezoelectric material that converts them into voltage pulses that are further processed by circuit conditioning to harvest energy	Ease of availability [14]	Diminished extent due to the conversion of stress/vibrations to a certain limited degree by the involved materials into electrical pulses	Energy harvesting on roads, pedestrian paths, railway platforms and anywhere where vibrations exist [99]
Multi-source Energy Harvesting	Combines two or more of the above harvesting methods	Versatility of harvesting due to combining various sources, always harvests a significant amount of power/energy as it is less likely that all the harvesting sources are not available or are under low performance conditions	Complexity of integration and working, costly due to use of diverse and multiple components	Combines all the applications in which the individual harvesting methods described above are used

fall on a parabolic dish to heat up the associated circuitry in [96]. A water tank acts as a cold temperature reservoir during daylight to generate the temperature difference for energy harvesting. During night time, temperature difference is created by the water tank and the atmosphere. A floating sensor device is designed in [97] that is capable of harvesting energy from solar radiations and the temperature difference between the water surface and the materials receiving sunlight. It is capable to float on water surface for several days and function without sunlight. The authors in [98] combine an electromagnetic generator with a TEG for irrigation system. The electromagnetic generation part consists of magnets attached to water pipes that induce voltage in a coil when rotated by a turbine. The thermoelectric part harvests the temperature difference between water pipes into electrical energy. An energy harvesting scheme utilizing solar, thermal and piezoelectric models is proposed in [99] that establishes electrical and mechanical designs of the proposed method. It harvests an energy of 22.3 kJ within 24 hours. Energy is harvested from the body heat and the motion of marine mammals in [100]. A micro TEG harvests energy from the temperature difference between the body and the ambient temperature and a triboelectric nanogenerator harvests energy from the mechanical movement of the mammals.

Table 1 summarizes the merit(s)/achievement(s), the amount of power/energy harvested, the depth at which the output is harvested, the demerit(s) and the year of the publication of each of the studied harvesting methods. These algorithms harvest energy using a PCM [63], [64], [65], [66], [67], [68], [69], [70], [71], [72], [73], [74], [75], [76], [77], [78], TEG [81], [82], [83], [84], [85], [86], [87], [88], [89], [90], [91] and multi-source [94], [95], [96], [97], [98], [99], [100] harvesting. The achievement/merit of every algorithm highlights its main benefit. The demerit of each algorithm indicates the potential parameter(s) to work for further improvement in future work. The depth value at which the output is harvested indicates the use of a harvesting method and its capability to be deployed either at or under the water surface. The harvested output of each method shows the maximum harvested and recorded amount of energy/power mentioned in the studied paper. The symbol x shows that a parameter is not specified in the original paper by the researchers.

III. COMPARISON OF THE HARVESTING CAPACITY OF THE CLASSIFIED THERMAL ENERGY HARVESTING TECHNIQUES

Figures 3 and 4 show the top ten maximum harvested power and energy values in W and kJ (kiloJoules), respectively, taken from Table 1. The Logarithmic scale is used to conveniently express the minimum as well as the maximum values, that are otherwise difficult to express on a non-logarithmic scale. The reason of separately depicting power and energy plots is that in the studied papers, some researchers have expressed their harvested output in terms of power while others have used energy as a parameter of representation. Figure 3 shows that the multi-source method harvests the maximum power due to the combination of various sources. It is followed by PCM harvesting method. The lowest power is harvested by the TEG due to being sensitive to a certain temperature difference range. Figure 4 shows that the maximum energy is harvested by the PCM followed by multi-source harvesting. The TEG again harvests the minimum output. A comparative analysis of underwater thermal energy harvesting using TEG, PCM and multi-source strategies as well as kinetic and piezoelectric energy harvesting methods is shown in Table 2. It shows that the phase change material is utilizable in a diverse number of applications and is independent of the day-night cycle but its performance varies from one material to another and some materials are toxic as well. The TEG harvesting is fast in response due to the use of semiconductor materials but they have low output power due to being sensitive to a certain range of temperature.

The kinetic energy harvesting uses waves motion to harvest energy, which is usually easily available. However, due to varied amplitude of the waves, the harvested output is variable and is also affected by seasonal and geographical variations. The piezoelectric harvesting uses the vibrations and stress of water pressure to harvest energy.

IV. COMPARATIVE ANALYSIS OF THE HARVESTING TECHNIQUES WITH OTHER HARVESTING METHODS

Figure 5 shows the number of publications for one decade: 2014-2024, for the three classified thermal energy harvesting methods: PCM, TEG and multi-source. It shows that the PCM is mostly utilized worldwide for thermal energy harvesting. There are a number of possible and likely reason for this trend. Firstly, there is a diversity in the existence of phase change materials with different thermal and physical properties such as thermal conductivity, melting and solidification points, variety of existence and the diversity in cost. These points ensure the selection of a specific PCM according to the global harvesting conditions and environments. As a result, the PCM is mostly utilized for underwater thermal energy harvesting. Moreover, the phase change materials are usually utilized within a specific temperature range without negative environmental effects that enhances their scope in underwater thermal energy harvesting. Also, the trend in the use of PCM for thermal energy harvesting is increasing in the recent years as is evident from the corresponding increasing publications count trend. The multi-source energy havering technique comes second in terms of utilization for thermal energy harvesting followed by the TEG harvesting.

Figure 6 classifies the discussed algorithms in terms of extent of the harvested output power/energy. The first class of algorithms harvests power or energy with an extent smaller than or equal 1 W or 1 J. This class of algorithms is enough to power low power underwater devices such as sensor nodes. The second class of algorithms harvests an amount of power or energy that is greater than 1 W or 1 J but less than 1000 W or 1000 J. This class is capable to power devices requiring low to medium power/energy while algorithms used to operate

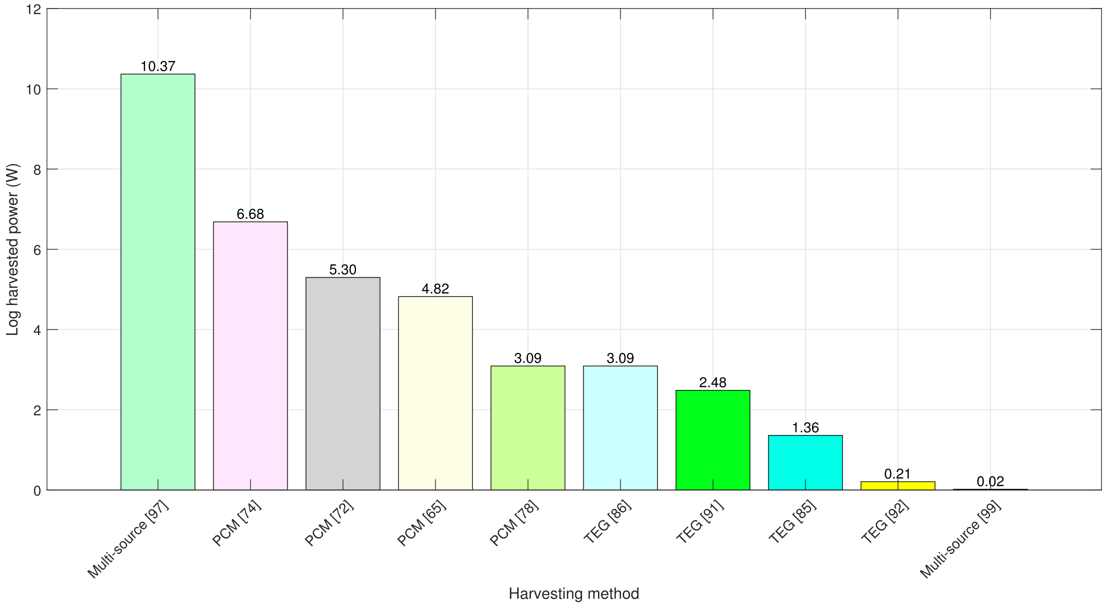

FIGURE 3. Power harvested by PCM, TEG and multi-source methods on Logarithmic scale.

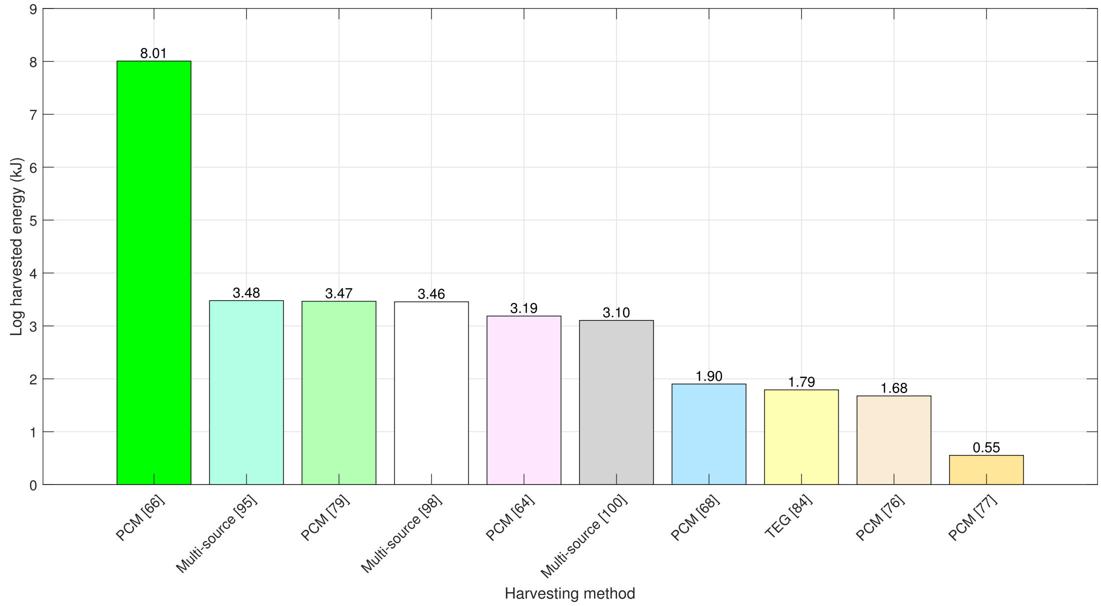

FIGURE 4. Energy harvested by PCM, TEG and multi-source methods on Logarithmic scale.

high power demanding devices are characterized by their harvesting capability of greater than 1000 W or 1000 J. There are also algorithms that have not shown (measured) the harvested output in the description and are categorized in the undetermined category.

V. CHALLENGES IN UNDERWATER THERMAL ENERGY HARVESTING AND FUTURE INVESTIGATION

There are a number of challenges related to underwater thermal energy harvesting that require to be further addressed. They are:

- **Low Harvesting Efficiency**. The extent of thermal harvested energy is usually low, especially the energy harvested by the TEG. This challenges the perpetual operation of devices, especially devices requiring power higher than milliWatt range.
- **Requirement of a Significant Temperature Difference**. The TEG devices require a constant source of heat to maintain a threshold temperature difference to harvest energy. In a similar fashion, the phase change materials also require a specific temperature difference to transform physical states and harvest energy. This

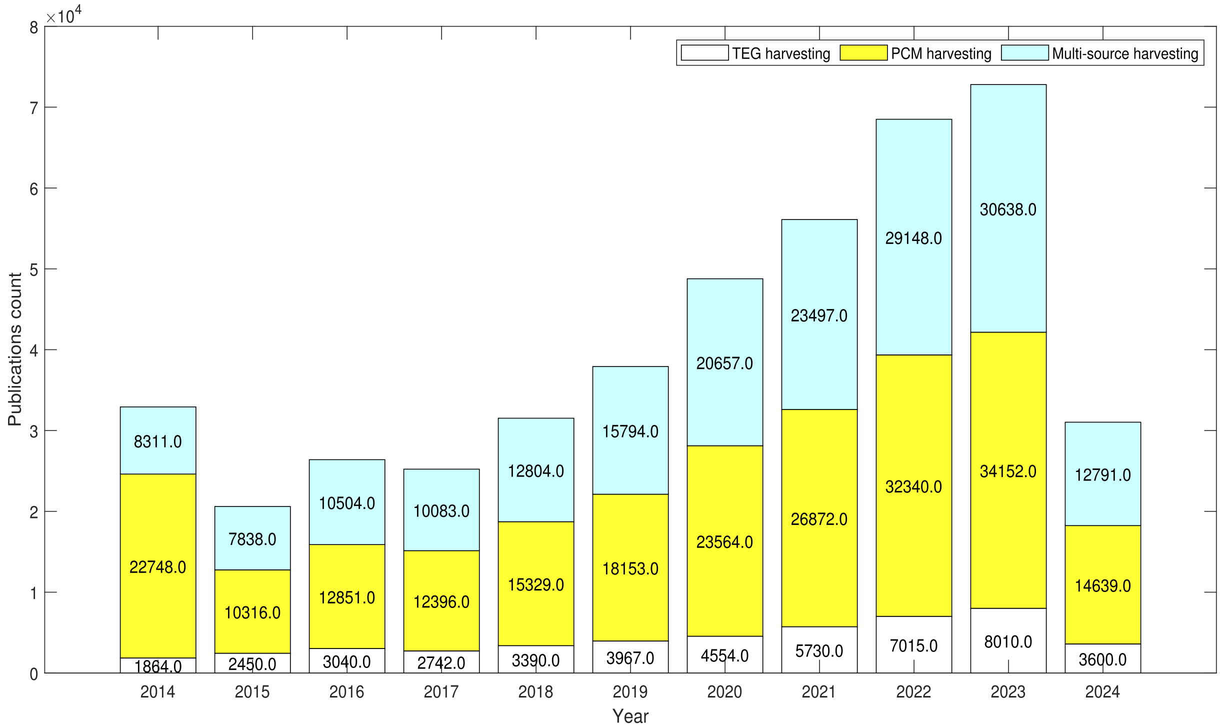

FIGURE 5. Publications count on the classified energy harvesting techniques: PCM, TEG and multi-source in the latest decade: 2014-2024, searched on https://app.dimensions.ai/.

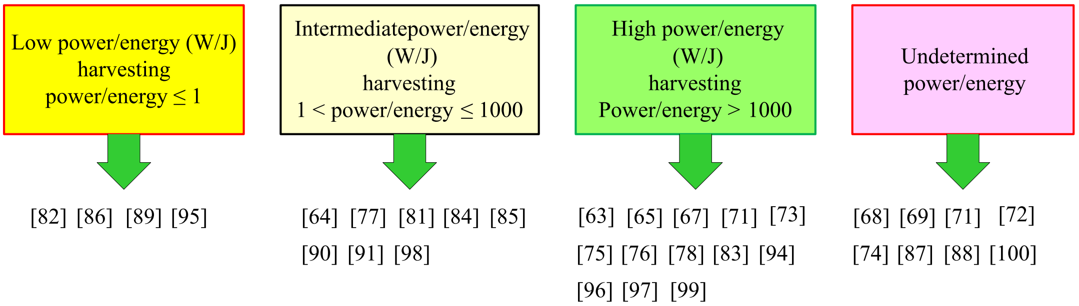

FIGURE 6. Classification of algorithms based on extent of harvested output power/enrgy.

limitation adversely affects the energy harvested for device operation at a low depth, as the temperature difference in a water body increases with increasing depth. Therefore, in such conditions, the harvested energy many not be sufficient to power the involved devices.

- **Geographical and Seasonal Variations in Water Temperature**. The temperature of water bodies varies with locations and seasons. This affects the harvested amount of energy, especially in conditions when the temperature difference is low, such as during the winter season.
- **Materials and Processes-dependent Harvesting**. Since the temperature difference in a water body exists up to a certain limit, the energy harvesting becomes dependent, to a significant extent, on the materials and processes involved in harvesting. This, in effect, demands sophistication in these steps to harvest the maximum possible energy.
- **Diversity in PCM Properties Varies its Harvesting Capability and Environment-friendliness**. The thermal properties of the phase change materials vary significantly from one material to another. This results in corresponding variations in the harvested extent. Moreover, the toxicity of some of these materials poses a significant danger to the marine life.
- **High Cost of PCM**. Some of the PCM materials are expensive so their use in the energy harvesting processes will increase the harvesting cost.
- **Complexity of Integration of Multi-source Harvesting**. Since multi-source energy harvesting involves various energy harvesting techniques, it has a high complexity of operation and integration of the individual sources.

- **Special Design and High Cost of Materials Maintenance**. Since the underwater environment is harsh and unpredictable, the thermal energy harvesting devices working in it require special design to withstand the environmental effects such as bio-fouling, extreme temperature, humidity, salinity, effects of oxygen and other reactive and toxic materials in water. Moreover, these devices require constat monitoring that increases the maintenance cost.

VI. CONCLUSION

The latest and state-of-the-art techniques and algorithms developed in the latest decade (2014-2024) for underwater thermal energy harvesting are studied, analyzed and classified in terms of operation for harvesting energy. The classes of algorithms included phase change materials, thermoelectric and multi-source based harvesting. The algorithms are analyzed and compared in terms of energy efficiency and applications in the underwater environment and in various other applications. The publications count of the algorithms in underwater and general thermal energy harvesting in the latest decade are highlighted. The harvesting results indicate that hybrid (multi-source) and PCM methods have the greatest amount of harvested power and energy, respectively.

The conducted study is helpful and useful for the researchers in marine environment to utilize the described techniques for powering devices in a diverse set of underwater and offshore applications. Moreover, it provides a foundation for further working on the existing loopholes for enhanced thermal harvesting efficiency.

VII. FUTURE WORK

The points for future research investigation towards enhanced thermal harvesting efficiency are:

- **Sophisticated Techniques and Materials for Enhanced Efficiency**. Since the efficiency of thermal energy harvesting is inherently low, future investigation requires the development of sophisticated materials and methods to enhance the efficiency. For instance, reducing the value of temperature difference at which a TEG or PCM starts to detect the temperature change and harvests, which can be accomplished by altering the properties of the existing materials and developing advanced materials and processes. For instance, the heat exchange process can be optimized for enhanced efficiency [115], [116].
- **Multi-source Energy Harvesting and Integration**. The multi-source energy harvesting and its integration as a unified system requires further research to efficiently harvest and store the total energy. This will not only enhance the harvesting efficiency but the storage efficiency as well.
- **PCM as a Thermal Energy Storage Element**. The PCM is mainly used as an energy harvesting element in the thermal engine of the harvesting devices. The capability of the PCM to ensure thermal energy storage can be investigated in future research endeavors.
- **Energy Harvesting Feasibility Prediction of Underwater Sites using Machine/Deep Learning**. The computation of parameters involved in energy harvesting prediction such as water pressure and temperature variations with depth, density, speed and salinity for underwater sites can be accomplished first. Then, these parameters can be used to evaluate the energy harvesting feasibility of underwater sites by predicting the harvested extent using deep/maching learning algorithms. This will provide a prediction of the possible harvesting capacity of an underwater site.
- **Use of Optimization Algorithms for Operation, Storage and Geometry Optimization for Enhanced Harvesting Efficiency**. The operation, storage and geometries of the harvesting devices can be optimized with the latest optimization algorithms for enhanced energy harvesting efficiency.

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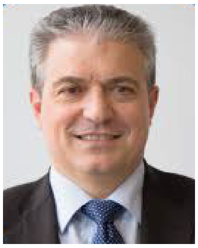

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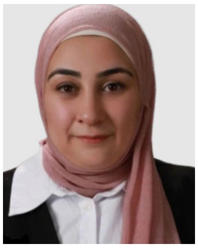

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