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# Investigating the Performance of Metal Surfaces Modified by Laser on the Efficiency of Water Harvesting from Humid Air

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## Abstract
The population growth and consequently lack of fresh water resources, are the main concerns of developed communities. Providing water from air humidity is an efficient, clean, and sustainable solution that can supply sweet and fresh water. In this study, different metal surfaces including copper, steel, and aluminum plates have been prepared as a hydrophobic or hydrophilic surfaces through laser, to investigate the amount of collected water at 294.15 K under fully humid environment (100% humidity), at different encounter angles with plates (45, 70, and 90 °). Moreover, the metal plates along with small or large meshes have been also tested. In addition, polytetrafluoroethylene plates have been prepared via laser in order to water harvesting from humid air. It has been shown that all surfaces treated with laser have better efficiency for water harvesting in comparison with the plates without laser. Likewise, the angle of 45° has had the highest amount of collected water on all surfaces. Eventually, it has been observed that steel plate modified with laser 1 has had higher efficiency for producing drinking water.
**Keywords:** Humid air, Laser, Metal surfaces, Water harvesting.

## 1. Introduction
Although the quality of human life has increased dramatically in the last century, according to the United Nations reports more than 785 million people worldwide still do not have access to clean drinking water resources (UNID, 2016). One of the main reasons for the lack of access to clean water resources is the remoteness of population centers from fresh water resources, which forces them to travel long distances daily to reach these resources (Hillie and Hlophe, 2007; Randhir and Genge, 2005; UNID, 2016). Various solutions have been proposed in order to overcome this challenge.

Rainwater storage (Worm, 2006; Furumai, 2008; Vieira et al., 2013; Şevik and Aktaş, 2022), groundwater abstraction (Clark, 1985; Munoz-Reinoso, 2001; Wada et al., 2010), cloud seeding (Dennis, 1980; Rosenfeld and Woodley, 1993) and desalination (Al-Agha and Mortaja, 2005; World Health Organization, 2011) are some ways used in some regions of the world. The results show that these methods require high maintenance and operating costs and high technology, which has made utilizing these methods not economically viable (Bhushan, 2020).

Therefore, many researches have been carried out to find a fundamental solution to provide access to water resources. The results show that the water harvesting from fog is one of the basic sweet drinking water supply solutions. Special harps (Shi et al., 2018), conical surfaces (Gurera and Bhushan, 2019), barbed cones (Brown and Bhushan, 2016), polymeric fiber meshes (Ganesh et al., 2017), wrinkled fibers (Zhu et al., 2017) or capillary symmetric channels (Brown and Bhushan, 2016) utilized by this method in order to fog water harvesting.

In general, various researches in this field have been done in order to improve, optimize and compare with other methods. In these researches, the most important parameters affecting the performance of water collectors from fog have been identified and investigated. The most important parameters influencing the fog water harvesting are the geometry, wettability and surface material (Olivier, 2002; Jarimi et al., 2020; Bhushan, 2020; Nioras et al., 2021). Schunk et al. (2018) designed a new fog collector and tested in Morocco. Finally, they proved that this design (three-dimensional structure) performs better than Woven fabrics such as conventional Raschel mesh.

Moreover, Knapczyk-Korczak et al. (2020) used commercial Raschel mesh incorporating electrospun polyvinylidene fluoride (PVDF) fibers to prepare an appropriate medium for collecting fog with the maximum water collection efficiency. Metal meshes located in cooling towers harvest water from the fog. Water droplets sit on the meshes and move down due to gravity (Ghosh et al., 2020). Wettability of meshes is also one of the parameters affecting the performance of collectors by facilitating the movement of water droplets (Seo et al., 2016; Wang et al., 2019). They altered mesh wettability and made them hydrophilic (HPL), super-hydrophilic (SHPL), or super-hydrophobic (SHPB) via surface treatments containing either electrophoretic deposition of $TiO_2$ nanoparticles or wet chemical etching of stainless steel meshes.

It is indicated that the most suitable drainage has been due to $TiO_2$-coated HPL meshes, which has had the maximum value at a 15° mesh inclination angle (Wang et al., 2019; Ghosh et al., 2020). Various researchers have always sought to increase the efficiency of water extraction from fog. Inspired by Namibian beetles, Wang et al. (2021) developed a new way to harvest water from hydrophilic and hydrophobic plates. They used titanium dioxide photocatalysis and ultraviolet radiation for their purpose. Their results showed that the best fog water collecting efficiency occurred for these materials. Other attempts were made to use lasers to increase water harvesting efficiency. Razi et al. (2016) designed a new 316L grade steel surface using a nanosecond laser.

They studied different surface properties such as wettability and surface chemistry in different states. The results showed significant changes in wettability and oxygen surface content occurred under different laser surface conditions. Yang et al. (2019) used laser on several metallic surfaces, and prepared the linear or lattice pattern plates. The fabricated surfaces showed primary hydrophilicity and then converted gradually to super-hydrophobicity via the increment of exposing time to ambient air. In addition, they analyzed the wettability conversion using X-ray photoelectron spectroscopy (XPS). They showed that the roots of this super-hydrophobicity were due to carbon content increment, and the dominance of the C–CH functional group bonds.

Furthermore, Jagdheesh et al. (2022) studied on modification of non-fluorinated super-hydrophobic aerospace aluminum alloy (Al7075) plate using laser and high vacuum procedure for 4 h. They indicated the synergistic influence of hierarchical structures, and the dominant presence of non-polar components is essential for ultra-hydrophobic characteristic. Gürsoy et al. (2023) were coated the ordinary polypropylene fabrics with polymeric thin films using chemical vapor deposition method in order to effective fog harvesting application. Their obtained fabrics enhanced with hydrophobic thin film showed an excellent fog harvesting efficiency.

Zhou et al. (2023) were fabricated a polypropylene/graphene based surface with improved harvesting properties. The wettability of surfaced have helped to accelerate droplet condensation and aggregation, for improvement of mass transfer in a fog harvesting system. Their surface had reached a collection efficiency of 1251 $mg.cm^{-2}.h^{-1}$.

Nano and microscale structures are critical for the stable super-hydrophobic properties with a great degree of water repellency for a higher volume of water droplets. Moreover, the sole existence of nanoscale constructions on hydrophilic aluminum alloy plates with a dominant presence of non-polar materials can yield merely near the super-hydrophobic surface because of the accidental spacing of nanoscale protrusions. Based on research, a combination of hydrophilic and hydrophobic can have better results for water production than any of the mentioned materials.

However, all parameters must be carefully checked from an industrial point of view (Zhou et al., 2023). In this study, considering the most important parameters affecting water fog harvesting (moisture, temperature, wind speed, angle of plate, type of material of plates), collected water in different conditions was measured and the results were interpreted in order to find the optimal solution. Water production with this method and with the help of suitable levels can be implemented for mountainous areas with high humidity such as Javaher Deh area in Ramsar city or in Kiasar area in the north of Semnan city and Finsk.

## 2. Materials and Methods

### 2.1. Laser process

Lasers have many advantages over traditional light sources. Linear radiation, high density and high brightness along with energy accumulation are among these advantages. Lasers can travel long distances and create temperatures of several thousand degrees and there is a high energy density in the laser spot at their focal point. The high coherence of the lasers allows them to have a high focus on a small area. Due to the high density of energy at that small area, photochemical reactions or removal of materials resulting from the breaking of chemical bonds may occur. To write patterns on aluminum, copper and steel surfaces, a system of laser direct writing was used. Polytetrafluoroethylene (PTFE) is a hydrophilic material that can be widely used for filtration, water extraction and etc. due to its hydrophobicity and chemical compatibility.

It has a smooth surface, light texture, high porosity and uniform fine-porous structure; thus, it has fast flow characteristics and is not easy to absorb. PTFE plates and metal surfaces along with meshes have been also tested. All the metal surfaces have been modified via the laser characteristics mentioned in Table 1, and all these plates have been subjected to the contact angle test after the laser modification. Moreover, each surface has been placed on a proper holder for 5 hours with a distance of 4 cm. In addition, the encounter angle of these plates has been adjusted equal to 45, 70, and 90 degrees against the humidity outlet located inside the chamber. Also, the humidity was adjusted to 100% at 294.15 K.

It should be noted that the humidifier was placed outside the chamber. Furthermore, a glass container was fixed under the surface to collect and then weight the water harvested after 5 hours with a digital balance. Moreover, three different laser treatments and non-treated plate were compared in order to find the highest water harvesting efficiency. In more detail, Figure 1 has demonstrated the schematic diagram of experimental set up.

**Table1.** Laser treatment characteristics on metal surfaces

| Specifications | Laser1 | Laser2 | Laser3 |
|---|---|---|---|
| Repetition rate (KHz) | 100 | 90 | 500 |
| Wavelength (nm) | 355 | 1030 | 405 |
| Power (W) | 20 | 4 | 50 |
| Scanner linear speed (mm/s) | 500 | 50 | 500 |
| Spot size (nm) | | 300 | |
| Pulse duration (ns) | | 2000 | |
| Parallel line density ($mm^{-1}$) | | 2500 | |

### 2.2. Experiment setup

The saturated air enters the test chamber and collides with the plate attached to the stand, which is installed with a specific encounter angle. Saturated air turns into water droplets on condensed plates. Water droplets are directed by gravity into the collection chamber and stored. Fig.1 shows fog water harvesting system schematic.

### 2.3. Sample preparation

Square patches of 75 mm sides were cut from SS-304 meshes and rinsed first in deionized water and then in acetone under ultrasonic agitation for 20 min to remove surface dirty.

### 2.4. Contact angle measurement

For sessile deionized water droplets of 5 μL volume, contact angle measurements were measured using a goniometer (Holmarc Opto-mechatronics Pvt. Ltd, Ver. 8.0.0.0 with an inbuilt CCD-USB camera and a white, cold backlight). A standard low Bond-number, axisymmetric drop shape analysis (LBADSA) algorithm using the Young-Laplace analysis (built in the Holmarc image analysis software) was employed to calculate sessile droplet contact angles, as well as advancing and receding angles. The maximum uncertainty in the contact angle measurement was ± 1°.

### 2.5. Scanning Electron Microscopy (SCM) analysis

Field emission scanning electron microscope imaging was performed to visualize the surface texture and properties. The surface morphology, surface structure and internal porosity were examined by scanning electron microscopy (SEM). The results show that the laser surfaces are homogeneous and free of any impurities in structure or oxides created due to the preparation process (Fig. 2).

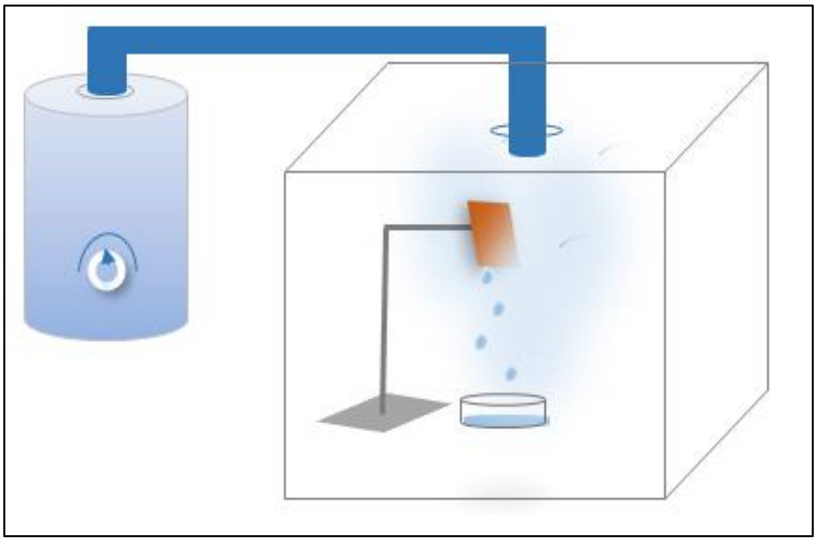

**Fig.1.** Fog water harvesting system schematic

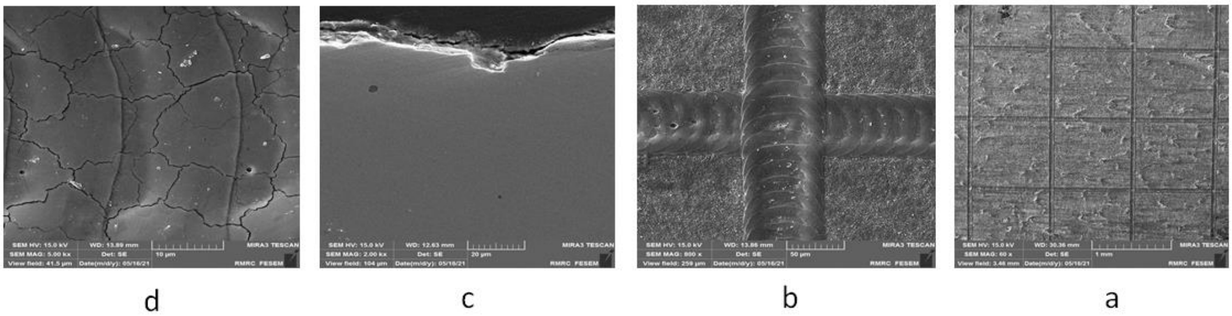


**Fig. 2.** SEM analysis of metal surface after laser irradiation in scales a) 1 mm, b) 50 micrometers, c) 20 micrometers and d) 10 micrometers

## 3. Results and Discussion

### 3.1. Mass flux measurements for laser treatment of plates

The mass flux of water collected on non-lasered and lasered surfaces of aluminum, copper and steel was measured and the results are illustrated in Table 2. Results show that, the amount of mass flux for collected water at 45° encountered angle is the highest for all materials and laser treatments.

At this encountered angle, the mass fluxes of collected water have the optimum position considering the collision of vapor droplets to the surface and the formation of liquid droplets and the subsequent flow of liquid droplets due to the gravity force. The area in front of water vapor encountering the plate and the slope of the plate and water sliding off the plate and collecting it have important contributions in water harvesting process. The smaller angle of the plate to the horizon, the more contact with the steam flow and the more absorption of steam occurs on the surface. But this absorption is beneficial to the process as long as the absorbed water is removed from the surface and the surface is not saturated with water.

By increasing the angle of the surface to the horizon, the absorbed water slides more easily and provides the surface for the absorption stage. These two problems are opposite to each other and for this reason we will have an optimal angle for maximum water harvesting. Surface properties such as hydrophobicity and heat conductivity, shape of laser formed channels, their depth and width can affect the ability of surfaces to harvest the water from the fogs. As it can be seen, the steel surfaces in all modifications have the best quality for water harvesting process.

**Table 2.** Mass flux of collected water at material surfaces under laser modification

| Surface | Encounter angle | No-laser | | Laser 1 | | Laser 2 | | Laser 3 | |
|---|---|---|---|---|---|---|---|---|---|
| | | Contact angle | Mass flux ($gr/m^2.hr$) | Contact angle | Mass flux ($gr/m^2.hr$) | Contact angle | Mass flux ($gr/m^2.hr$) | Contact angle | Mass flux ($gr/m^2.hr$) |
| **Copper** | 90 | 79.5 | 225.55 | 135.06 | 1142.103 | 117.19 | 884.148 | 104.13 | 1338.814 |
| | 70 | | 351.866 | | 2241.214 | | 1481.481 | | 1366.162 |
| | 45 | | 359.289 | | 3277.940 | | 1590.814 | | 1633.807 |
| **Aluminum** | 90 | 87.16 | 180.044 | 98.57 | 1167.555 | 114.39 | 1032.740 | 89.68 | 1438.725 |
| | 70 | | 269.466 | | 1135.140 | | 1344.207 | | 1464.903 |
| | 45 | | 381.4222 | | 1757.585 | | 1563.288 | | 1543.851 |
| **Steel** | 90 | 97.39 | 476.3556 | 130.79 | 2109.051 | 83.79 | 1356.725 | 58.81 | 1792.1777 |
| | 70 | | 579.259 | | 1827.362 | | 894.843 | | 1168.814 |
| | 45 | | 712.918 | | 3728.1777 | | 1602.541 | | 1916.740 |
| **PTFE** | 90 | - | 997.63 | 101.42 | 883.985 | 75.80 | 826.014 | - | 921.77 |
| **PTFE** | 45 | | 1439.259 | | 1469.777 | | 1244.84 | | 1391.407 |

As shown in Table 2, all surfaces along with laser have been hydrophobic plates. When the water droplets come in contact with the metal surfaces, these droplets are divided into really fine particles which are the nuclei formed (nucleation process). Then, the droplet nuclei join together over time and grow to form larger droplets (Growth process) and moisturize the solid surfaces (Knapczyk-Korczak et al., 2020).

Indeed, surfaces wetting characteristics have an intense effect on the water droplet transportation and their collection. The proposed mechanism for the amount of collected water in surfaces along with laser in comparison with non-laser surfaces can be expressed by Wenzel's and Cassie's analytical mechanism (Wang et al., 2019; Ghosh et al., 2020).

When a droplet is in contact with the surface, it completely fills the depressions of the rough surface. A rough surface has a higher contact area in comparison with a smooth surface. Particularly, when the accumulated droplets start nucleation on the surface, the growth process occurs through adjacent droplets. This steady accumulation continues until the critical volume is reached, and the droplets commence to move. Water droplets have low adhesion on hydrophobic surfaces and can easily slide on the surface and are placed in the collection container.

### 3.2. Comparing the performance of plates under laser treatment

Copper, aluminum and steel metal plates were subjected to laser treatment. The effect of laser treatment on each surface was evaluated. The power, frequency and wavelength of the laser, the speed of the laser operation affect the shape of the channels created on the surface and affect the surface hydrophilic/hydrophobic properties, the heat transfer and drain ability of the surface in making the water droplets flow.

#### 3.2.1. Copper surfaces

Fig. 3 illustrate the copper performance of different laser treatments. As it is clear from the figure, the application of laser 1 on copper plates has increased the amount of water harvesting with a much greater slope, which means a better effect for copper plates. It can be seen that laser application has always improved the surface for water harvesting. Laser 1 has had the best result for modifying the copper plate. In the comparison of laser 1 and laser 3, it can be seen that the speed of the laser is the same and the difference is in the laser power. The same laser speed gives the plate the same number of grooves.

On the other hand, adding power changes the width and depth of the groove. Therefore, more power has improved the depth of the created groove and improved the water drain ability network along the plate and improved water collection from the copper metal surface.

As it can be seen in Fig. 3, for the copper surface, the mass flux increased by decreasing the encounter angle from 90 to 45 degrees, and the maximum mass flux of water occurred at an angle of 45 degrees, under laser 1 conditions with was amount of 3277.940 $gr/m^2$.hr. Also, the laser 1 provided the highest contact angle of 135.06 degrees that improved the surface hydrophobicity comparing to the other laser conditions.

### 3.2.2. Aluminum surfaces

Fig. 4 illustrate the laser modification results of aluminum surfaces. Compared to laser 3, laser 2 has lower power and lower speed. But at an angle of 45 degrees, it has been able to show equal efficiency compared to laser 3. This result shows the effect of laser cutting characteristics on the formation of channels on the plate surface. At an angle of 70 degrees, lasers 2 and 3 have shown more efficiency than laser 1, which indicates the opposite effects of effective parameters on the water harvesting process.

### 3. 2.3. Steel surfaces

Fig. 5 shows the mass flux of collected water at the different laser treatments. It can be seen that the encounter angle of 70º has the lowest efficiency in water harvesting that indicate the existence of an optimal condition according to channel formed shapes and their geometrical properties.

Considering the fact that the condensation process depends on two factors of hydrophilicity or hydrophobicity and the heat conductivity of the metal surface. It can be expected that hydrophobicizing a surface that has high thermal conductivity can help increase the water harvesting due to water flowing on the s urface and emptying the surface for subsequent condensation.

Comparing to laser three, laser one has more power, it seems that the width of the created grooves has increased and a larger surface area of the metal has been modified. Also, in the comparison of laser two with three, since the power of laser two is less than that of laser one, but the speed of laser execution is ten times slower, it can be concluded that the speed of the laser is also has a high importance as well as the power. The slowness of the laser execution makes the laser process complete and the time needed to surface modification is given to the laser.

The shape, depth of the groove and the number of grooves created on the surface cause water to settle, accumulate or slide on the surface and affect the final extraction. It can be seen that creating grooves on the surface of the plate acts like a drainage and water collection network and collects water from the surface. Increasing the power of the laser increases the depth of the groove.

This increase (up to an optimal value) increases the collection of water from the surface, but increasing the depth of the groove causes water to remain inside it and reduces the water drainage. The speed of grooving on the surface increases the number of channels, and consequently improve the water drainage of the surface.

### 3.3. Mesh size effect on water harvesting

Table 3 reports the mass flux of collected water from metal surfaces along with small or large meshes at two different encounter angles (90˚and 45˚). Based on the results, the size of the meshes has little effect on the mass flux of the harvested water. This is true even at different angles encountered. Of course, this may not be a general principle because only two different sizes have been used. For a more accurate evaluation, different sizes should be used in a wide and detailed range of examination.

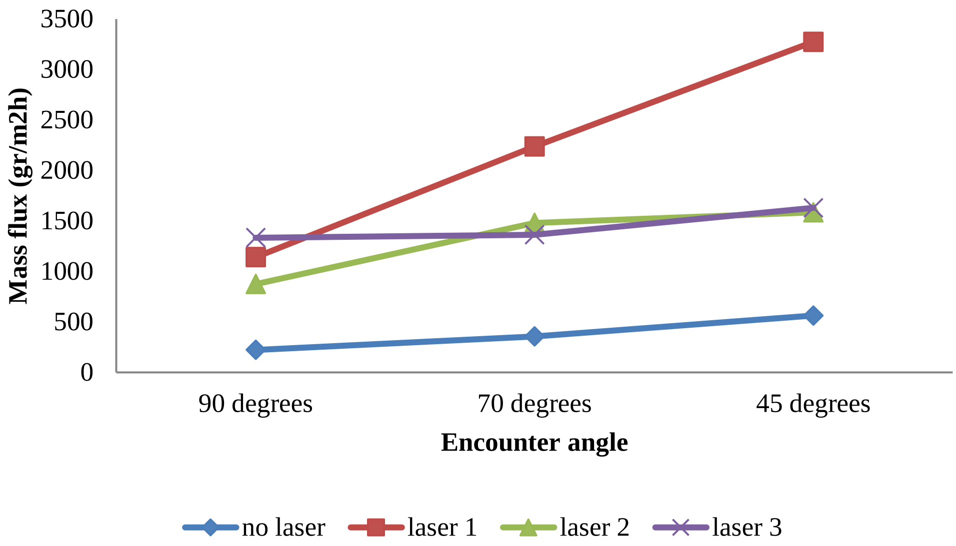


**Fig. 3.** Comparing the performance of copper plates under laser treatment

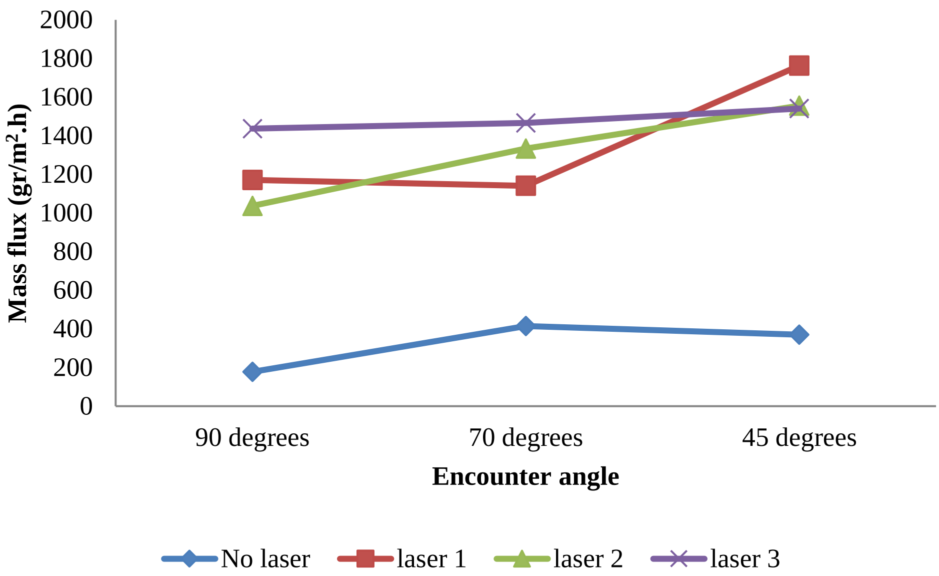


**Fig. 4.** Comparing the performance of aluminum plates under laser treatment

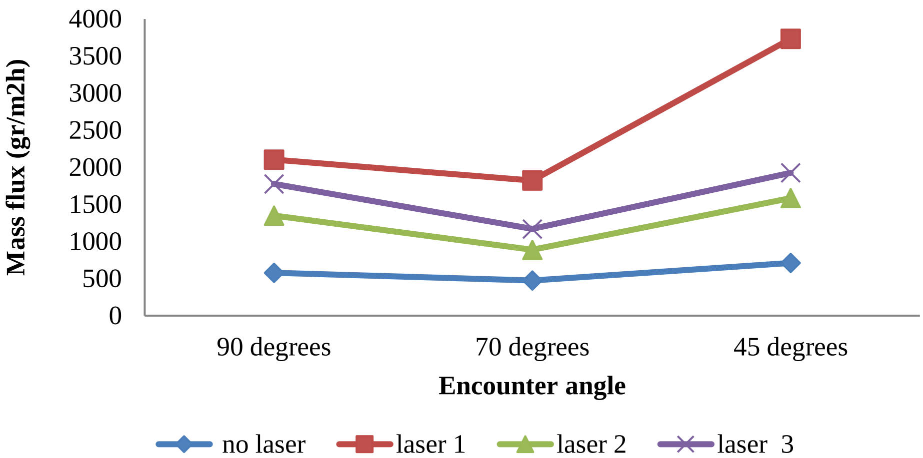


**Fig. 5.** Comparing the performance of steel plates under laser treatment

**Table 3.** Mass flux of collected water on metal surfaces along with mesh

| Surface | Mesh number | Encounter angle | Mass flux of collected water (gr/m$^2$.hr) |
|---|---|---|---|
| Small mesh | 1000 | 90 | 10.3346 |
| | | 45 | 10.4790 |
| Large mesh | 265 | 90 | 10.9909 |
| | | 45 | 11.007 |

| Type of method | Type of surface | Mass flux of collected water (kg/m$^2$.hr) | reference |
|---|---|---|---|
| Fog collecting | wire-to-plate electrostatic | 3.88 | Zeng et al. (2023) |
| Fog collecting | micro-structured metal meshes | 3.41 | Showket et al. (2024) |
| Fog collecting | Modified zinc plate | 0.57 | Wang et al. (2023) |

## 4. Conclusion

According to the water supply importance and its scarcity, the main aim of this study has been related to water harvesting from humid air. Certainly, although water harvesting from fog and humid atmosphere has not been a proper substitution for drinking water resources, but it can be a very good complement for deficiencies compensation. Thus, the water harvesting been carried out along with hydrophobic and hydrophilic surfaces treated by laser in order to investigate and optimize the parameters affecting the water collection process.

Therefore, various metal (steel, copper and aluminum) and PTFE surfaces were modified under three different modes of power, frequency and wavelength of lasers. Results showed that the metal surfaces had a significant improvement in the mass flux of the removed water after laser treatment. Although the water harvesting rate from the polymer surface before laser was higher than metal surfaces, but after laser treatment due to the modification of metal surfaces, their water harvesting rate became higher than PTFE surface.

The best modification results can be obtained through the laser 1 conditions. Experiments reveal that the encounter angle of 45 degrees for all three metals provide the maximum water harvesting rates, and steel showed more efficient than copper and aluminum. The results showed that small or large mesh size had a little effect on water extraction. Therefore, the best case for fog water harvesting occurs with a steel surface in the conditions of laser 1 and encountered angles of 45 degrees.

## 5. Disclosure Statement

No potential conflict of interest was reported by the authors

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