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THE IMPACT OF WATERS OF LOW QUALITY ON SOILING REMOVAL FROM PHOTOVOLTAIC PANELS

by

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Abstract

Soiling, bird droppings, or the accumulation of dust on the surface of photovoltaic cells, can significantly reduce the solar energy absorption and produce power losses. In solar plants where soiling is a problem, solar facilities use demineralized or distilled water for washing the panels to avoid mineral scale deposits that might interfere with solar irradiance absorption. However, in arid and dusty environments, water is normally scarce. For cleaning solar panels, the use of low quality water in lieu of the industry-standard demineralized water could conserve fresh water. The objectives of this research were as follows: evaluate the impacts of low quality water to wash solar panels on the energy output of photovoltaic systems; determine if the use of water of low quality promotes the deposition of any substances on the solar panel surface that can be detrimental to their performance; determine the chemical composition of the dust accumulated on the panels on the solar system where the research is being performed. A group of 264 photovoltaic panels, facing due south with a tilt angle of 32 degrees, located at the West Yard of the City of Las Vegas, Nevada were studied. The panels have been grouped into six independent sections and each section was washed using the following cleaning methods: distilled water, treated wastewater with surfactant (Sodium Dodecyl Sulfate), treated wastewater, groundwater, and vacuum cleaner (no water – dry cleaning). One group of panels was left without cleaning (control). Panel soiling cleaning was performed manually using a soft cleaning brush. Three gallons of water were used to wash each group of panels. In this study, the dust did not seem to have a great effect on the system performance, with the control group experiencing only a 1.88% reduction in mean efficiency due to dust accumulation. In this study, the solar panels did not get as dirty as expected because the study site is covered with compacted soil and small rocks specifically intended to abate dust. Furthermore, the results confirmed that cleaning the solar panels with distilled water was more effective when compared with the other cleaning methods. During the cleaning schedule period (8 total), the distilled water recovered a mean normalized system efficiency of approximately 1.32%, followed by the treated wastewater (0.92%), treated wastewater with surfactant (0.73%), vacuum cleaner (0.27%), and groundwater (0.24%). In addition, the results indicated that the dust particles accumulated on the panels contained silicon (Si), oxygen (O), aluminum (Al), carbon (C), chloride (Cl), sodium (Na), potassium (K), and other elements. The dust composition analysis performed by scanning electron microscopy coupled with an energy dispersive spectrometer (SEM-EDS) and the Thermo iCAP 6300 – ICP-OES Spectrometer detected that the dust particles identified on the surface of the photovoltaic panels were the same from the ground or caused by the light vehicular traffic in the urban area. The anions found in the dust composition were chloride, fluoride, nitrate, sulfate, and phosphate. Pyrolysis-GC/MS identified that the presence of organic compounds on the surface of the PV panels were related to the local suspended soil, pollen, and vaporized cooking oils. It was concluded that the dissolved minerals in the wastewater and principally in the groundwater negatively impacted the performance of the system (power output). Inadequate or inefficient cleaning methods, such as the use of groundwater to clean PV panels, can end up consuming more time and increasing costs. Evaluation of cost benefits regarding washing solar panels revealed that even when the electricity costs $0.1/kWh, it is not cost effective to wash the panels paying $1 per module. To be worthwhile either the washing cost would have to be lower or price of electricity would have to be higher.

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Chapter 1 - Background

Solar energy is the cleanest and most abundant of all renewable energy sources (Parida et al., 2011) and it can be generated by photovoltaic panels (PV) or by concentrating solar power (CSP) using heat engines. Photovoltaic (PV) cells convert sunlight into electricity (direct current – DC) without the presence of heat engines (Parida et al., 2011).The first reported observation of solar to electric conversion system was by Edmond Becquerel in 1839. His finding was reported in his "*Mémoire sur les effets électriques produits sous l'influence des rayons solaires*". With the beginning of the modern era of photovoltaics, silicon was the preferred semiconductor (Hanjalić et al., 2008). Solar thermal collectors have been in commercial manufacture since the 19th century. After the OPEC oil embargo (1973-1974), many governments invested in renewable energy research due to the significantly increase in the oil price (Tiwari & Dubey, 2009).

In the last ten years, the use of solar energy in the United States had a compound annual growth of approximately 60%, while the cost of installation dropped by more than 60%, leading the industry into new markets (SEIA, 2016).

Photovoltaic reliability and efficiency depend on factors such as the location (latitude, longitude, and solar irradiance), environment (temperature, wind, dust, rain), and type of PV panels used (monocrystalline, polycrystalline) (Ahmed et al., 2013).

The performance of PV panels can be affected by different factors such as weather conditions from high wind or rain clouds, dust from traffic or agricultural activities, fallen leaves, temperature, and pollution from different industries. Studying the impact of these factors may aid in improving the selection of panel technology, type, and location (Al-Ammri et al., 2013)

Dust is a term normally assigned to solid particles with diameters less than 500 µm. It is present in the atmosphere as a result of different sources: wind, pollution, volcanic eruptions, vehicles, and pedestrians. The aforementioned dust particles can accumulate on the surface of photovoltaic panels. The characteristics of dust settlement on PV systems depend on different factors such as dust properties (chemical, biological, electrostatic property, size, shape, and weight), wind velocity, glazing features (texture of the PV panel surface and coating), tilt-angle, orientation, ambient temperature, humidity, and site characteristics (local vegetation cover, pedestrian and vehicular traffic, and air-pollution) (Mani & Pillai, 2010).

Dust accumulation blocks the light from reaching the solar cells and can also change the thermal equilibrium of the PV system. As a result, accumulated particles may retain heat and increase the temperature on the panels (Shehri et al, 2016). While the solar cell temperature increases the power output and voltage of the PV system decreases (Al-Sabounchi et al., 2013).

Soiling, or the accumulation of dust and other substances on the surface of the solar panels, can significantly reduce the solar energy absorption and produce power losses. Zorrilla-Casanova et al. (2011) reported a mean daily energy loss caused by dust deposition on the PV panels of around 4.4% during a year, and in long intervals without rain, the losses were higher than 20%. After analyzing one year of power output from a PV system in Santa Clara, CA, Mejia et al. (2014) concluded that the PV site had a decrease in system efficiency from 7.2% to 5.6%. In another study, Smith et al. (2013) demonstrated that 28 days without cleaning the panels led to a power output loss of up to 6% in the Portland, Oregon, metro area. These results highlight the importance of cleaning PV panels in environments where the rainfall is not sufficient to clean them.

The method of cleaning is extremely important to improve the efficiency of PV panels. There are different cleaning methods of dust removal for PV panels. These methods include natural means (wind power, gravitation, and rainwater), mechanical techniques (brushing, blowing, vibrating, and ultrasonic driving), self-cleaning nano-film (surface covered with a pellucid nano-film), and electrostatic methods (electric curtain). However, most of these technologies are expensive and not widely used in the solar energy industry (He et al., 2011).

The loss of energy yield and the cost of labor and water are the main factors that influence solar panel cleaning schedules. The cleaning schedules depend on the installation site, local weather, vegetation, wind, and dust concentration (Sayyah et al., 2014). Bhattacharya et al. (2015) demonstrated that solar panels must be kept clean in order to maintain the maximum efficiency. Their study, realized in Tripura, India, indicated that it is very important to clean the surface of the modules, generally after one month because the efficiency decreases over time due to the presence of dust.

Brackish water, sea water, and wastewater can be utilized for washing the modules, but they require prior treatment which can considerably increase the costs (Saidan et al, 2016). Soiling investigations help to determine the costs and benefits of cleaning the PV panels versus leaving them without washing (Caron & Littman, 2012).

Large PV solar power plants are installed in different parts of the world, including Spain, Germany, China, India, the United States, the United Kingdom, and the Middle East. Many of these installations are located in arid or semi-arid regions and dusty environments, which are preferred because they have a high solar irradiance concentration. However, in desert regions, high quality water is scarce and its use should be carefully considered.

The objectives of the current research are:

(1) Evaluate the impacts on the energy output of photovoltaic systems when washing panels with water of low quality.

Research question: Is the normalized efficiency mean of the solar panels cleaned with distilled water, treated wastewater, treated wastewater with surfactant, groundwater, and vacuum cleaner significantly higher than the normalized efficiency of the control group?

Hypothesis: In solar plants where soiling is a problem, solar facilities use demineralized or distilled water for washing the panels to avoid mineral scale deposits that might interfere with solar irradiance absorption. It is hypothesized that using water of low quality will not significantly decrease the energy output of solar panels; although some waters may contain high levels of salts that would form precipitate, that can be minimized by treating the water for the compound concern (e.g. removing total dissolved solids, adding surfactants, diluting with fresh water, etc.). The use of low quality water such as treated wastewater and groundwater in lieu of the industry-standard demineralized water could conserve fresh water.

(2) Determine if the use of water of low quality promotes the deposition of any substances on the solar panel surface that can be detrimental to their performance.

Research question: Can dissolved minerals or even surfactant present in the different types of water negatively impact the performance of the photovoltaic system?

Hypothesis: Even the most precise cleaning method can leave some residue on the surface. This residue can manifest in different forms such as particulate, thin film or molecular, ionic, and microbial contamination (Kohli & Mittal, 2012). Therefore, if water of low quality is used to wash PV panels, the impacts of these residues need to be evaluated to assure that the cleanliness is within acceptable limits.

(3) Determine the chemical composition of the dust accumulated on the solar panels where the research is being performed.

Research question: What types of materials are accumulated on the surface of PV panels and what are their potential sources.

Hypothesis: The soiling composition on the PV modules at the West Yard of the City of Las Vegas is expected to have a similar composition from the local environment, including dust and plant debris blown by wind, soot from nearby highway, bird droppings, etc.

Chapter 2 – Literature Review

2.1 Water use

Macknick et al. (2012) provided an estimation of operational water withdrawal and water consumption factors for generating technologies in the United States. The authors concluded that concentrating solar power technologies that use a recirculating cooling system have the highest water consumption; non-thermal renewables such as PV (maximum of 5 gal MW^{-1} h^{-1}) and wind have the lowest water consumption factors, along with thermal technologies that utilize dry cooling. PV systems may need water for panel washing; however, industry practices indicate that most PV system operators do not wash the panels. Figure 1 represents the water consumption for solar energy technologies (gal MW^{-1} h^{-1}). The location and the climatic conditions can affect the efficiency and water use rate. Other factors that may impact water use concentrations are the age of the plant, thermal efficiency, age of the cooling system, and water source.

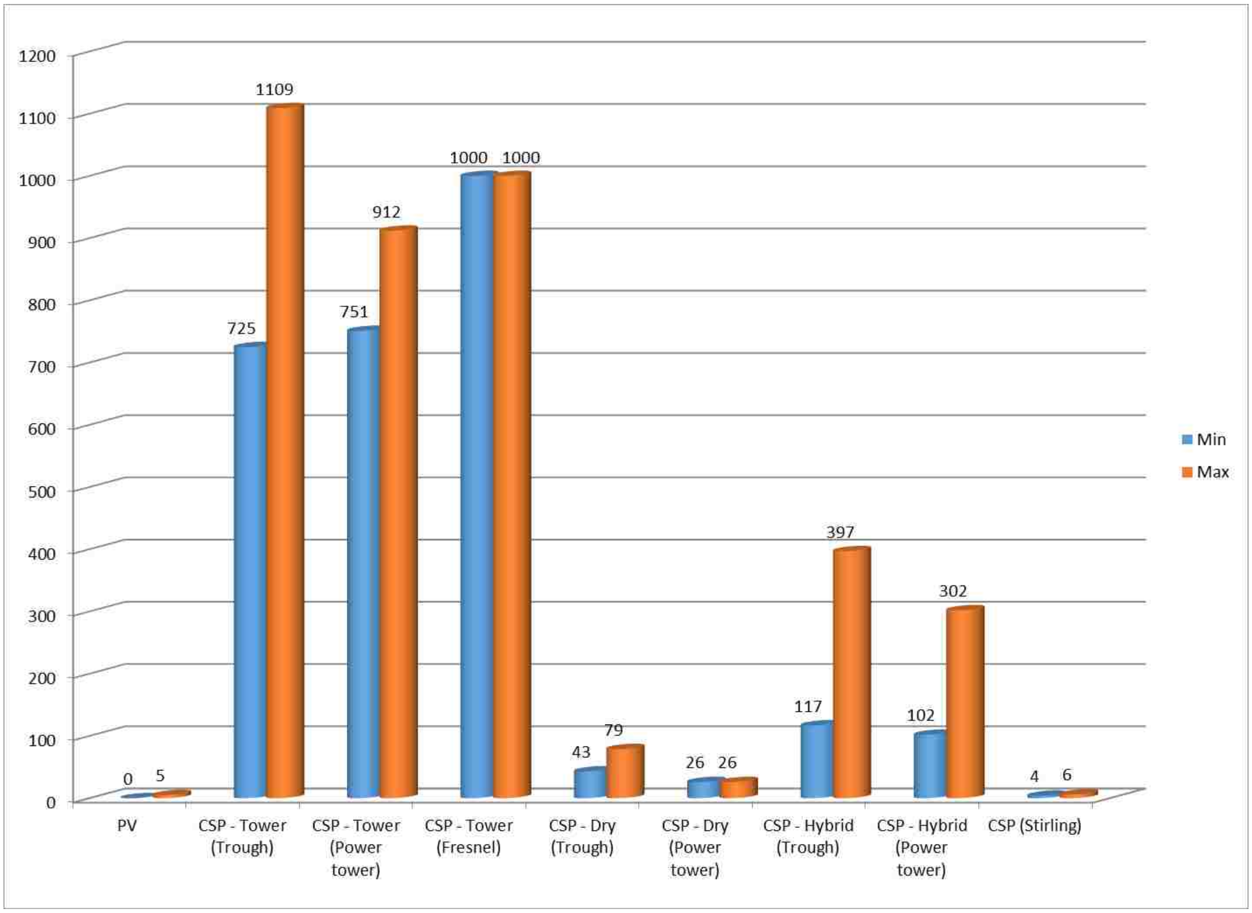


Figure 1. Water consumption for solar energy technologies based on the data from Macknick et al (2012), showing that PV and dry cooling consumes less energy than concentrating solar power that uses wet cooling

Renewables such as PV and wind require no water during normal operation. However, water is required in manufacturing and construction of these facilities (U.S. Department of Energy 2006). The study realized by Averyt et al. (2008) assumed that combustion turbines, internal combustion engines, wind, photovoltaic and hydroelectric generators do not require water for cooling.

Spang et al. (2014) compared the water consumption of energy production for over 150 countries. They estimated that around 52 billion cubic meters of fresh water is consumed annually. The research revealed that the quality and quantity of water varies by energy process and technology. For example, wind and solar require small quantities of water, while the cultivation of biofuel feedstock crops needs an enormous amount of water.

Meldrum et al. (2013) investigated the life cycle water use for electricity generation. In their review, they also observed that the total life cycle water use is lower for electricity generated by PV and wind technologies. The water withdrawal for PV power plant equipment life cycle is estimated between 1 to 1600 gal MWh^{-1}. On the other hand, thermoelectric generation technologies have the highest life cycle water use.

CSP facilities have water demands for cleaning mirrors or heliostats. The reduction in freshwater usage may increase costs or decrease the efficiency. The use of reclaimed water (municipal wastewater) is an alternative option that could minimize the impact of the power sector on freshwater resources and wastewater treatment facilities (Macknick et al., 2012).

2.2 Characteristics of Dust Accumulate on Solar Panels

The dust composition varies from each location, where urban areas might have airborne particles from vehicle emissions or utility plants and agricultural areas might have particles from fertilizers or plant matter. Desert regions are expected to be dominated by quartz, feldspar and other sand components (Karmerski, et al., 2014).

According to Maghami et al. (2014), dust can be considered the particles that come from different types of environment such as soil and pollution. These authors investigated the accumulated dust on the surface of solar panels using scanning electron microscopy and energy dispersive X-ray spectroscopy (SEM/EDS). The results showed the presence of siliceous, alumina, and cement which come from a new construction building that is located very close to the site. In addition, organic dust containing carbon, sodium, potassium, and chlorine was also identified.

Olivares et al. (2017) studied the soiling composition on PV modules in four locations with different climatologic characteristics in the Atacama Desert. The authors analyzed the samples using SEM/EDS and the images presented particles with a propensity for spherical and prismatic geometry. The results revealed that the chemical composition of the dust found on the surface of the panels was the same from the ground. However, the four different locations presented diverse specific mineral compounds.

Mehmood et al. (2017) analyzed the dust composition from PV modules in the area of Dhahran, Kingdom of Saudi Arabia. Elemental analyses were performed using SEM/EDS, the same utilized by Maghami et al. (2014) and Olivares et al. (2017). This research showed that the dust present in this area contains a significant amount of calcium, oxygen, carbon, and silicon. Other elements present in a low percentage are aluminum, magnesium, iron, sodium, potassium, and tin.

In a similar study, Javed et al. (2017) investigated the dust accumulated on PV panels located in Doha, Qatar. The most abundant element found in this study was calcium, followed by silicon, iron, magnesium, and aluminum. Furthermore, the dominant minerals present were calcite, dolomite, and quartz.

2.3 Cleaning Schedules

In places where dust is a concern, the investment in cleaning techniques is important to restore the efficiency of the system. The restoration can be done by washing, mechanical removal, and hybrid techniques. Washing is the use of fluids to remove soiling and to clean modules' surfaces. This method should be applied with some effective recycling system to avoid waste water. The mechanical removal includes wiping, forced air, and brushing. These techniques tend to use less water, but require care due to abrasiveness of the dust particles that can damage the modules. The hybrid techniques are combinations of washing and mechanical, brushing, and wiping with forced air (Kazmerski, 2014). Figure 2 presents four different cleaning techniques.

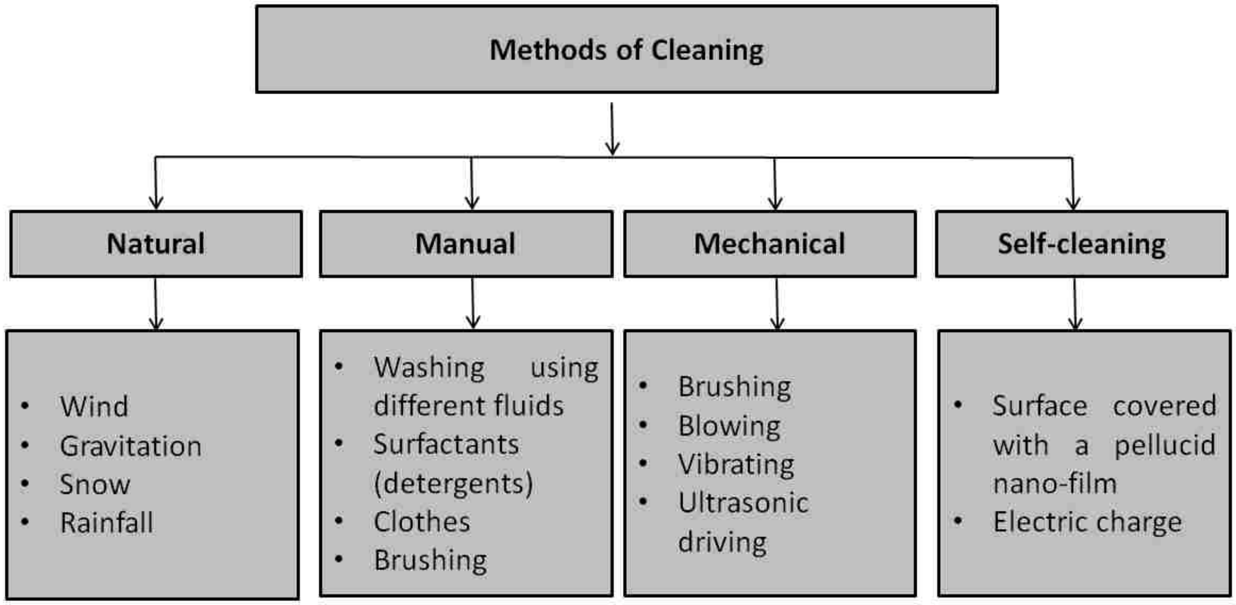


Figure 2. Different cleaning methods used to clean solar PV panels

Dust can stick on the surface of the solar panels due to Van der Waals adhesive forces. These forces are very strong and cleaning methods must be strong enough to wash these particles away. The dust can be removed naturally, mechanically, electromechanically, and electrostatically (Ahmed et al. 2013).

The buildup of particles on the surface of the panels can cause various issues, including issues with the component’s performance. Analytical tests may be required to verify the efficacy of cleaning. Particles can be determined using a direct method or indirectly by extraction. The efficacy of solvents for particle removal depends on the soil, substrate, size of the particles, and type of cleaning agent employed. Some analytical techniques used are: scanning electron microscopy/electron dispersive X-ray, Fourier transform infrared spectroscopy and electron spectroscopy for chemical analysis (Kanegsberg, 2001).

In most climates and in U.S locations, cleaning is normally not necessary as soiling losses are minimal and the dust is generally removed by wind and rainfall. On the other hand, if humidity is present in the region, it can transform the dry dust into clustered and sticky dust causing a reduction in the effective solar radiation reaching the panels due to scattering, absorption, and reflection (Sinha et al, 2014).

It is important to determine the cleaning frequency that will maximize the panels' efficiency and power generation while keeping cleaning costs low. Selecting the correct brush type is essential to achieving a good level of cleaning, and preventing the surface of the panels from damage and scratches (Shehri et al, 2016).

ElDin et al. (2013) recommend that the cleaning schedule be based on the geographical location and be done during cloudy days in drought areas and polluted urban areas. It is recommended to clean the modules early in the morning or during the evening before they are exposed to intense solar radiation (Mohamed & Hasan, 2012).

Nazar (2015) described three different methods that are used to clean dust from solar panels. The first, the rugged robot can be used to clean the modules with a designed brush and no water required. The second is a self-cleaning technique that works with electric charge sending a dust-repelling wave cascading over the surface of the material, removing the dust away from the panel. This type of cleaning would be more effective for large-scale installations since it can help reduce maintenance costs. The last method, the robotic vacuum cleaner, uses a two stage cleaning process to remove dust effectively from PV modules. A rolling brush disperses the dust towards the vacuum cleaner.

Mani & Pillai (2010) recommended a general cleaning cycle to mitigate the impact of dust, based on the climate zone characteristics and conditions that influence PV performance and dust deposition. For example, for low latitude areas with a wet-dry tropical climate zone, where trade winds dominate during the dry season, a weekly cleaning may be recommended for moderate dust accumulation, and daily cleaning in case of intense dust accumulation. In another situation, for a mid-latitude grassland climate with annual precipitation around 81 cm, a less intense (weekly or even biweekly) cleaning might be adequate.

Mejia et al. (2013) estimated the impacts of one annual washing based on the soiling losses and the summer drought. The results indicated that the site would have yielded 1.75% more annual energy if it had been washed halfway through the summer. On the other hand, if an automated cleaning system were installed, an average of 11.1% of annual energy would be possible.

After observing the negative impact of dust accumulation on PV panels, Saidan et al. (2016) concluded that scheduled cleaning, especially for large scale solar power plants is essential to minimize the soiling effects on solar modules. Nonetheless, typical cleaning methods are not easily applicable in desert areas due to the distance from water sources, required transportation, and storage capabilities. More research is needed to investigate the right cleaning mechanism based on the frequency of cleaning, scale, and costs.

Kalogirou et al. (2013) suggested that during spring and autumn, cleaning can be done every 2-3 weeks if no rain occurs. For the summer months, cleaning frequency will depend on the costs and losses in the performance of the system. Furthermore, in the winter months no cleaning is needed due to adequate rain.

Al-Sabounchi et al. (2013) analyzed the impact of accumulated dust deposition on PV modules in the Abu Dhabi industrial area. They noted that the highest reduction in power production occurred in July in the range of 27%. They recommended a monthly cleaning schedule for the surface of the panels to get reasonable results.

Maghami et al. (2016) reviewed the performance effects and mitigation of power loss due to soiling on solar panels. This study showed that the amount of dust on the surface of the panels affected the overall energy output. For this reason, weekly cleaning during dry seasons and daily washing after intense dust accumulation is suggested.

Chamaria et al (2014) investigated the consequences of dust on Solar PV modules. Based on this study, the authors recommended a daily cleaning cycle in high dust density areas and low latitude areas with medium dust density. For mid-latitude regions a weekly cleaning may be adequate, and for high latitude areas dust may not be a concern.

Martinez-Plaza et al. (2015) investigated the impact of module cleaning frequency in Qatar. The aim of the experiment was to estimate the washing frequency based on the ambient condition of the region. Three different cleaning frequencies were used for the modules: weekly, bi-monthly, and bi-annually. The results indicated that weekly cleaning was enough to keep the modules at constant yield levels. However, the system performance decreased over 1% when modules were not cleaned, or no rain was present for more than 30 days.

Ali et al. (2015) explored the dust effect on the performance of two different types of photovoltaic modules (monocrystalline silicon and polycrystalline silicone). They concluded that the performance of the PV modules decreased with the amount of dust that was deposited on their surfaces. Additionally, the monocrystalline module had a higher reduction in the percentage efficiency when compared with the polycrystalline. The study highlighted that the modules require regular cleaning to minimize these efficiency losses.

2.4 Natural Cleaning

Rainfall is considered to be the most efficient natural cleaning agent for eliminating particles from PV surfaces, as it naturally reestablishes the performance of the modules. However, light rainfalls may not clean the panels and could make performance worse (Sayyah et al., 2014).

Sarver et al. (2013) related in their literature review that in some conditions, nature can be the most effective and least costly cleaning agent for dust problems. The natural cleaning effect of rain and snow has been observed by the authors in numerous studies in different parts of the world. Generally, the rain washes away dust and soiling restoring collector performance to nearly original capacities.

According to Sayyah et al. (2014) natural cleaning has various advantages: there is no cleaning cost; high wind can remove larger dust particles; heavy rainfall and melting snow can restore system efficiency; and tracking systems can be used to increase the cleaning efficiency of rain. On the other hand, the disadvantages can be related to the infrequent rain events in arid and semi-arid areas; and light rainfalls followed by dust winds can increase the dust deposition on panels. Al-Ammri et al. (2013) reported that after a light rain, the losses on the panels increased from 2.3% to 15%.

Sulaiman et al. (2014) studied the influence of dirt accumulation on performance of PV panels. The authors observed that particles such as dust and sand can be washed away by rain. However, the presence of moss requires specific cleaning methods. Besides that, this research concluded that the water droplets from rain would not affect the performance of the system significantly.

Zorrilla-Casanova et al. (2011) studied the losses caused by the accumulation of dust on the surface of PV modules. One of the reference cells was cleaned manually everyday with water and the other one was only cleaned by rain. The results showed that in rainfall events, a good cleaning of the dust was achieved, which helped the system to recover its initial performance. Even a light rain (below 1 mm) was sufficient to clean the glass. In another study, Mejia et al. (2013) concluded that light rain events (below 0.5 mm) during the summer were not enough to clean the panels. The efficiency of the PV plant increased only after a rain event in the fall.

Smith et al. (2013) evaluated the efficiency of PV panels after manual cleaning and natural rainfall in Portland, Oregon, USA. During a period of 17 days without rain, the panels accumulated 0.85 g/m^2 of dust, which resulted in an output power loss of 4% when compared to panels kept clean with lint-free cotton pads. A single natural rainfall of 2.8 mm of precipitation over 3 hours was sufficient to clean the panel, and restore the power output to within 1% of the power expected from a clean panel. Therefore, the possibility of using rainfall as a natural means of cleaning can help contractors in developing appropriate cleaning protocols for different climate situations.

Caron & Littman (2012) studied the energy lost due to soiling on PV modules in the Southern Central Valley and Carrizo Plain of California. In the first location, great amounts of rainfall were enough to keep the soiling levels at a low average of 0.8% (Nov 2010 to Mar 2011). However, in the summer, less rainfall was observed and the average soiling level increased. On the Carrizo plain, no rainfall was reported for just over three months (Jun 4 to Sept 10). The lack of rain caused up to a 5% energy loss until the module was cleaned by rain fall. Even a light rainfall (0.5 mm) was enough to clean a dirty frameless module in areas with lighter soiling rates.

Naeem & Tamizhmani (2015) studied the climatological relevance to the soiling loss of 24 polycrystalline PV modules. In this experiment one PV module was kept soiled all the time and the other was cleaned by a window washing broom using detergent free water. They observed in their research that a heavy rain (13.2 mm) can act as a cleaning agent for either type of module, while a light rain can be a cleaning agent for dirty PV modules but a soiling agent on clean modules. Besides that, the authors related that wind speed and relative humidity seemed to have a direct influence on the soiling loss. It was observed that as relative humidity increased, the soiling rate also increased. On the other hand, the soiling rate decreased with increased wind speed. Then, high winds could be considered as natural cleaning agents.

Schill et al. (2015) studied the impact of soiling in the efficiency of PV modules at one test site located on the Canary Islands. In this investigation they noted that a light rain event caused partial shading of the modules by accumulation of dirt on the lower cell rows. However, these modules were completely cleaned after a stronger rainfall event that washed the soiling away.

Gostein et al. (2014) investigated the soiling levels from five solar power plants in the desert southwest of the United States, the Arabian Peninsula, and Western Australia. The authors estimated based on these five sites that a rainfall threshold of approximately 3.5 mm is required for performance recovery with 50% probability. However, specific rainfall requirements may be different for each site based on the type of contaminants present in the area. Predicting this parameter is important to control future plant performance.

Bouchalkha (2015) studied the dust effect on solar panels in Abu Dhabi. The small amount of rainfall and the high level of dust in this region require more attention than other parts of the world. The author observed that the thicker the dust layer, the greater the loss of efficiency. Also, after a few days the output performance of the system decreased 10%. Then, the solar panels require a cleaning schedule every 10 to 15 days under normal weather conditions with no sand storms. If a sand storm happens, the modules should be cleaned immediately after the storm to restore the performance of the system.

Kalogirou et al. (2013) studied the effects of soiling on three types of PV panels: monocrystalline, polycrystalline, and amorphous silicon. They observed that the dust episodes were followed by heavy rain events (not usual), which were unable to clean the dust from the solar modules. They concluded that the panels need to be cleaned after a dust event, and cleaning should be done using deionized water and a sponge to optimize the cleanliness. However, no cleaning was required in the winter months due to adequate amounts of rainfall.

2.5 Manual Cleaning

The most commonly used method of manual cleaning for PV panels in small-scale installations uses tap or distilled water (frequently mixed with detergent) and a soft wiping cloth. For large-scale PV plants, high-pressure water jets and brushes are commonly used (Sayyah et al., 2014).

Manual cleaning is similar to the method used to clean windows of buildings. Special brushes are used to prevent scratching the surfaces. In addition, some brushes are connected directly to a water supply to wash and scrub at the same time (Maghami et al. 2016).

According to Sayyah et al. (2014) cleaning with a high-pressure water jet has more disadvantages than advantages. The advantages can be related to efficiency: Panels can be maintained routinely; and the cleaning can be performed whenever required. The disadvantages are the cost for labor (requires trained personnel) and water; efficient cleaning may require demineralized or distilled water (water resources are limited in some areas); deposition of organic salts that can create a film over the glass; and the use of surfactants that can be harmful to the environment.

Abd-Elhady et al. (2011) examined the removal of dust particles from the surface of solar cells using three types of surfactants: anionic (Sodium Dodecyl Sulphate), cationic (Cetylpyridinium Bromide) and zwitterionic (Tween-80). They found that the surfactant effectiveness is dependent on the electrical charge of the deposited particles. Anionic surfactants were effective in removing sand particles, while cationic were more effective in removing carbon particles. The influence of the zwitterionic surfactant depends on the pH value of the water used. The authors concluded that a mixture of the anionic and the cationic surfactants lead to the best cleaning effect, which they defined as capable of cleaning with the least amount of water.

In a similar study, Moharram et al. (2013) studied the effect of water and surfactants on the performance of PV panels in Cairo, Egypt. The experimental setup consisted of six photovoltaic modules and the surfactants Sodium Dodecyl Sulphate and Cetylpyridinium Bromide, the same used by Abd-Elhady et al. (2011). The authors found that when using non-pressurized water, the efficiency of the PV panels decreased by 0.14%/day and by 50% after 45 days of cleaning. However, when using the mixture of anionic and cationic surfactants, the best cleaning results were produced since the efficiency did not decrease during the same period of cleaning. The authors concluded that dust accumulation can reduce the efficiency of the panels quickly in arid and dusty environments. Furthermore, cleaning PV panels using their proposed mixture of surfactants minimizes the amount of water needed.

Khonkar et al. (2014) explored the importance of cleaning concentrated photovoltaic arrays (CPV) versus PV arrays. CPV differs from the PV technology by using lenses or mirrors to focus sunlight onto a small area, which is more efficient. To clean the arrays reverse osmosis (RO) filtered water, a surfactant and a commercial grade pressure washer were used. Water with diluted (100:1) Crystal Simple Green, Sunshine Makers manufacturer, Inc., was used as a surfactant that efficiently removed the oily film on the primary light entry surfaces of the array. This study concluded that both systems were affected by dust accumulation and they require cleaning. However, soiling had around a five times stronger effect on the UHCPV arrays than the conventional PV array. The soiling decreased the UHCPV power output by almost 15%, and the power output by the conventional PV array by about 3%. This result showed that the impact of soiling is different for different kinds of PV systems, and therefore, the necessity of cleanliness also differs.

Appels et al. (2013) investigated different types of water for cleaning panels. Several types of water were used: hard tap water, soft tap water, rainwater captured at the start of a rainshower, demineralized water (all ions removed), reverse osmosis permeate, demineralized water with dissolved ammonia, and demineralized water with dissolved detergent. The authors concluded that panels should only be cleaned with soft tap water or demineralized water when available due to the amount of solids that other types of water can leave on the surface of the panels. However, when using a detergent or diluted ammonia, the surface must be rinsed to avoid creating an ideal surface deposition for dust particles.

Brooks et al. (2013) analyzed the consequences of soiling on flat-plate photovoltaic modules in Arizona over a seven-month period. One string was cleaned weekly with Windex (glass cleaner with detergents, solvents, fragrance, ammonia-D™, and alcohol) and one was not cleaned. The results indicated an approximate performance improvement of 1% from cleaning. However, natural soiling in the urban arid-desert of Arizona does not seem to decrease the power output of a PV module by more than 1%. Therefore, cleaning modules may not be recommended because of cost and/or water use. Additionally, the modules in this study were mounted over an asphalt lot, which could explain the small amount of dust. Another hypothesis can be related to the aerosols found in this area, which did not cause the same amount of soiling as those found in different places.

In a study of two large scale solar arrays in the region of Puglia, Italy, two different washing techniques were adopted. The arrays had been exposed to the environment for over one year before washing. One plant was cleaned with only pressurized distilled water, while the other plant was also brushed. The authors concluded that the soiling effect is related with the soil type and the washing method. These two different cleaning methods seem to have a direct effect on the Standard Test Conditions (STC), where the mean STC power of the brush cleaned PV modules was bigger than the modules only sprayed with pressurized distilled water. For the arrays built on the sandy soil the losses were about 6.9%, while the arrays built on a compact ground had losses of 1.1% (Pavan et al., 2011).

Bunyan et al. (2016) studied the output power efficiency of two identical PV panels. One was cleaned daily with running water and a clean cloth and the other one was cleaned monthly for one year. One meter of soft tissue was wetted with filtered water for the PV panel cleaning. The results showed a decrease in the efficiency of the cleaned monthly panel during the months of April (15.07%), May (13.74%), October (10.68%), and December (8.74%) with a dust deposition that varied from 0.00821 to 0.0422 mg/cm^2.

Mohamed & Hasan (2012) investigated a schedule of weekly cleaning on PV modules in an area classified as rural desert. The modules were cleaned manually with a detergent-water mixture and hand cleaning materials. The amount of water utilized was around 5 liters per module. The results revealed that the weekly cleaning maintained performance losses between 2 – 2.5%.

Shehri et al. (2016) reviewed different cleaning mechanisms including a dry cleaning technique using robotic systems and the impact of brushing on the transmission of the glass.

The study compared the effect of brushing for different durations (30 sec, 4 min, 8 min and 12 min) versus brushing, washing and wiping (Kimtech). They concluded that dry cleaning using Nylon brushes did not have a significant impact on the optical characteristics of the glass surface. The use of water and delicate wipers yielded a higher cleaning efficiency than that of the nylon brushes. The dry cleaning, no matter the duration, did not restore the original transmittance of the glass panel.

Al-Ammri et al. (2013) investigated the effect of dust and other impurities on PV panel performance. The experiment was done in different mono-crystalline panels, where one was kept clean all the time, one was cleaned weekly, another cleaned monthly, and the last one was left dirty (without cleaning). The total average losses for three months were around 14.1%, 47.8%, and 58.9% for the weekly cleaned, monthly cleaned, and not cleaned, respectively.

John et al. (2014) analyzed three different cleaning techniques for lightly, medium, and heavily soiled samples. First, the panels were cleaned using compressed air of 60 psi for 5 minutes, followed by a brush cleaning assisted by compressed air of 30 psi for some seconds and then water. The results revealed that the short circuit current (Isc) before cleaning was 96.7%, 90.3%, and 58.6% for the lightly, medium and heavily soiled samples, respectively. After the compressed air clean the Isc increased to 98.2%, 95.3%, and 89.4%. The last steps using the brush assisted by the compressed air clean and water improved the Isc to close 99% for all three different samples.

Papers covered in this review highlight the importance and significance of cleaning PV panels. Table 1 summarizes information source, geographical location, publication year, type of solar panel utilized, type of water utilized, duration of the study, and principal conditions and observations of the study.

Table 1. Summary of different types of water that have been utilized for cleaning PV panels over the past years

Year	Authors	Location	Type of solar panel device	Type of water	Period of study	Conditions
2011	Abd-Elhady et al.	Egypt	PV glass	Water with surfactants: anionic (Sodium Dodecyl Sulphate), cationic (Cetylpyridinium Bromide), zwitterionic (Tween-80)	Laboratory experiments	Deposited particles were removed using surfactants utilizing the minimum amount of water
2011	Pavan et al.	Puglia - Italy	PV system	Pressurized distilled water and brushed pressurized distilled water	over 1 year	One plant was cleaned only with pressurized distilled water; while the other plant was also brushed
2011	Zorrilla-Casanova et al.	Málaga - Spain	PV module	Natural rainfall and manual cleaning with water	1 year	One of the reference cells was cleaned manually everyday with water; and the other one was only cleaned by rain
2012	Mohamed & Hasan	Mourzuq - Libya	PV module	Detergent mixed with water	4 months	The modules were cleaned manually by detergent mixed with water and use of hand cleaning materials; the amount of water utilized was around 5 liters per module
2012	Caron & Littmann	California - USA	PV module	Rainfall	over 1 year	The study evaluated the rainfall effects on PV modules in the Southern Central Valley and Carrizo Plain, California

Year	Authors	Location	Type of solar panel device	Type of water	Period of study	Conditions
2013	Moharram et al.	Egypt	PV module	Non-pressurized water and water with a mixture of 2 surfactants: anionic (Sodium Dodecyl Sulphate), cationic (Cetylpyridinium Bromide)	45 days	Cleaning methods were designed to minimize the consumption of water
2013	Appels et al.	Belgium	Glass and PV modules	Hard tap water, soft tap water, rainwater, demineralized water, reverse osmosis water, ammonia dissolved in demineralized water, and detergent dissolved in demineralized water	58 days	Effect of dust accumulation on the power output of a PV module (natural and artificial dust) was tested by cleaning with different types of water and solution
2013	Brooks et al.	Tucson - Arizona - USA	PV modules	Windex (glass cleaner with detergents, solvents, fragrance, Ammonia-D, and alcohol)	7 months - field and lab experiments	One string was cleaned weekly with Windex (glass cleaner with detergents, solvents, fragrance, Ammonia-D, and alcohol), one was not cleaned
2013	Smith et al.	Porland - Oregon - USA	PV panels	Lint-free cotton pads and natural rainfall	over 1 year	A group of 8 PV panels with a tilt of 30 degrees were tested; all PV panels had been exposed to the open atmosphere without manual cleaning for over one year when the cleaning protocols began

Year	Authors	Location	Type of solar panel device	Type of water	Period of study	Conditions
2013	Mejia et al.	Santa Clara - California - USA	PV module	Natural Rainfall	1 year	A large commercial site (86.4 KWdc) was quantified during the summer with respect to rain events
2013	Al-Ammri, Ghazi, Mustafa	Baghdad - Iraq	PV module	Unspecified	3 months	The experiment was realized in different mono-crystalline panels, where, one was kept clean all the time, one was cleaned weekly, another cleaned monthly, and the last one was left dirty (without cleaning)
2013	ElDin, Abel-Rahman, Ali	Alexandria - Egypt	PV module	Commercial detergent from Egyptian local market	5 weeks	Two PV modules were used; one was kept clean, while the other was left under the atmospheric natural dust deposition
2013	Kalogirou, Agathokleous, Panayiotou	Cyprus	PV module	Rainfall	1 year	The study analyzed the effects of soiling on three types of PV panels: monocrystalline, polycrystalline, and amorphous silicon
2014	Khonkar et al.	Saudi Arabia	CPV and PV arrays	Reverse osmosis (RO) filtered water, a surfactant, and a commercial grade pressure washer	4+ weeks	Arrays were cleaned using reverse osmosis (RO) filtered water, a surfactant, and a commercial grade pressure washer

Year	Authors	Location	Type of solar panel device	Type of water	Period of study	Conditions
2014	Gostein, Caron, Littmann	Southwest of the United States, the Arabian Peninsula, and Western Australia	PV Module	Rainfall	1 year	This research presented optimal cleaning frequencies and amount of rainfall necessary to clean dirty modules
2014	John, Tatapudi, Tamizhmani	Mesa - Arizona - USA	PV Module	60 psi compressed air clean, brush assited 30psi compressed air clean, and water	1.5 years	In this experiment the panels were cleaned using compressed air of 60 psi for 5 minutes, followed by brush cleaning assisted by compressed air of 30 psi for some seconds and then water
2015	Naeem & Tamizhmani	Mesa - Arizona - USA	PV Module	Window washing broom using detergent free water and rainfall	3 months	In this experiment one PV module was kept soiled all the time, and the other was cleaned by a window washing broom using detergent free water
2015	Schill, Brachmann, Koehl	Canary Islands	PV Module	Rainfall	Unspecified	In this study the irradiation sensors were cleaned and not the modules
2015	Bhattacharya, Chakraborty, Pal	Tripura - India	PV Module	Unspecified	6 months	This study analyzed the influence of dust on two identical panels, where one was kept clean throughout all the experiment

Year	Authors	Location	Type of solar panel device	Type of water	Period of study	Conditions
2015	Martinez-Plaza et al	Qatar	PV Module	Rainfall and tap water	1 year	This research investigated three different cleaning frequencies for PV modules: weekly, bi-monthly, and bi-annually
2016	Bunyan et al.	Kuwait	PV panels	Filtered water and a clean cloth	1 year	The output power efficiency of two identical PV panels were investigated; one was cleaned daily and the other was cleaned monthly for one year
2016	Shehri et al.	Thuwal - Saudi Arabia	Glass samples	Nylon brushes, delicate wipes and water	1 week	The study compared the effect of brushing for different durations (30 sec, 4 min, 8 min and 12 min) versus brushing, washing, and wiping (Kimtech)

Chapter 3 - Methodology

3.1 Photovoltaic System Experimental Design

A group of 264 PV panels, facing due south with a tilt angle of 32 degrees, located at the West Maintenance Yard of the City of Las Vegas, Nevada, were used for the research (Figure 3). The panels are all polycrystalline, manufactured by SolarWorld USA, with a rated power output of 240 W and 245 W, and an expected efficiency varying from 14.31-14.61%. Electrical characteristics of each module used in this study are show in Table 2. Table 3 presents the thermal and physical characteristics of the PV modules.

Figure 3. Location of the City of Las Vegas West Maintenance Yard solar site used in this research (Source: Google Earth)

Table 2. Expected electrical performance of City of Las Vegas West Yard Solar Plant under STC: 1000 W/m2, 25°C, AM 1.5 (Sunmodule, Hillsboro, Oregon - USA)

Electrical Characteristics	SW 245 Poly	SW 240 Poly
Maximum power (P_{max})	245 W	240 W
Open circuit voltage (V_{oc})	37.5 V	37.2 V
Short circuit current (I_{sc})	8.49 A	8.44 A
Maximum power point voltage (V_{mpp})	30.8 V	30.2 V
Maximum power point current ($_{Impp}$)	7.96 A	7.96 A
Module efficiency	14.61%	14.31 %
Power tolerance	0 / +5 Wp	0 / +5 Wp
Maximum system voltage (V_{max})	1000 V	1000 V
Maximum reverse current	16 A	16 A

Table 3. Thermal and physical performance of solar modules of the City of Las Vegas West Yard solar plant under STC: 1000 W/m2, 25°C, AM 1.5 (Sunmodule, Hillsboro, Oregon - USA)

Thermal Characteristics	
Nominal operating cell temperature	46˚C
Temperature coefficient of I_{sc}	0.081%/K
Temperature coefficient of V_{oc}	-0.37%/K
Temperature coefficient of P_{mpp}	-0.45%/K
Operating Temperature	-40˚C to 85˚C
Component Materials	
Cell Type	Poly crystalline
Cells per module	60
Cell dimensions	156 mm x 156 mm
Panel dimensions	1675 mm x 1001 mm x 31 mm
Front	Tempered glass (EN 12150)
Weight	21.2 kg (46.7 lbs)

A monitoring system for the solar panel was set up at the site that includes a Campbell Scientific Incorporated (CSI) model CR1000 datalogger (Figure 4). The sensors include a Vaisala model HMP45C-L Temperature and Relative Humidity Probe. For wind speed and direction, the system uses an R.M. Young model 03002 Wind Sentry Set. Two CMP3-L Pyranometers are used to measure the global horizontal radiation and the plane of array irradiance. A TE525WS-L Rain Gage to measure the rainfall, and a 10 thermocouple CS220-L type Es to measure temperature were installed at the back of the solar panels.

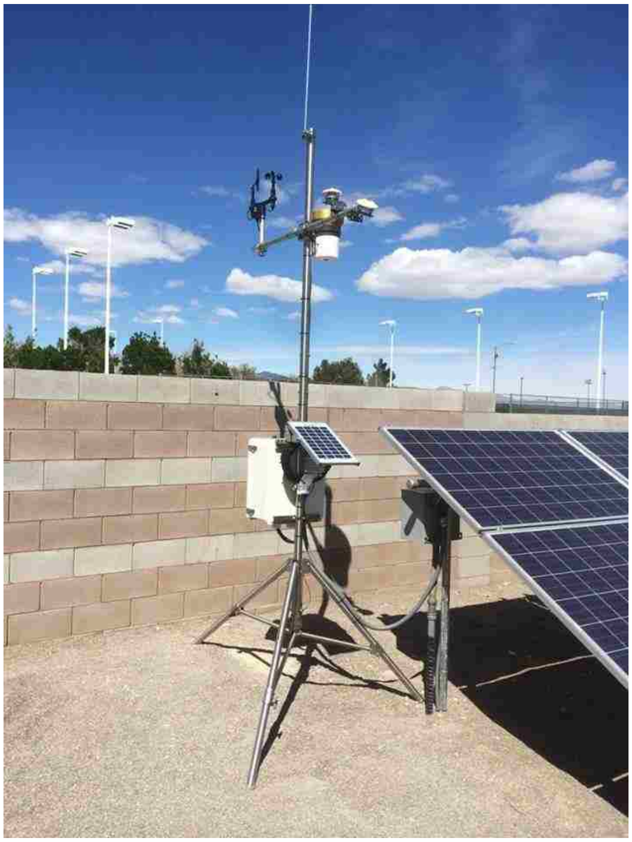


Figure 4. Weather Station installed at the City of Las Vegas West Maintenance Yard to assist in the data collection for the solar plant

The solar plant (Figure 5) has six inverters (Fronius IG Plus V 10.0-1 UNI, Portage, IN - USA) that are responsible for changing the direct current (DC) into alternating current (AC) and measuring the daily power output.

Figure 5. Instrumented 264 PV modules located at the West Maintenance Yard of the City of Las Vegas used in the study

3.2 Experimental Approach

The impact of different types of water on soiling removal from PV panels and the chemistry of dust were both investigated. Five groups of PV panels were cleaned eight times over 18 months, while another group was not cleaned throughout the experiment. Parameters such as power output, solar insolation, temperature, and rainfall were measured to determine which type of cleaning methods presented the better efficiency recovery over time. In addition, samples from the dust were collected directly from the panels before and after washing and chemical analyses were performed to characterize the dust composition. Furthermore, the quality of the wash water, resulting from panel washing, was also evaluated.

The potential accumulation of compounds, present on the PV panels, was examined by scanning electron microscopy (SEM) coupled with an energy dispersive spectrometer (EDS). For this part of the research, small pieces of tempered glass were attached with Velcro to the large solar panels. During the washing procedure, these compounds were also washed and their surface examined for potential deposits. In addition, the washed pieces of tempered glass were also examined for cleanliness by measure the contact angle of a drop of water placed on their surface, using a goniometer.

For the analysis of panel washing impact on energy output, only sunny days and daily measurements between 10 am to 2 pm were considered. This time was selected to avoid shading effects on the panels and end of day difference between seasons. The period from June 1, 2016 to December 7, 2017 was studied. A total of 317 days were utilized in the data analysis. All the PV panels had been exposed to the open atmosphere without cleaning for several years when the manual cleaning began in February, 2017.

3.3 Panel Washing Procedures

The panels have been grouped into six independent sections (Figure 6), and each section was washed using different cleaning solution as presented in Table 4. Soiled panel cleaning was performed manually using a soft cleaning brush (Mr. LongArm 0405 Soft Flow-Thru Brush, Greenwood, MO – USA). Each solar panel group was cleaned early in the morning to avoid interferences in the power output.

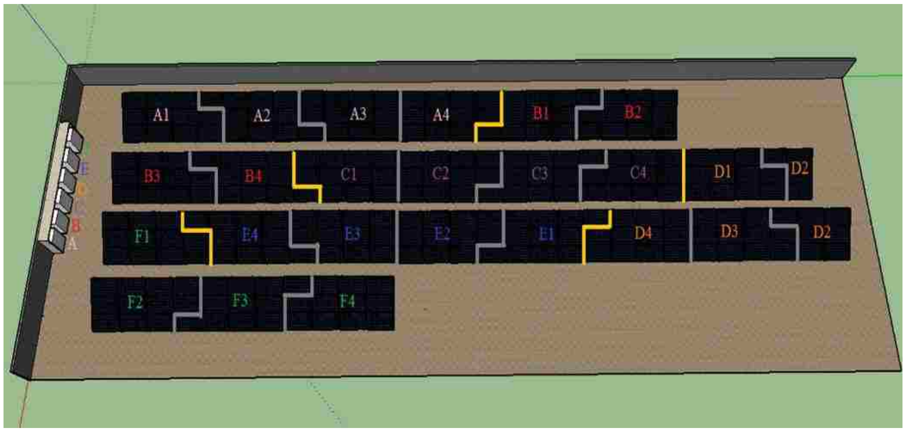


Figure 6. Design of the West Yard Solar site (each letter represents one group of panels)

Table 4. Cleaning solution for each group of panels and respective installed power rating (kW)

Group	Cleaning solution	Number of SW 240 Panels	Number of SW 245 Panels	Installed power rating (kW)
A	Distilled water	44	0	10.56
B	Treated wastewater with surfactant (Sodium Dodecyl Sulfate)	44	0	10.56
C	Control (no cleaning)	44	0	10.56
D	Treated wastewater	15	29	10.705
E	Groundwater	18	26	10.69
F	Vacuum cleaner (no water)	11	33	10.725

The amount of water utilized was 3 gallons (11.4 L) for each group of panels with an area of 794 ft^2 (73.77 m^2). It is around 1.44L per each 100 ft^2 of panels. The treated wastewater and the groundwater were collected from the city of Las Vegas Water Pollution Control Facility, using a 5-gallon water bottle. The distilled water utilized in this study was the Arrowhead Brand. The Karcher WV 50 vacuum cleaner (Denver, CO – USA) was used for Group F.

The composition of each water source utilized was determined using methods listed on section 3.6. In addition, the composition of the wash water, which contains the soiling removed from the panels and source water was evaluated.

To determine whether all groups of panels were similar and have the same characteristics, all PV panels were cleaned with 45 gallons (170.34 L) of distilled water under a sunny day, and a comparison of the efficiency for each group was performed. However, after comparing the normalized efficiency for all groups of panels, it was concluded that a strong rainfall that occurred in January 22, 2017 was a very efficient cleaning for the panels. For this reason, this heavy rain (19.3 mm) was utilized as the beginning point for the efficiency comparison purposes. The difference observed between each group of panels and the control group was 1.79%, 0.071%, 1.354%, 0.29%, and 0.327% for group A,B,D,E, and F, respectively.

To keep all groups of panels with the same normalized efficiency, the percentage difference mentioned previously was added to each group of panels.

3.3.1 Panel Cleaning Frequency

Determining the cleaning frequency for PV panels depends on different variables such as water accessibility, water transportation, water storage, labor work, cleaning time needed, field size, and costs. In this study, it was not possible to determine a cleaning schedule since the amount of dust accumulated on the panels was small and several rainfall events occurred during the study. The solar panels did not get as dirty as expected. Figure 7 summarizes the cleaning schedule and surfactant amount utilized in the study. The concentration of the anionic surfactant (Sodium Dodecyl Sulfate) was based on the study of Moharram et al. (2013).

Figure 7. Cleaning schedule and the concentration of the anionic surfactant (Sodium Dodecyl Sulfate) utilized to wash solar panels

3.3.2 Soiling Samples and Wash Water Collection

Samples of soiling accumulated on the panels were collected from the dirty panels using a glass microfiber filter (55mm, Whatman GE healthcare) and chemical analyses were performed to characterize the organic content.

During cleaning, the wash water from each panel set was collected in long containers placed along the panels and the resulting water was reutilized to wash the same panel set (Figure 8). The wash water was analyzed for pH, Conductivity, Total Dissolved Solids (TDS), Total Suspended Solids (TSS), anions, and metals.

Figure 8. Panel cleaning process using a soft brush and long containers to collect the wash water for analysis

Tempered glass samples with dimensions of 16.51cm x 10.16 cm x 0.762 cm (width x Length x thickness) were fixed (Figure 9) to the solar panels for dust sample collection. The attachment of the tempered glass was needed to have a sample that could be brought to the laboratory for SEM-EDS and goniometer analysis.

Figure 9. Tempered glass samples fixed to the solar panels to verify the amount of dust accumulated per cleaning, and the efficiency of cleaning

3.4 Solar Panel Performance Data (Normalized Efficiency)

Since the solar radiation and temperature varies every day, the power output is not a parameter that can be used alone to compare the group of panels. Therefore, the normalized efficiency of the PV panels, denoted by η , has been evaluated using the following equation:

$$\eta = \frac{\int(P)}{\int(I) * A} + \alpha * \sum_{day=1}^{N} (T - T_{avg}(day))$$ **Equation 1**

where:

P (KW) is the power output generated from the PV,

A (m^2) is the area,

I (KWh/m^2) is the Plane of Array (POA) insolation,

α (%/°C) is the module power temperature coefficient,

N is the number of days,

T (°C) is the average panel temperature for the whole data set, and

$T_{avg}(day)$ (°C) is the daily average panel temperature from 10 am to 2 pm (i.e. time chosen for this research to avoid panel shading).

The integration method utilized in this research for equation 1 was the trapezoidal rule, summarized below as equation 2 and equation 3.

$$\int(P) = \int_{t_0}^{t_{final}} P(t)dt = \sum_{i=1}^{16} \frac{E(t_{i-1})+E(t_i)}{2} * \Delta t \qquad \textbf{Equation 2}$$

where:

t_0 = 10 am is the initial time,

t_{final} = 2 pm is the final time, and

Δt = ¼ hour is the time step. This yields a number of 16 grid points on our time interval [10 am, 2 pm].

$$\int(I) = \int_{t_0}^{t_{final}} I(t)dt = \sum_{i=1}^{240} \frac{I(t_{i-1})+I(t_i)}{2} * \Delta t \qquad \textbf{Equation 3}$$

where:

t_0 = 10 am is the initial time,

t_{final} = 2 pm is the final time, and

Δt = 1/60 hour is the time step. This yields a number of 240 grid points on our time interval [10 am, 2 pm].

Next, the daily average panel temperature from 10 am to 2 pm is calculated as

$$T_{avg}(day) = \frac{1}{240} \sum_{t=1}^{240} T(t_i) \qquad \textbf{Equation 4}$$

where:

$T(t_i)$ = Temperature of the solar panel at the time t_i on a specific day

Last, the average panel temperature for the whole data set is calculate as

$$T = \frac{1}{N}\sum_{day=_1}^{N} T_{avg}(day) \qquad \textbf{Equation 5}$$

All measurements were saved daily to an excel file for analysis. A comparison of all cleaning methods was performed using equation 1 (normalized efficiency equation). The temperature was also investigated in the equation due to the excessive heat, which can significantly reduce the output of a PV system. The amount of rainfall observed in each day was analyzed to determine the capacity of washing away the dust and restoring the efficiency of the solar system. The cleaning efficiency of each water was compared with the control to verify if these types of water can be used in the future for soiling removal from PV panels.

3.5 Statistical Analysis

Statistical analysis was used to determine the statistical significance and the confidence intervals of the experimental data. Panel efficiency data from the time period of February 24, 2017 to December 7, 2017 was used in the analysis, since scheduled cleanings of the solar panels were performed during this time period. In addition, the chemistry of accumulated dust on the control group and the vacuum clearer group were compared with the composition of the tempered glass sample. The statistical tests were run using the Data Analysis tool package in Excel.

3.5.1 Statistical Analysis: Normalized Efficiency

For the analysis, 95% confidence interval was computed for each group of solar panels for the normalized efficiency mean. This yields that if the same population of solar panels is sampled on numerous occasions and confidence intervals are computed on each occasion, the resulting confidence interval will contain the population mean in approximately 95% of the cases and will fail the other 5%.

T-test of statistical significance was used to evaluate whether the difference in normalized efficiency means between each cleaning group and the controlled group was significant. The five cleaning groups are: distilled water, treated wastewater with surfactant, treated wastewater, groundwater, and vacuum cleaner. Table 5 presents the research hypothesis and the null hypothesis.

Table 5. Research hypothesis and the null hypothesis to compare PV panel efficiency washed with different water sources types

Research hypothesis: The normalized efficiency mean of the cleaning group is significantly different than the normalized efficiency mean of the control group.
Date to be used: power output generated from the PV panels, plane of array insolation, and temperature.
The null hypothesis: There is no difference between the normalized efficiency mean of the cleaning group and the normalized efficiency mean of the control group.
Statistical tests: Confidence interval and test of significance.

Afterwards, the one-tailed and two-tailed t-tests were calculated using the Data Analysis package. Statistical quantities, such as mean, variance, degrees of freedom, t-value and P-value were computed according to the algorithm of the t-test.

According to Navidi (2010) the one-tailed test is utilized with a hypothesis that specifies the expected direction of the results, (e.g. the efficiency of the cleaning group is higher than the efficiency of the control group). In this case, only one extreme end, i.e. tail, of the distribution contributes to the P-value. On the other hand, the two-tailed t-test is utilized with a general type of hypothesis of the results, (e.g. the mean of one group is greater or less than the mean of the other group). In this case, both tails of the distribution contribute to the P-value. To that end, we look for a t value that falls into either one of the extreme ends, i.e. tails, of the distribution. Since the significance level is 0.05, the two-tailed test assigns half of alpha to testing the statistical significance in one path and half of alpha to testing statistical significance in the other path. Once using a two-tailed test, the possibility of the correlation in both directions is tested. Overall, the two-tailed test involves taking a more extreme value to reach the statistical significance than the one-tailed test. The P-value for the one-tailed test is half the P-value of the two-tailed test.

3.5.2 Statistical Analysis: Dust Composition

T-test of statistical significance was used to evaluate whether the difference in the composition of the tempered glass sample is significant different from the dust composition found in the control group and the vacuum cleaner group. In addition, statistical tests were also used to verify if the composition of the dust found in control group is significantly different from the dust found on the vacuum cleaner group. The five elements analyzed are: sodium, aluminum, silicon, potassium, and oxygen. Table 6 presents the research hypotheses and the null hypotheses for each test.

Table 6. Research hypotheses and the null hypotheses to compare tempered glass sample composition with the composition found in the control and vacuum cleaner group

Research hypothesis 1: The composition of the tempered glass sample is significant different from the dust composition found in the control group

The null hypothesis 1: There is no difference between the composition of the tempered glass sample and the dust composition found in the control group

Research hypothesis 2: The composition of the tempered glass sample is significant different from the dust composition found in the vacuum cleaner group

The null hypothesis 2: There is no difference between the composition of the tempered glass

sample and the dust composition found in the vacuum cleaner group
The hypothesis 3: The composition of the dust found in control group is significantly different from dust found in the vacuum cleaner group.
The null hypothesis 3: There is no difference between the composition of the dust found in the control group and the dust found on the vacuum cleaner group

3.6 Analysis of the Wash Water

Conductivity, total dissolved solids, total suspended solids, pH, and chemical oxygen demand were tested at UNLV Environmental Engineering Laboratory. Metal samples (Al, As, B, Ba, Ca, Cd, Co, Cr, Cu, Fe, K, Mg, Mo, Na, Ni, P, Pb, S, Se, Si, Sr, and Zn) were sent to Utah State University Analytical Laboratories (USUAL) (Logan, UT) for analysis.

The anions analyzed in this research were chloride (Cl^-), fluoride (F^-), nitrate (NO_3^-), sulfate (SO_4^{-2}), bromide (Br^-), and phosphate (PO_4^{3-}). Anion samples such as nitrate, sulfate, and phosphate were tested at UNLV Environmental Engineering Laboratory. However, chloride measurements were performed by USUAL (Logan, UT). Fluoride and bromide were sent to Silver State Analytical Laboratories (Las Vegas, NV) for analysis. Table 7 summarizes the analytical methods for each parameter.

Table 7. Analytical methods used to characterize the source and the wash water from PV panel cleaning

Parameter	Method	Limits	Equipment
pH	Hach 8156	0 to 14	Accumet Research Model AR25
COD	Hach 8000	0.7 to 40.0 mg/L (ULR); 3 to 150 mg/L (LR); 20 to 1500 mg/L (HR)	Spectrophotometer Hach DR 5000
TDS	Standard Methods 2540C	N/A	Filtration apparatus and drying oven
TSS	Standard Methods 2540D	N/A	Filtration apparatus and drying oven
Conductivity	YSI Model 63	0 to 499.9 µS/cm	YSI Model 63
Metal scan	ICP	Varies by metal	Thermo iCAP 6300 – ICP-OES Spectrometer
Chloride	QuikChem Method 10-117-07-1-A	0.1 mg/L	QuikChem 8000
Fluoride	EPA 300.0	0.1 mg/L	Ion chromatography (IC)
Nitrate	Hach 10206	0.23 to 13.50 mg/L NO_3^--N or 1 to 60 mg/L NO_3^- (LR)	Spectrophotometer Hach DR 5000
Sulfate	Hach 8051	2 to 70 mg/L $SO4^{2-}$	DR900 Hach
Bromide	EPA 300.1	200 µg/L	Ion chromatography (IC)
Phosphate	Hach 8048	0.02 to 2.50 mg/L $PO4^{3-}$	DR900 Hach

3.7 Evaluation of Panel Cleanliness after Washing

The goniometer KSV CAM200 (*KSV Instruments*, Monroe, CT, USA) was used to measure the contact angle on the tempered glass samples surface. After washing and drying naturally, the tempered glass samples were collected from the solar site and analyzed for the contact angle in three different points of each tempered glass sample.

A drop of distilled water was dispensed from a needle on the glass surface and a high speed camera (CAM200) was utilized to capture the drop shape throughout the process. The OneAttension software (Biolin Scientific USA, Paramus, NJ) automatically detected the drop shape and performed an image analysis determining the contact angle at each point. The

Young-Laplace method was used for all experiment. The picture of the drop of distilled water is shown in Figure 10 after processing by OneAttension software using the Young-Laplace contact angle method.

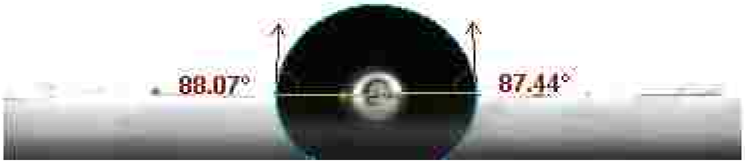


Figure 10. Left and right contact angle located on the surface of the tempered glass sample

3.8 Dust Chemical Composition

The dust composition remaining on the tempered glass samples were analyzed with a JEOL JSM-5600 Scanning Electron Microscope (JEOL USA, Peabody, MA) coupled with an Energy Dispersive Spectrometer (EDS). The SEM creates images of a sample by scanning it with a focused beam of electrons. EDS determines elemental analysis of a sample generating a unique set of peaks in its X-ray spectrum (Maghami et al., 2014).

Five tempered glass samples were fixed per group of panels to verify the chemistry of the soiling residue remaining after wash. After each washing (from 4th wash to the 8th wash) a tempered glass sample was collected from each group of panels, including the control group. The cleaned tempered glass samples were then examined using SEM-EDS.

Once dried, the piece of tempered glass sample was coated with gold. The coating process is applied to avoid the accumulation of electrostatic charge and keep the sample electrically conductive. The experiment was run at 15 kV beam energy, spot size 45, and 20 mm working distance. For each compound 5-515 particles were target by SEM, depending on the amount of soiling remaining; cleaner glass samples were examined with smaller number of readings (5-10). The particles present in the samples were selected for element concentration analysis using an EDS and the percentage element concentration in each tempered glass sample was determined.

3.9 Organic Matter Determination in the Dust Samples

The dust samples of the panels were collected using a glass microfiber filter (55mm, Whatman GE healthcare) and Pyrolysis-GC/MS was used to characterize organic matter. Pyrolysis GC-MS was performed using a Varian Saturn 2200 MS/MS with CP-3800 GC (Palo Alto, CA). Pyrolysis was performed with a CDS Analytical (Oxford, PA) pyroprobe 2000. Samples were analyzed by adding the glass microfiber filter (GFC/F) into a 2-mm diameter quartz tube. Then, the quartz tube was packed with quartz wool (Radnor, PA) and 20 µL of the derivatization agent, 25% Tetramethyl ammonium hydroxide (TMAH) was added to the quartz wool. The sample was inserted into the pyroprobe, dried for at least 30 seconds, at 90˚C before heating at 600˚C for 10 seconds followed by 10:1 split ratio injection into the GC with a Rtx-5ms column with dimensions of 30 m x 0.25mm and a phase thickness of 0.25 um (Restek, Bellefonte, USA) (Sylva, 2017). The following temperature program was used for the GC: initial temperature was set at 40˚C for 6 minutes; ramp up rate of 10˚C/min was used to reach 280˚C; and temperature was maintained for an additional 10 minutes. Helium gas was used as the carrier gas at a flow rate of 1 mL/min. Varian MS Workstation (Version 6.8, Walnut Creek, CA) was used for peak identification. Similar procedures were performed by Sylva (2017) in the UNLV Chemistry Laboratory.

The output chromatogram for the analysis shows the intensity of the signal versus time. To determine the compounds present, the software Varian MS Workstation was used to identify the potential organic molecules present in the soiling samples.

Chapter 4 – The impact of different types of cleaning on soiling removal from PV panels

One objective of this research was to evaluate how soiling impacts the energy output from solar panels. The experimental set-up to investigate these impacts was described in Chapter 3, section 3.2. In brief, five set of panels were washed with distilled water, treated wastewater with surfactant (Sodium Dodecyl Sulfate), treated wastewater, groundwater, and a vacuum cleaner. The data were measured using the normalized efficiency equation (Equation 1). Following, the results of this investigation are presented and evaluated.

Results and Discussion

4.1 Normalized Efficiency

Figures 11 to 15 compare the normalized efficiency (Equation 1) for each group of panels versus the control group (no cleaning) during 18 months. The graphs show the days at which rain occurred, the amount of rainfall per day, and the date of panels washing. The manufacturer rated module efficiency was expected to be around 14.61% for the SW 245 module and 14.31% for the SW 240. However, the maximum normalized efficiency observed was 12.24% in the group of panels washed by distilled water.

After starting the cleaning schedule (8 total) on February 24, 2017, the highest normalized mean efficiency was observed in the distilled water (11.79%), followed by the treated wastewater (11.74%), treated wastewater with surfactant (11.72%), vacuum cleaner (11.67%), groundwater (11.66%), and the control group (11.64%).

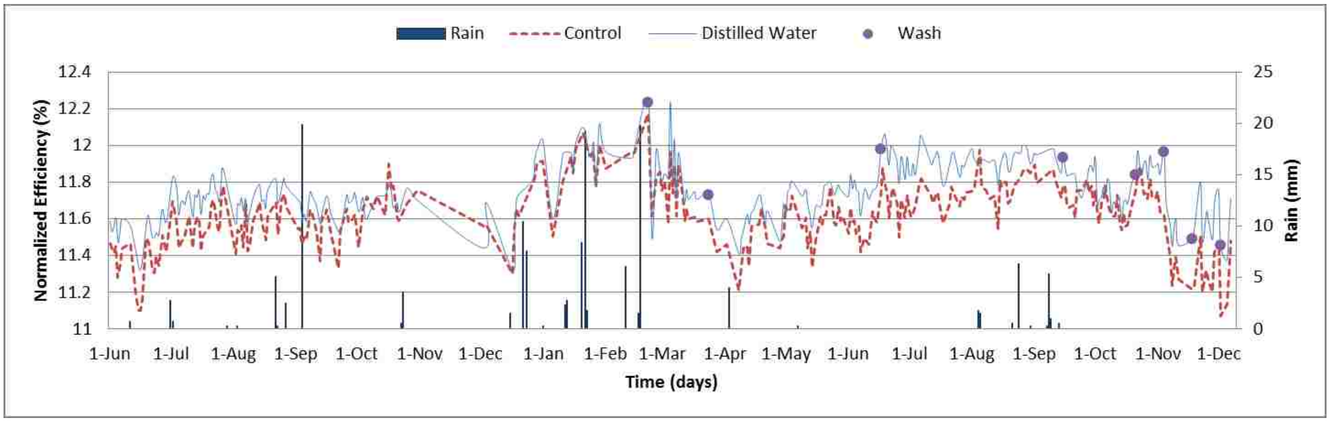


Figure 11. Normalized efficiency for the distilled water group versus the control group, amount of rainfall per day, and the date of panels washing during 18 months

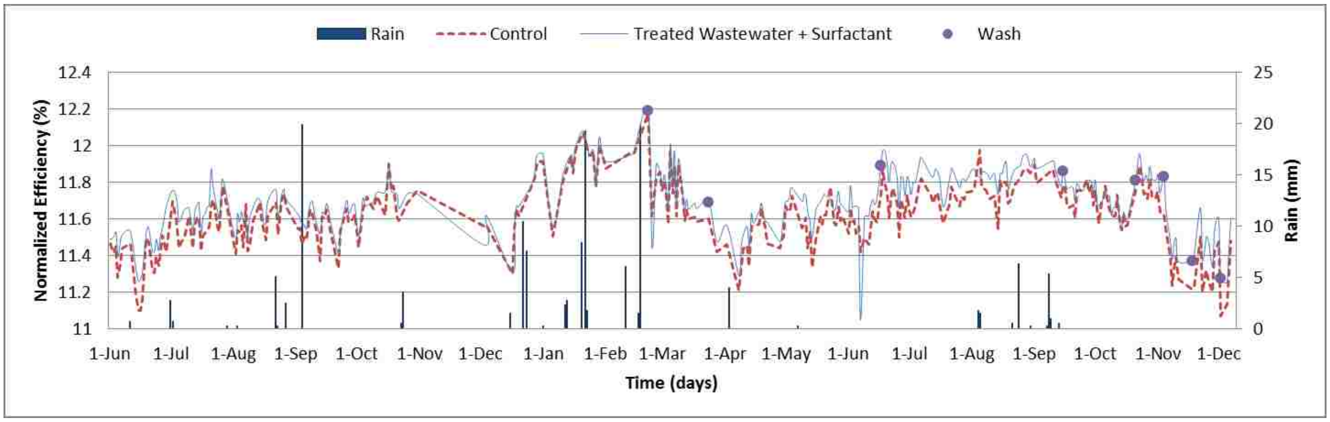


Figure 12. Normalized efficiency for the treated wastewater with surfactant group versus the control group, amount of rainfall per day, and the date of panels washing during 18 months

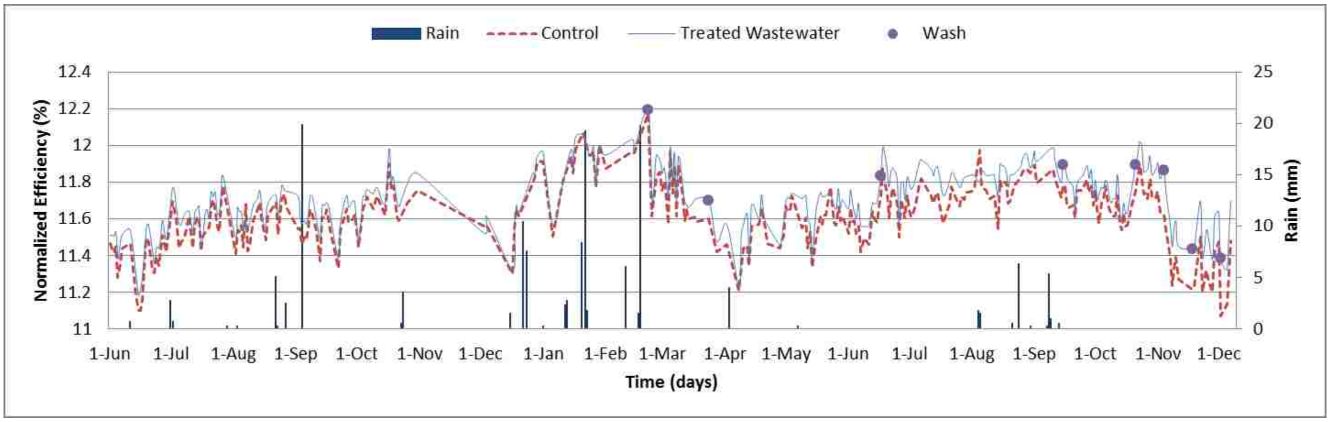


Figure 13. Normalized efficiency for the treated wastewater group versus the control group, amount of rainfall per day, and the date of panels washing during 18 months

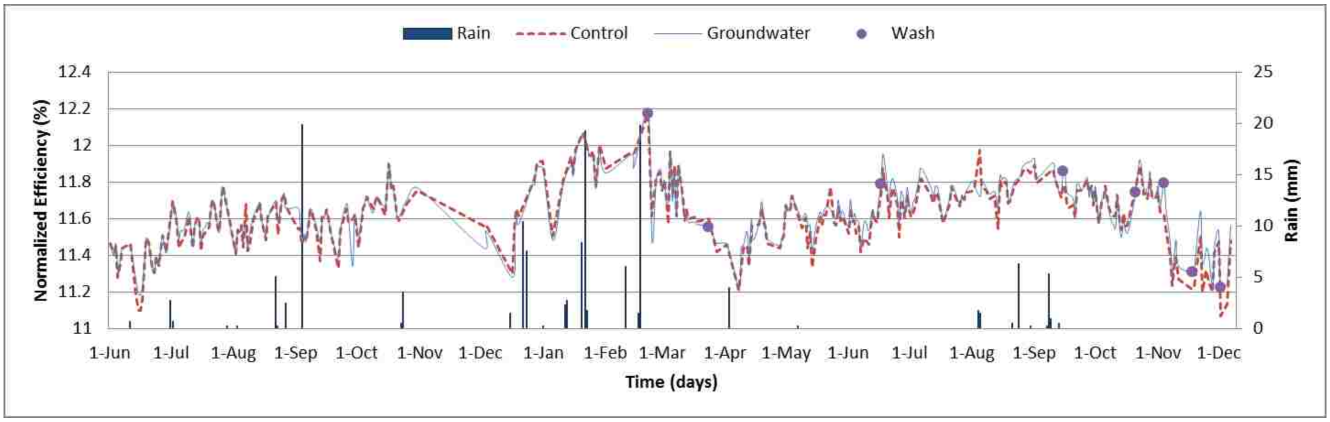


Figure 14. Normalized efficiency for the groundwater group versus the control group, amount of rainfall per day, and the date of panels washing during 18 months

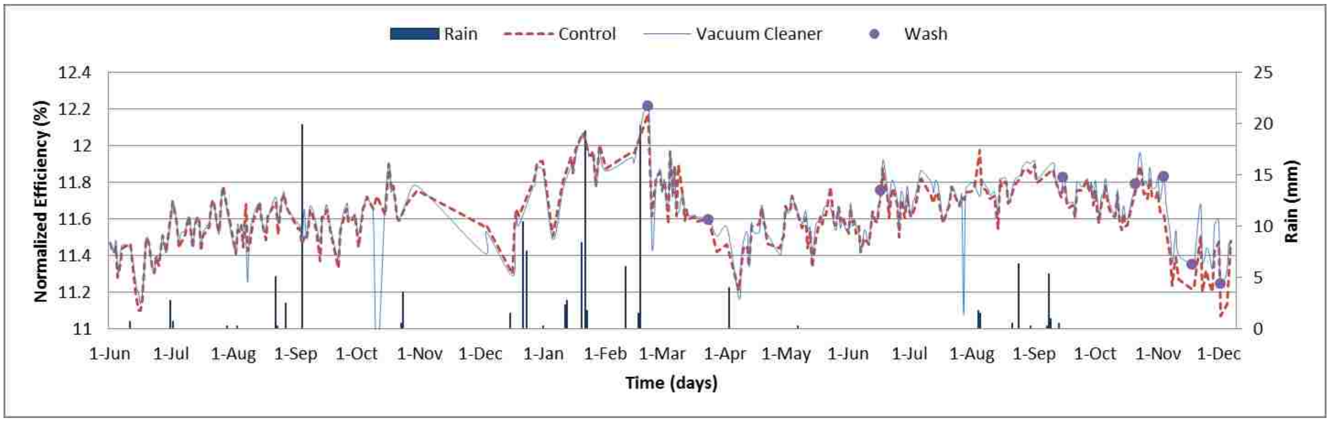


Figure 15. Normalized efficiency for vacuum cleaner group versus the control group, amount of rainfall per day, and the date of panels washing during 18 months

To evaluate the impact of the dust on PV panels, the mean daily normalized efficiency (Equation 1) was calculated only after washing the panels. The results revealed that distilled water recovered the power output by 1.88%, followed by the treated wastewater (1.41%), treated wastewater with surfactant (1.06%), vacuum cleaner (0.75%), and groundwater (0.64%). Since the distilled water is the cleaner water, the percentage mean efficiency reduction caused by dust in the control group was around 1.88%.

During the cleaning schedule period (from February 24, 2017 to December 2, 2017), the recovered mean normalized efficiency was calculated based on the difference between the mean normalized efficiency of each cleaning group and the control group. The results revealed that the distilled water recovered a mean normalized efficiency of the system by around 1.32%, followed by the treated wastewater (0.92%), treated wastewater with surfactant (0.73%), vacuum cleaner (0.27%), and groundwater (0.24%).

However, when considering the whole data set of the study (from June 1, 2016 to December 2, 2017), that is, including the soiling period with no periodic cleanings (from June 1, 2016 to February 23, 2017), the recovered mean normalized efficiency dropped to 1.15% for distilled water, followed by the treated wastewater (0.77%), treated wastewater with surfactant (0.64%), groundwater (0.16%), and vacuum cleaner (0.15%). These results revealed that the soiling has a slight effect on the normalized efficiency of the PV panels.

Different results were observed in the literature for locations other than Nevada. After a year of research in Málaga - Spain, Zorrilla-Casanova et al. (2011) concluded that the mean of the daily energy loss caused by dust was around 4.4%. Furthermore, in the absence of rain, daily energy losses could be more than 20%. In another study realized in Canary Islands, Schill et al. (2015) observed a drop of around 20% in the efficiency of the PV modules within 5 months. Bhattacharya (2015) observed a reduction among 9% to 13% in the efficiency of the PV modules located in Tripura - India. Bunyan et al. (2016) compared the output power efficiency of two identical PV panels placed on Kuwait. The results showed that the PV panel output was considerably affected in the months of April (15.07%), May (13.74%), October (10.685%), and December (8.742%). After 11 weeks of study in Taxila - Pakistan, Ali et al. (2015) demonstrated that the percentage efficiency reduction of monocrystalline and polycrystalline modules was 3.55% and 3.01%, respectively. Ali et al. (2015) results for polycrystalline modules are higher than the results obtained in this study (1.88%). These differences in the efficiency and power output of each study are related to the variance in the local weather, vegetation, and dust concentration and composition, and of course the location of the solar plant.

4.2 Statistical Evaluation of the Normalized Efficiency

Statistical evaluations were performed to determine the confidence intervals for each cleaning group and to verify if the normalized efficiency mean of the cleaning group is significantly different than the normalized efficiency mean of the control group.

4.2.1 Confidence Intervals

Table 8 presents the statistical results for each cleaning group and the confidence level of 95% based on the distribution of the experimental data. The highest normalized mean efficiency was observed in the distilled water (11.79%), followed by the treated wastewater (11.74%), treated wastewater with surfactant (11.72%), vacuum cleaner (11.67%), groundwater (11.66%), and the control group (11.64%) as presented in the section 4.1. The maximum normalized efficiency, with value 12.24%, was attained for distilled water group, while the minimum normalized efficiency, with value 11.05%, was achieved for the treated wastewater with surfactant.

Table 8. Statistical results for each cleaning group

Water type	**Distilled water**	**Treated Wastewater + Surfactant**	**Control**	**Treated Wastewater**	**Groundwater**	**Vacuum Cleaner**
Mean (%)	11.79	11.72	11.64	11.74	11.66	11.67
Standard Deviation	0.153	0.161	0.169	0.151	0.154	0.159
Minimum (%)	11.37	11.05	11.07	11.22	11.22	11.08
Maximum (%)	12.24	12.19	12.17	12.19	12.17	12.21
Confidence Level (95%)	0.0217	0.0229	0.0240	0.0215	0.0219	0.0226

The 95% confidence intervals were calculated to cover the true normalized efficiency mean of the groups since the normalized efficiency mean of the group is not exactly the same as the true sample mean. The lower confidence limit (LCL) and the upper confidence limit (UCL) were calculated for each group of panels, giving the 95% confidence interval to equal to (LCL, UCL).

Therefore, based on Table 9, the panels washed with distilled water have a 95% confidence interval given by (11.767%, 11.81%). The same 95% confidence interval for the panels washed with treated wastewater with surfactant is (11.697%, 11.742%), for the control is (11.611%, 11.659%), for the treated wastewater is (11.720%, 11.763%), for the groundwater is (11.642%, 11.686%), and for the vacuum cleaner is (11.643%, 11.689%). In summary, these intervals give us the range of values which is likely to contain the population parameter of interest, i.e. the true normalized efficiency mean.

The panels washed with distilled water, treated wastewater, and treated wastewater with surfactant has confidence intervals that do not overlap with the confidence interval of the control group. To that end, the means of these cleaning groups can be considered significantly different than the mean of the control group. This type of test/comparison leads to a result that is more significant than the individual value of P would indicate. The groundwater and vacuum cleaner group panels' confidence intervals overlap with the confidence interval of the control group. In general, if two confidence intervals do overlap, the two means may or may not be significantly different. Further investigations are needed such as a t-test analysis described next.

Table 9. Confidence interval for each group of solar panels

Water Sample	Lower Confidence Limit (LCL)	Upper Confidence Limit (UCL)
Distilled water	11.767	11.810
Treated Wastewater + Surfactant	11.697	11.742
Control	11.611	11.659
Treated Wastewater	11.720	11.763
Groundwater	11.642	11.686
Vacuum Cleaner	11.643	11.689

4.2.2 Statistical Test of Significance

Table 10 presents the results from running the t-tests for all the cleaning groups. It depicts the mean of the normalized efficiencies of each cleaning group, their corresponding variances, degrees of freedom, Df, t-statistics, and then t-critical and P-values for one-tailed and two-tailed tests.

The results showed that only the groundwater and vacuum cleaner group had a t Stat lower than the t Critical, and that the P-value was not lower than 0.05, which is the significance level. For these two groups, the hypothesis cannot be rejected. For distilled water, treated wastewater with surfactant and treated wastewater, we can reject the null hypothesis. Thus, the normalized efficiency mean of these cleaning groups is significantly different from the normalized efficiency mean of the control group.

The results presented in Table 10 revealed that all cleaning groups had a t Stat higher than the t critical and that the P-value was lower than 0.05 for the one-tailed test. Thus, the null hypothesis can be rejected for all the cleaning groups, and it can be concluded in favor of the research hypothesis.

Table 10. T-test results

Water type	**Distilled water**	**Treated Wastewater + Surfactant**	**Treated Wastewater**	**Groundwater**	**Vacuum Cleaner**	**Control**
Mean	11.79	11.72	11.74	11.66	11.67	11.64
Variance	0.0234	0.0259	0.0229	0.0239	0.0253	0.0285
Df	380	383	379	381	383	NA
t Stat	9.379	5.017	6.534	1.726	1.843	NA
P(T<=t) one-tail	3.069E-19	4.032E-07	1.032E-10	4.261E-02	3.305E-02	NA
t Critical one-tail	1.649	1.649	1.649	1.649	1.649	NA
P(T<=t) two-tail	6.139E-19	8.064E-07	2.063E-10	8.522E-02	6.610E-02	NA
t Critical two-tail	1.966	1.966	1.966	1.966	1.966	NA

4.3 Effects of the Cleaning Process on the PV Panels

After comparing the normalized efficiency, the cleaning results indicated that the dissolved minerals in the wastewater and principally in the groundwater affected the performance of the system (power output). The solids present in the groundwater negatively impacted the cleaning performance of the system. The cleaning with this type of water should be avoided due to the fact it is not effective in removing the particles from the PV panels. Furthermore, the vacuum cleaner was not efficient in removing the dust from the solar panel’s surface. This cleaning method was spreading the dust from one side of the panel to the other side.

The cleaning with treated wastewater was more effective when compared with the treated wastewater with surfactant as could be observed in the previous results presented in section 4.1. This fact can be explained by the amount of surfactant utilized in the cleaning process. The first and second cleaning process used 0.5 g/L of surfactant, and the third and fourth utilized 0.1 g/L. The high amount of surfactant utilized in these washes was not sufficiently rinsed off, leaving remaining residuals on the surface of PV panels, which probably affected their efficiency.

Apples et al. (2013) explained that after washing the solar panels using water with surfactants, the surface must be rinsed off to avoid the deposition of dust particles. Abd-Elhady et al. (2011) indicated that the surfactant behavior depends on the electrical charge of the dust that is present on the surface of the panels.

In order to save water, each cleaning solution was reused until the entire panel group was cleaned. From visual inspection, the end of the cleaning process resulted in a water with a high concentration of solids. While the distilled water was removing great amount of solids, the treated wastewater and groundwater was probably removing part of the solids and leaving their dissolved minerals deposited on the surface.

The presence of bird droppings (Figure 16) was not found uniformly in the groups of panels. In addition, cleaning those panels was the most time consuming part in the cleaning schedule. The vacuum cleaner was not able to remove the bird droppings, which contributed for the low mean normalized efficiency in this group.

Figure 16. Bird droppings for (a) Group B on October 14, 2016, and (b) Group C on June 17, 2017

In this study, the solar panels did not get as dirty as expected. The solar set up is located on a site with compacted soil and covered with small rocks to abate dust. Pavan et al. (2011) indicated that the soil type and the washing technique have an important role in the soiling effect. Their study revealed that with sandy soil, the losses were around 6.9% while on compact soil the losses were 1.1%. Therefore, the PV panels cleaned with pressure water and brushes presented a better power output when compared with the panels cleaned only with pressure water.

4.4 Effects of Natural Cleaning on PV Panels

During this study, 34 rainfall events were observed. The mean amount of rainfall for the 34 events was around 4.12 mm. Out of 34 events, seven rainy days were evaluated (June 11, 2016 (0.76 mm), July 29, 2016 (0.25 mm), August 3, 2016 (0.25 mm), August 22, 2016 (5.08 mm), October 23, 2016 (0.5 mm), May 7, 2017 (0.25 mm), and August 5, 2017 (1.52 mm)) for their potential to recover the system power output.

This research has identified that even a light rain (0.25mm) such as the event that happened on August 3, 2016 was enough to recover the power output of the system located on city of Las Vegas West Maintenance Yard solar site. The normalized efficiency recovered for distilled water, treated wastewater with surfactant, control, treated wastewater, groundwater, and vacuum cleaner was 0.098%, 0.093%, 0.118%, 0.13%, 0.116%, and 0.123%, respectively. This normalized efficiency (Equation 1) was calculated based on the day before and after the rainfall event.

Even though the solar panels were exposed to same amount of rainfall, some panels still presented soiling near the edges (Figure 17). This event can explain the normalized efficiency difference for each group of panels. In similar study, Schill et al. (2015) observed that a light rainfall did not wash the soil off totally. The dust got accumulated in the lower area of the panels.

Figure 17. Presence of soiling near the edges

Even operating under the same conditions, the difference between the power outputs from each group of panels can be also associated with the inconsistency in panel manufacturing. The spread in the data can be due to errors in the normalization process and error in each of the measurements: CMP11 (±3%), T-type thermocouples (±0.3° C).

On the other hand, it is believed that wind and rain carried particles to the surface of the panels lowering their normalized efficiency. Evidence for this statement included the rainfall event on July 2, 2016. This event caused dust deposition during the cleaning process.

Cleaning methods for PV panels are not intensively investigated among researchers because many of them believe that the rain is sufficient to clean the PV surface and restore the system efficiency (Maghami, 2016). Caron & Littmann (2012) observed that even 0.5 mm of rainfall was enough to completely clean the panel modules when soil is present in small amounts. Their study was not able to determine the minimum amount of rain required for cleaning all panels.

Zorrilla-Casanova et al. (2011) also concluded that even a light rainfall (less than 1 mm) was sufficient to clean the panel’s surface. Apples et al. (2013) determined that the rainfall had a major cleaning effect on bigger particles but a minor cleaning effect with particles smaller than 10 μm. For Smith et al. (2013), a single rainfall was enough to clean the surface of the panels and restore the power output of the system. Similar results related with the rainfall were observed in this study. Rainfall events that happened on August 2, 2017 (1.77 mm) and August 3, 2017 (1.52 mm) were sufficient to clean the surface of all groups of panels (Figure 18).

Weekly or monthly cleaning was not justified in this research because the dust deposition on the glass of the PV modules did not considerably degrade the performance of the PV system. Furthermore, most of the rain events were enough to keep the solar panels clean. Inadequate or inefficient cleaning methods, such as the use of groundwater to clean PV panels, can end up consuming more time and increasing costs. The same result was reported by Sinha et al. (2014), which stated that cleaning schedules are not necessary when soiling is not a big concern and dust is regularly removed by the rainfall.

Figure 18. Clean surface after rainfall events that happened on August 2, 2017 (1.77 mm) and August 3, 2017 (1.52 mm)

Different from this study, Kalogirou et al. (2013) determined that the cleaning frequency depends on the season. Their study showed that in the winter, the rainfall is sufficient to clean the PV surface. However, in the summer, cleaning is recommended instantly after a dust incident and every 2-3 weeks. Bouchalkha (2015) also indicated that regular cleaning is required every 10 to 15 days under regular weather conditions.

4.5 Accumulated dust on the Tempered Glass Sample

The accumulated dust was examined from October 8, 2017 to December 2, 2017 (56 days total). In this period of time no rainfall events were observed. Figure 19 indicates that dust deposition increased over time. The accumulated dust on the surface of PV panels in 56 days ranged from 0.023 mg/cm^2 to 0.086mg/cm^2.

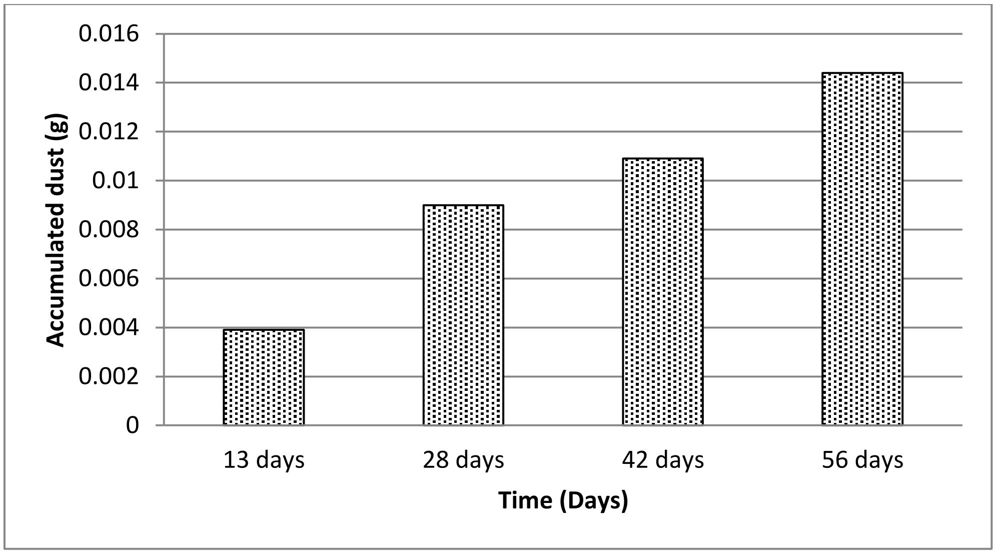


Figure 19. Accumulated dust on the panel's surface located at the West Maintenance Yard of the City of Las Vegas from October 8, 2017 to December 2, 2017

In similar study realized in Portland - Oregon, Smith et al (2013) measured 0.85 g/m^2 of natural particulate deposition in a period of 17 days. Bunyan et al. (2016) showed that the monthly dust accumulation on the PV panels located on Kuwait varied from 0.00821 to 0.0422 mg/cm^2.

4.6 Total Dissolved Solids, Total Suspended Solids, and Conductivity of the Wash Water

Total dissolved solids (TDS) and total suspended solids (TSS) are important parameters to evaluate how the water quality can affect the cleanliness of solar panels. According to Khonkar et al. (2014) the water choice for cleaning is very important and the TDS should be around or below 100 parts per million (100 mg/L). Water with high TDS may promote mineral deposits on the surface of the panels. It happens when the water evaporates after cleaning and leaves residuals behind, which can negatively affect the performance of the system.

Figure 20 shows the TDS before and after washing the panels. Distilled water was the only type of water utilized in this study with less than 100 mg/L. The treated wastewater and groundwater had a range of 915 to 1110 mg/L, and 3680 to 5375 mg/L, respectively. The distilled water after washing the panels presented a TDS lower than 100 mg/L only in the fourth (60 mg/L) and fifth (67.5 mg/L) wash.

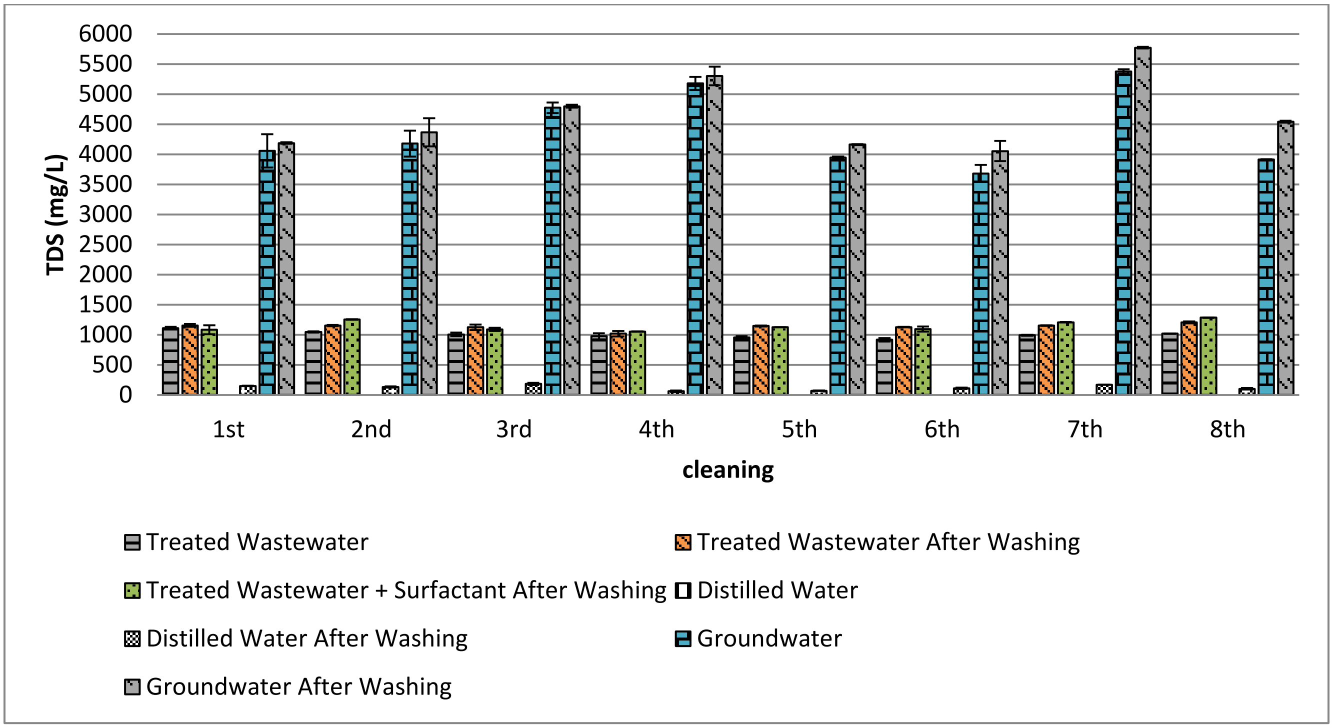


Figure 20. Total dissolved solids before and after washing the PV panels located at the West Maintenance Yard of the City of Las Vegas

The treated wastewater and the groundwater after washing the surface of the PV panels presented a significant increase in the TDS amount as shown in Figure 20. The same behavior was observed for the treated wastewater with Sodium Dodecyl Sulfate, except in the first wash, where 5.68g of this surfactant was used. Figure 21 shows the remaining solids on the surface of PV panels after washing.

Presence of remaining solids on the surface of the panels was noted after washing the arrays utilizing each type of cleaning solution. Although cleaning solutions were used to remove particles from the panels, the addition of particles was also observed. This can be explained by the fact that the water types previously contained different types of particles. Therefore, the washing process resulted in particle removal, but it also resulted in particle addition. The water reuse process may have aggravated this problem.

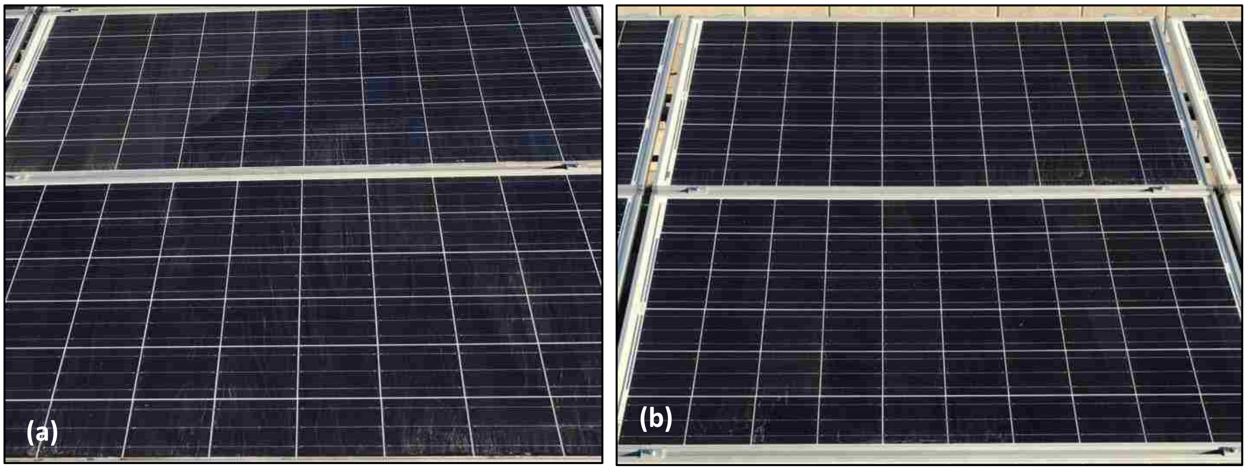


Figure 21. Presence of residuals after cleaning. (a) Groundwater. (b) Treated wastewater with surfactant

Figure 22 shows the TSS before and after washing the panels. The treated wastewater and groundwater presented a TSS concentration lower than 3.1 mg/L and 20.1 mg/L, respectively, while the distilled water did not show any amount of suspended solids. However, after washing the panels, these concentrations increased considerably, as shown in Figure 22.

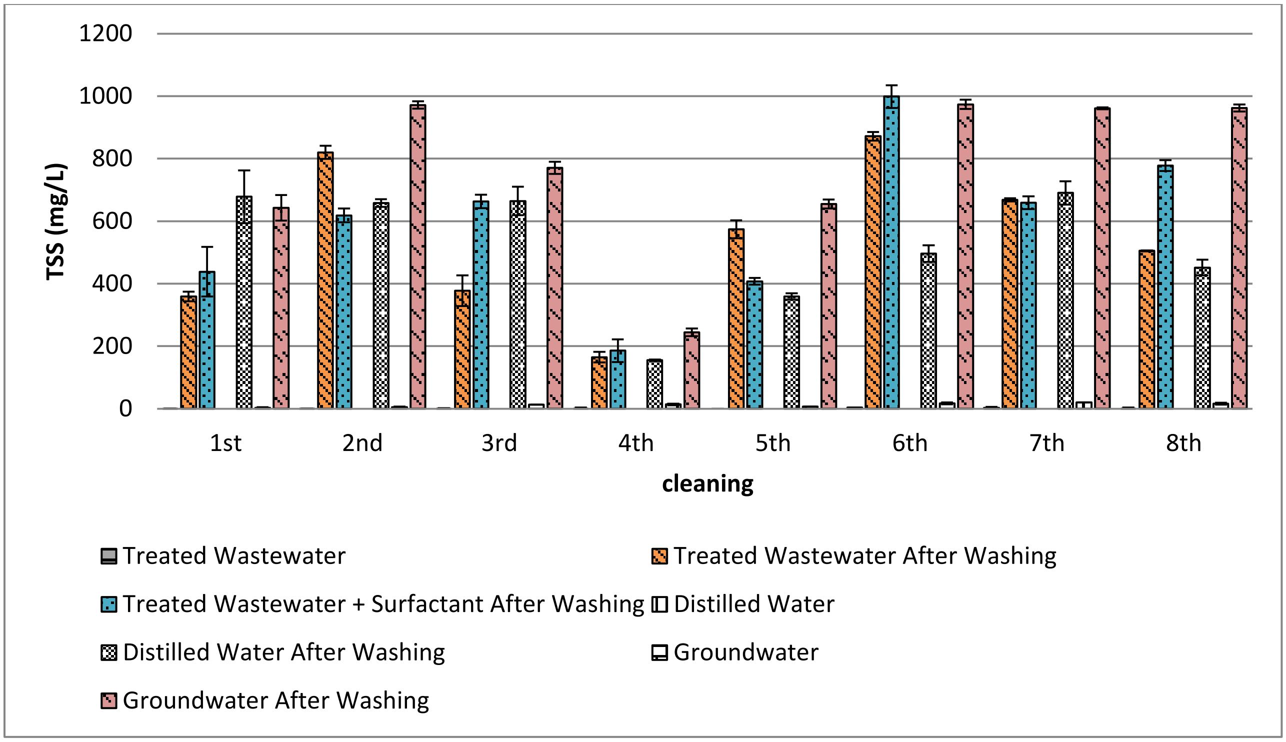


Figure 22. Total suspended solids before and after washing the panels

The excessive presence of solids in the water can affect the system efficiency, leaving these particles to accumulate on the surface of the panels. Shehri et al. (2016) showed that it is an issue because the dust accumulated on the surface of PV modules may increase the temperature more than the usual due to the fact that these particles retain heat.

Sarver et al. (2013) indicated in their literature review that the degradation in PV performance is not only related to the dust composition, but also, the size distribution and type of soil. Apples et al. (2013) specified that cleaning panels should be done only with tap water or demineralized water.

Conductivity is another important water quality parameter and it is directly related to TDS. This parameter is related to the amount of dissolved ions present in the water. A water sample with an excessive concentration of ions has a higher conductivity when compared with a sample containing few ions. Figure 23 presents the conductivity before and after washing the panels for each cleaning.

Distilled water indicated a very low conductivity value (less than 3.8 μS/cm). However, a significant increase was noted after washing the PV panels with this type of water. The highest conductivity was detected in the second wash (208 μS/cm) as shown in Figure 23. This indicates the solids accumulated on the panel contain solids that dissolve once in contact with water. On the other hand, the treated wastewater and groundwater indicated a high conductivity even before washing the panels, which was confirmed by the anion analysis. This anion investigation indicated the presence of chloride, phosphate, and nitrate. Groundwater had the highest conductivity when compared with other cleaning solutions due to the substantial presence of ions that came from dissolved minerals. This is expected, since the shallow groundwater in Las Vegas, the one collected for this research, has high levels of TDS and high conductivity.

The findings revealed that all water types increased the conductivity after washing the solar panels. Therefore, this increase in conductivity indicates the dissolution of solids that were present as dust in the panels, promoting a higher concentration of ions in each sample.

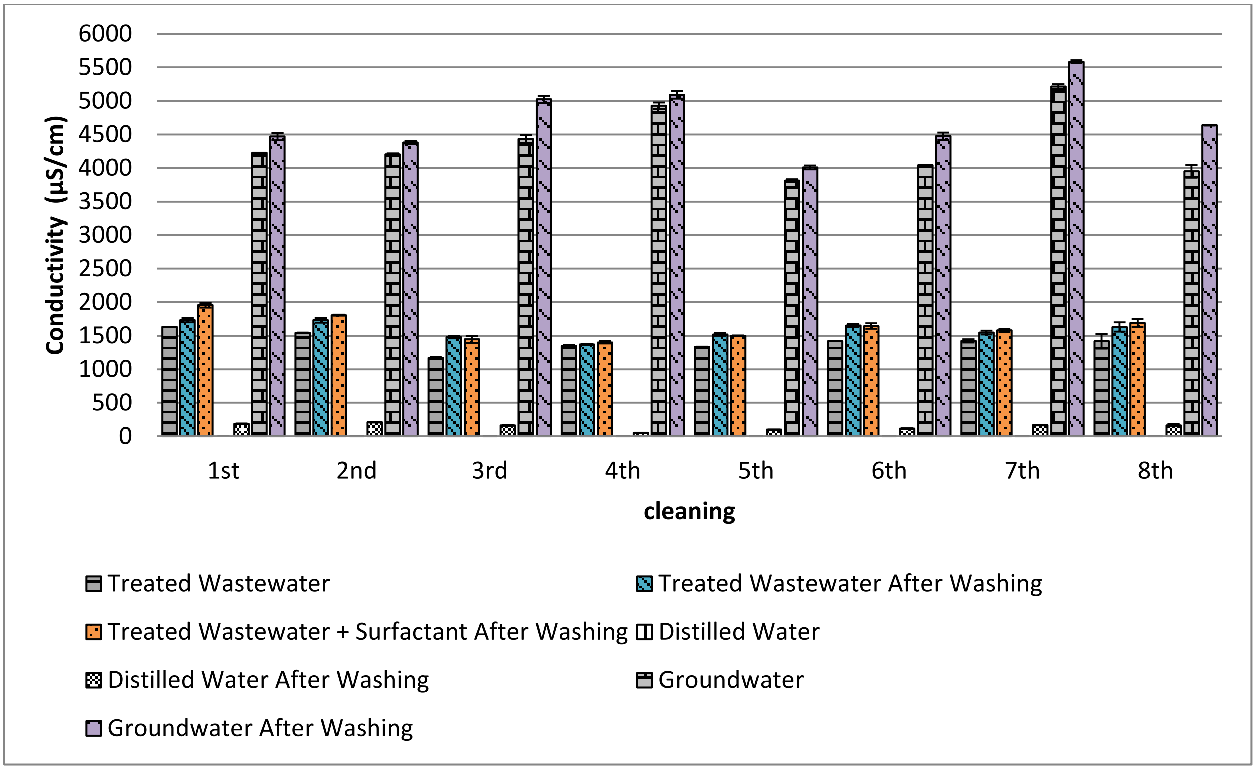


Figure 23. Conductivity before and after washing the panels

4.7 pH of Wash Water

Figure 24 shows the pH values before and after washing the panels for the different waters. According to the United States Environmental Protection Agency (US EPA, 2010), the pH permit for effluent discharge is within the range of 6 to 9. The treated wastewater utilized in the eight washes had a range of 6.47 to 7.67, meeting the discharge requirements. The treated wastewater after cleaning the solar panels had a range of 7.05 to 7.43. Mehmood et al. (2017) demonstrated in their study that the pH increases with the reduction of the dust concentration.

The range of pH for treated wastewater with surfactant after washing the panels, groundwater, and groundwater after washing the panels was 6.67 to 7.46, 7.07 to 7.96, and 7.3 to 7.69, respectively. The most noticeable difference was observed in the distilled water that had a range of 4.1 to 5.62, and the distilled water after washing the panels presented a range of 6.52 to 7.41. This was expected since distilled water has low or no buffering capacity, so its pH can be easily impacted by any ion that dissolves when contacting the solids of the panel. The metals analysis revealed significant amounts of alkaline earth metals such as magnesium, calcium, strontium, and barium. Alkali metals such as sodium and potassium were also detected. These alkaline metals may increase the pH of the sample.

Yilbas et al. (2015) indicated that dust particles containing alkali (NaOH) and alkaline earth metals ($CaCO_3$) compounds might increase the pH when dissolved into the water. The presence of alkaline and alkali metals were observed in the dust and water samples by the EDS and Thermo iCap 6300 – ICP analyses, respectively. The pH for distilled water in the first wash was not measured.

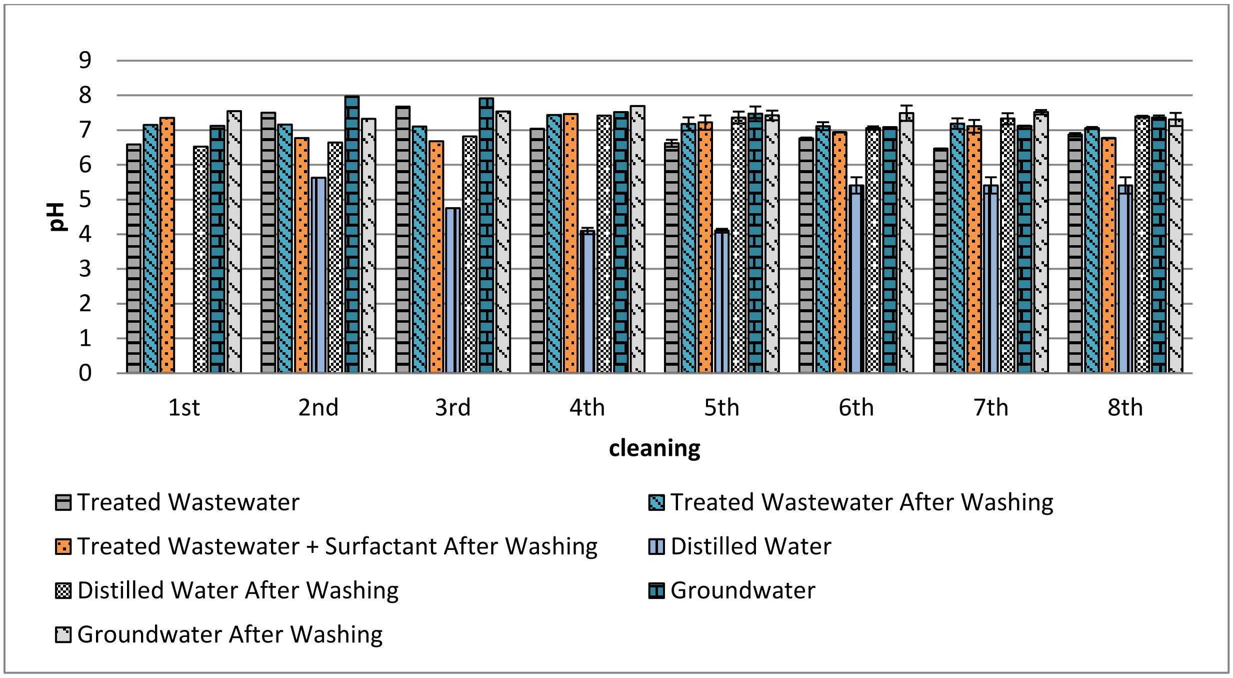


Figure 24. pH of water before and after washing the panels

4.8 Chemical Oxygen Demand of the Wash Water

Figure 25 presents the COD results before and after washing the panels. COD indicated the amount of oxygen required to oxidize all compounds (organics and inorganics) in the different cleaning waters. This test was performed in the last four washes of the solar panels.

Before cleaning the panels, a relatively low COD was observed in the treated wastewater (range from 20 to 29 mg/L) as shown in Figure 25. The only COD exception happened in the sixth wash, where groundwater had a COD of around 33.5 mg/L. Distilled water did not contain any COD, which was expected since this water does not contain organic matter.

After washing the surface of the solar panels, all cleaning solutions presented a higher COD. This result revealed that part of the organic matter present on the panels was removed with the cleaning. Higher COD concentrations detected after washing the PV panels were found in the treated wastewater with surfactant, followed by the treated wastewater, groundwater, and distilled water. The wash water from the panel washed with distilled water presented a COD range from 23 to 38 mg/L.

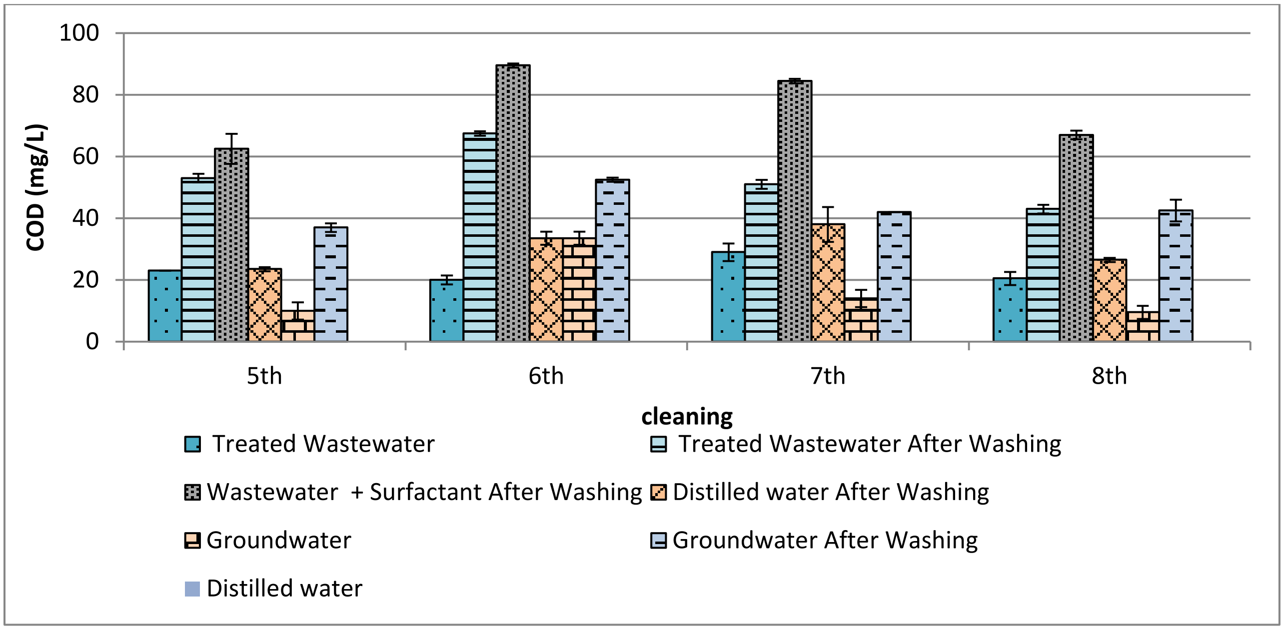


Figure 25. COD before and after washing the PV panels

4.9 Measure of the Cleanliness of Panels using a Goniometer

Table 11 shows the contact angle mean and standard deviation for each cleaning solution, including the control group. The tempered glass utilized in this research has a contact angle usually around 108°, which characterizes a hydrophobic surface. The contact angle was measured in 3 different spots for each glass sample from the fourth to the eight wash.

According to Yuan & Lee (2013) a contact angle lower than 90° implies that wetting on the surface is likely to happen. On the other hand, a contact angle higher than 90° means that the fluid may minimize the contact with the glass surface and generate a dense liquid drop. Kohli (2012) indicated that a low contact angle means a clean surface and a contact angle higher than 90° presents a dirty or contaminated surface.

In this research, the goniometer readings did not show a significant difference in contact angle for the different washing methods. Therefore, there was no relationship between contact angle and cleanliness.

Table 11. Contact Angle (°) for each cleaning solution

Wash	**Distilled Water**		**Wastewater + Surfactant**		**Control**		**Wastewater**		**Groundwater**		**Vacuum Cleaner**	
	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std
4 wash	95.7	7.2	88	9.9	105.6	3.9	97.1	3.4	96.2	8.8	104.2	2.7
5 wash	110.2	1.4	99.1	4.6	98.6	5.1	104.9	9.4	102.4	5.5	101.3	1.4
6 wash	89	4.6	93.9	5.5	97.3	2.6	85.8	0.8	92.9	5.1	107.4	3.5
7 wash	90	8.2	89.6	8.2	98.4	9.6	87.0	3.4	86	5.6	105.4	8.5
8 wash	91.5	2.7	101.6	9.1	89.3	4.3	89.4	0.9	88.4	1.1	102.2	4.7

4.10 Cost Evaluation

The cost evaluation was performed to relate the price of washing the PV panels and the energy loss cost caused by soiling. Table 12 shows the power loss, considering the 1.88% loss caused by soiling during the 18 months of study at the West Maintenance Yard of the City of Las Vegas. The calculation of the power output loss was performed monthly by adding 1.88% to the real power output obtained in this research. To evaluate the cleaning costs, two different rates were considered: $0.084/kWh and $0.1/kWh. Within 18 months, the power loss amounted to $102 and $122 for $0.084/kWh, $0.1/kWh, respectively.

Table 12. Estimated power loss due to soiling for a 63.8kW solar power plant located at the West Maintenance Yard of the City of Las Vegas

Month	**Power output**	**Power loss**	**Dollars Lost**	**Dollars Lost**
	(kWh)	(kWh)	At a rate of $0.084/kWh*	At a rate of $0.1/kWh
Jun-16	3898.7	73.30	6.2	7.3
Jul-16	4256.7	80.03	6.7	8.0
Aug-16	3954.1	74.34	6.2	7.4
Sep-16	4152.2	78.06	6.6	7.8
Oct-16	4845.6	91.10	7.7	9.1
Dec-16	1758.4	33.06	2.8	3.3
Jan-17	2676.3	50.31	4.2	5.0
Feb-17	1505.3	28.30	2.4	2.8
Mar-17	3525.6	66.28	5.6	6.6
Apr-17	3366.7	63.29	5.3	6.3
May-17	4197	78.90	6.6	7.9
Jun-17	5038.7	94.73	8.0	9.5
Jul-17	3596.6	67.62	5.7	6.8
Aug-17	3975.1	74.73	6.3	7.5
Sep-17	3608.2	67.83	5.7	6.8
Oct-17	5638.8	106.01	8.9	10.6
Nov-17	3182	59.82	5.0	6.0
Dec-17	1697.5	31.91	2.7	3.2
Total	64873.5	1219.62	102	122

* Source: Pvwatts calculator (https://pvwatts.nrel.gov/)

To evaluate the impact relationship between washing the panels and energy loss, a large solar power plant was also considered. According to Sempra Renewables, the Copper Mountain Solar 1 located in Boulder City, Nevada, has a capacity of 58 MW, and contains 1,000,000 modules and it generates enough renewable energy to power approximately 18,000 California homes annually. Considering that the residential electricity consumption in California averages 573 kWh/month (Electricity local, 2018) the power output produced can be estimated to be about 10,314,000 kWh. Assuming soiling at Sempra would be similar to the one observed at the City of Las Vegas (i.e. 1.88% loss) 193,903 kWh would be lost annually, that would correspond to $ 16,287 dollars for a kwh cost of 0.084/kWh.

Solar panels cleaning companies in Nevada charge by unit panel. Table 13 presents an estimation of cleaning costs using three different prices and the total cost to wash all 264 polycrystalline PV panels used in this research. The table also contains an estimate of cleaning costs for the modules from Copper Mountain Solar 1.

The results revealed that even when the electricity costs $0.1/kWh, it is not cost effective to wash the panels paying $1 per module. To be worthwhile either the washing cost would have to be lower or price of electricity would have to be higher. In summary, for the photovoltaic plant studied, located in the Las Vegas area, cleaning is not recommended because the dust deposition on the glass of PV modules does not considerably degrade the performance of the PV system and the cost of washing does not outweigh the benefits.

Table 13. Estimation of costs relating the price of washing the PV panels and the energy loss cost caused by soiling

Location	**COLV**	**Sempra**
Number of panels	264	1000000
Total cleaning cost considering $1/panel	264	1000000
Total cleaning cost considering $2/panel	528	2000000
Total cleaning cost considering $5/panel	1320	5000000
Power loss (1.88%) (kWh)	1219	193903
Dollar lost at a rate of $0.084/kWh ($)	102	16288
Dollar lost at a rate of $0.1/kWh ($)	122	19390

Table 14 shows the percentage recovery and the costs of cleaning the PV panels with five different methods. The results revealed that washing the panels with distilled water would recover 856kWh from 1219kWh. However, as explained before, the price for cleaning is higher than the energy profit loss caused by soiling. The worst case scenario is observed in the cleaning process performed with groundwater and the vacuum cleaner, where the net gain is less than $22 per 18 months.

Table 14. Cost evaluation considering the percentage loss caused by dust and the five different cleaning methods

Cleaning Method	**Percentage recovery from 1.88%**	**Power output recovery from 1219 kWh**	**Dollars Lost**	**Dollars Lost**
		(kWh)	At a rate of $0.084/kWh	At a rate of $0.1/kWh
Distilled Water	1.32	856.30	71.93	85.63
Treated Wastewater + Surfactant	0.73	473.58	39.78	47.36
Treated Wastewater	0.92	596.76	50.13	59.68
Groundwater	0.24	155.62	13.07	15.56
Vacuum Cleaner	0.27	175.14	14.71	17.51

Figure 26-27 simulates different percentage loss caused by dust and the costs for this research (COLV) and for the Copper Mountain Solar 1. After analyzing the three different prices for cleaning, it was possible to conclude that a cleaning schedule for this research would be recommended only if a loss of 6% caused by dust was observed and the price for cleaning were $1 per panel. When considering the cleaning price of $2 per panel, a cleaning schedule would be recommended after a loss of 9% for a rate of $0.1/kWh, and after a loss of 12% for a rate of $0.084/kWh. For the large solar plant at Sempra, cleaning schedule would be recommended for a loss of 20% due to the large amount of panels in this solar site.

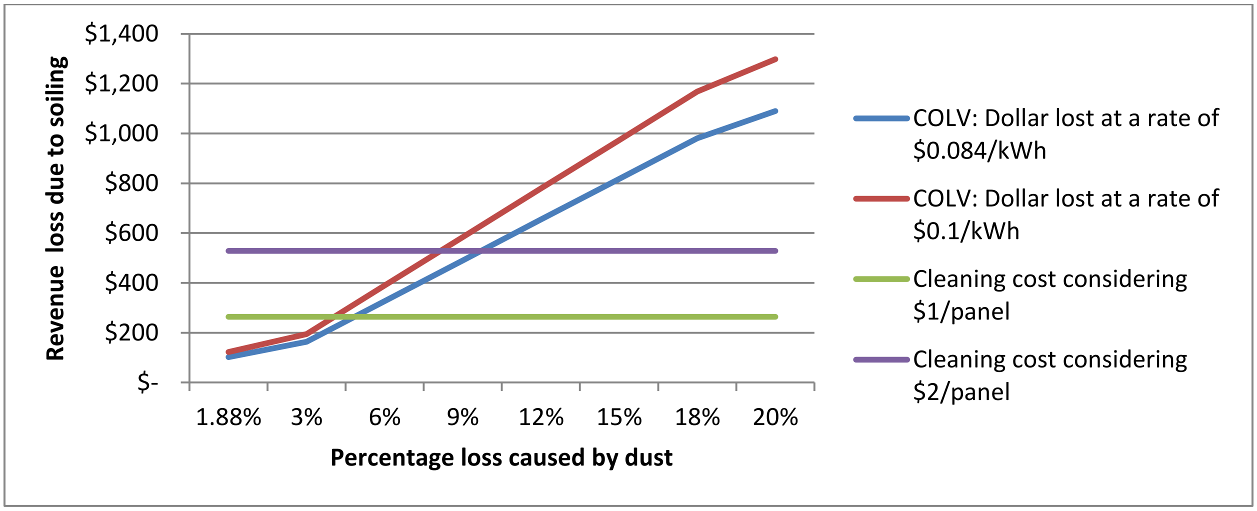


Figure 26. Simulation of different percentage loss caused by dust considering when it is cost effective to wash the solar panels located at COLV

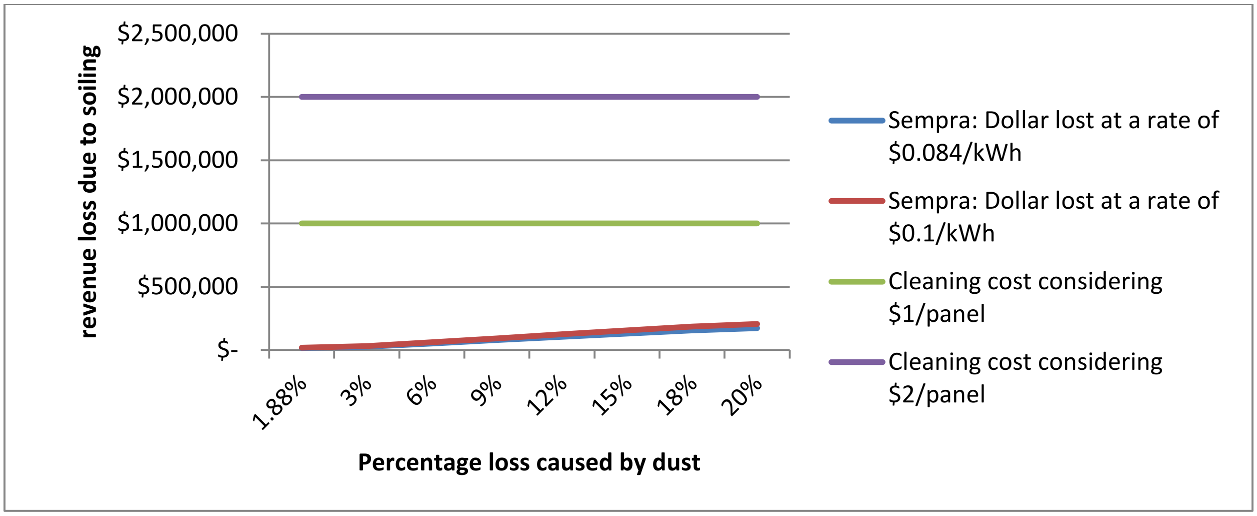


Figure 27. Simulation of different percentage loss caused by dust considering when it is cost effective to wash the solar panels located at Sempra

Chapter 5 – Characterization of Dust Accumulated on Solar Panels

One objective of this research was to determine the chemical composition of the dust accumulated on the solar panels where the research was performed. The experimental set-up to investigate the chemistry of the dust was described in Chapter 3, section 3.2 and subsection 3.3.2. In brief, samples of soiling accumulated on the panels were collected from the dirty panels using a glass microfiber filter and chemical analyses were performed to characterize the organic content. Furthermore, tempered glass samples were attached with Velcro to the large panels and washed together with the solar panels using the different water types. The washed pieces of tempered glass were then examined by scanning electron microscopy (SEM) coupled with an energy dispersive spectrometer (EDS) to determine the potential accumulation of mineral deposits or the presence of remaining dust particles. Below, the results of this investigation are presented and evaluated.

Results and Discussion

5.1 Inorganic: Dust Composition on Glass Samples (SEM-EDS)

Figure 28 shows the dust elemental composition found in the tempered glass samples when analyzed by SEM-EDS. This graph indicates the mean percentage of each element present in the glass sample after the washing processes. Independent on the water used to wash the panels, oxygen, silicon, calcium and potassium composed the largest percentages. The chemical composition of the glass utilized in this study was 45.63% oxygen, 32.6% silicon, 12.16% potassium, 5.24% aluminum, and 4.37% sodium. Therefore, the presence of these elements needs to be taken into consideration when evaluating potential mineral deposits.

The results from the SEM-EDS revealed that most of the dust accumulated on the surface of the panels is composed of sodium (Na), aluminum (Al), silicon (Si), potassium (K), oxygen (O), carbon (C), magnesium (Mg), calcium (Ca), sulfur (S), boron (B), chloride (Cl), zinc (Zn), and iron (Fe). The analysis shows that the elemental composition of remaining elements on the glass surface was different for different water types used to clean the panels. The group of panels cleaned with the vacuum cleaner was the only group where the presence of iron was detected (fifth and seventh wash). A logical explanation for this finding cannot be provided. The group cleaned with treated wastewater and surfactant was the only group where the presence of zinc (sixth wash) was noticed, although at small levels. As expected, chloride was not identified in the group washed with distilled water, but it was detected in all other groups.

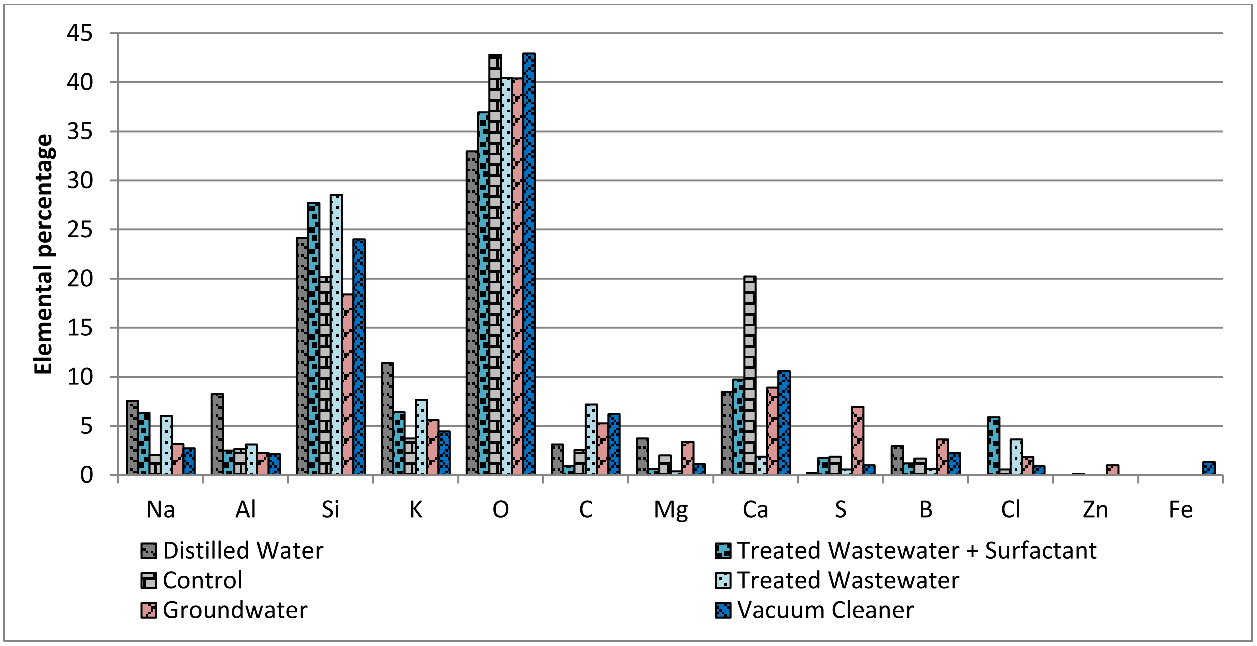


Figure 28. SEM-EDS elements remaining on the surface tempered glass after washing with various water types

The percentage composition of remaining elements also changed with each wash. However, that may be associated with the amount of SEM readings in each piece of glass. Some pieces of glass had more particles than others and the number of reading was larger.

In the group washed with distilled water, sodium was not detected in the seventh wash, magnesium and calcium in the eighth wash and boron in the fourth, fifth, and seventh wash. In addition, the presence of carbon was only identified in the fourth wash.

The principal Earth's crust elements are O, Si, Al, Fe, Ca, Na, K, and Mg. These compounds are responsible for 98.5% of the soil composition (Markoski & Mitkova, 2012; Olivares et al., 2017). As expected, many of the crust elements were identified in this study and indicated that most dust remaining on the panels are from soil, presumably of local origin.

Green at el. (2013) studied the atmospheric particulate carbon in Las Vegas, Nevada. The authors identified that the four main sources that contribute to $PM_{2.5}$ carbon in the Las Vegas Valley are paved road dust, on-road gasoline vehicles, residential wood combustion, and on-road diesel vehicles. The paved road dust contained crustal elements such as Al, Si, K, Ca, Ti and, Ba. Additionally, Cl, Fe, Zn, Cr, and Mn were also observed. The same elements were identified in this study with exception of the Ti and Ba. The presence of the compounds cited above indicates that the soil present on the surface of the PV panels comes from local roads.

Figure 29-32 presents some examples of SEM micrographs of the glass sample after cleaning the surface of the panels. The agglomeration of particles (Figure 29) can be observed after washing the glass sample with wastewater and surfactant (sixth wash). The surfactant sodium dodecyl sulfate utilized in this study has the following chemical composition: $C_{12}H_{25}NaSO_4$. For this reason, the presence of sulfur in the group washed with treated wastewater and surfactant is very likely associated with the use of the surfactant.

The presence of oxygen, sodium, aluminum, silicon, chloride, and potassium were detected in this sample. Figure 30 indicates particles containing sulfur, chloride, calcium, oxygen, sodium, magnesium, aluminum, silicon, and potassium after washing the surface of the panels with groundwater (seventh wash). Silicon (41.48%), oxygen (36.82%), potassium (8.59%), aluminum (7.8%), and sodium (5.31%) were the components detected in the particle represented in the distilled water group (eighth wash) (Figure 31). The presence of oxygen

(49.19%), silicon (30.27%), aluminum (10.14%), magnesium (5.94%), and calcium (4.46%) were obtained in the particle in Figure 32 (fifth wash for the vacuum cleaner group).

The wastewater used contains high levels of calcium, magnesium, potassium, sodium, and sulfur. And, the groundwater used contains high levels of calcium, potassium, magnesium, sodium, sulfur, and silicon. The higher presence of these elements was detected on SEM-EDS results on the surface of the tempered glass.

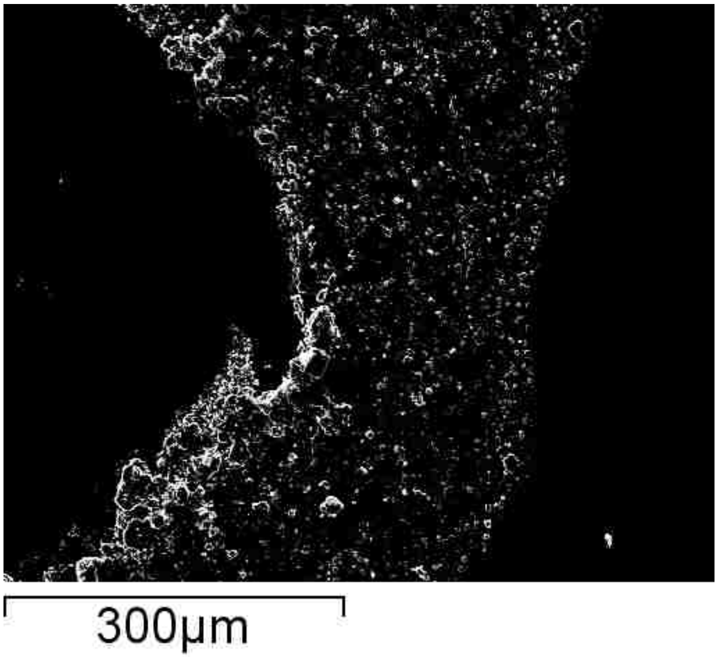


Figure 29. Agglomeration of particles observed when washing solar panels with treated wastewater and sodium dodecyl sulfate surfactant

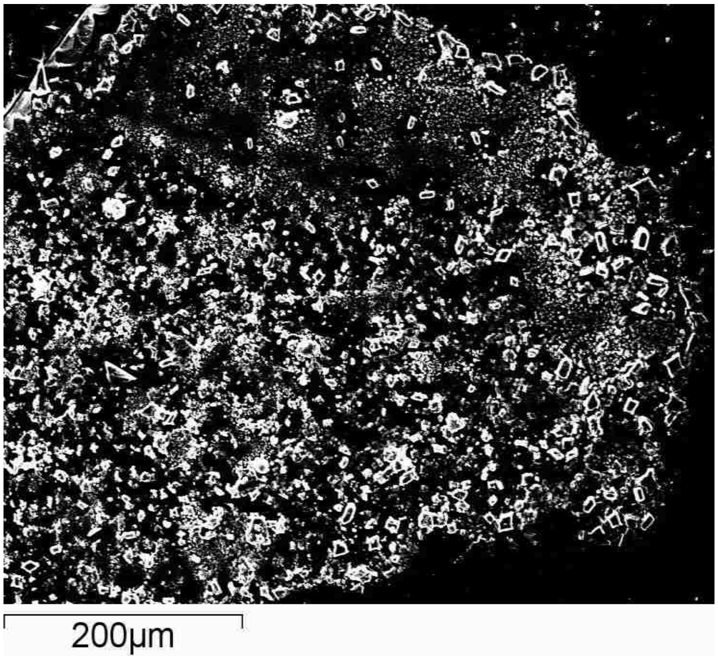


Figure 30.Presence of different particles on tempered glass sample after washing solar panels with groundwater

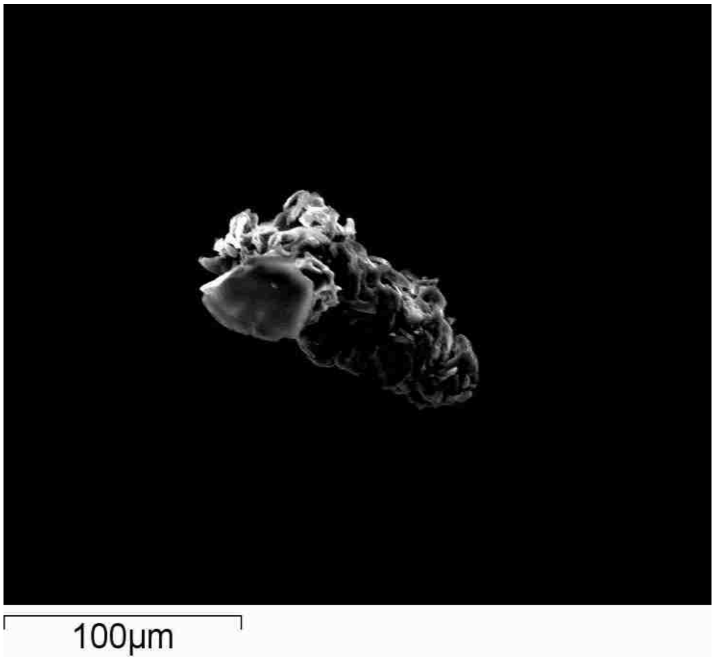


Figure 31. Particle on glass sample from solar panels washed with distilled water

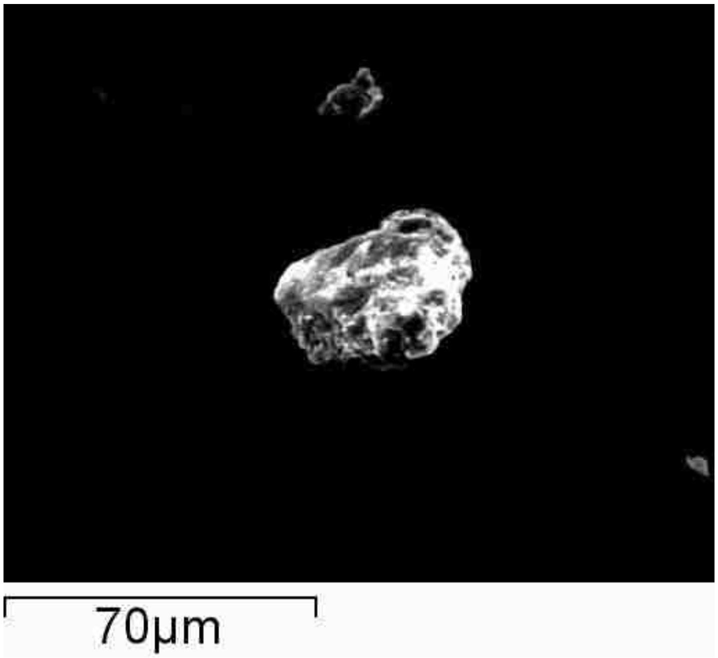


Figure 32. Particle on glass surface from solar panels cleaned with a vacuum

5.1.1 Statistical Evaluation of Solids Composition Remaining on Tempered Glass after Washing with Different Water Types

Figure 33 compares the mean chemical composition of the tempered glass utilized in this study with the mean dust composition found in the control and the vacuum cleaned panel groups. The graph shows that sodium, aluminum, silicon, potassium, and oxygen are higher in the glass samples than the control and vacuum cleaner group. Aluminum and oxygen are slightly higher in the control group when comparing with the vacuum cleaner group.

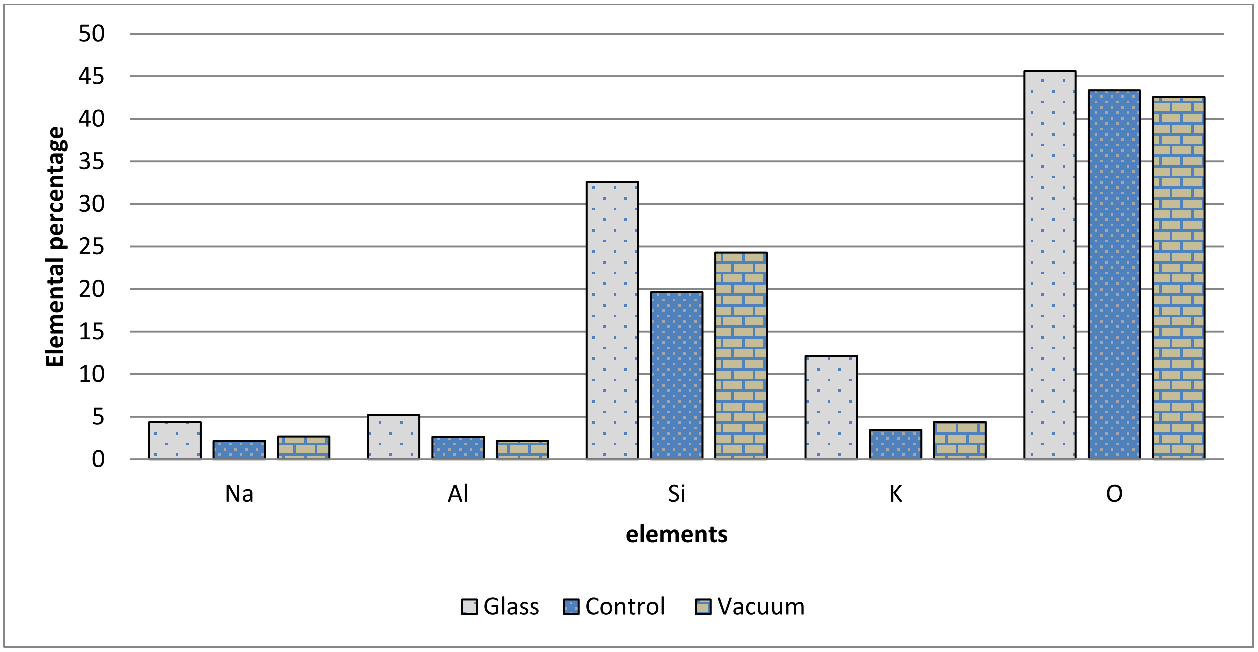


Figure 33. The mean chemical composition of the tempered glass compared with the mean dust composition found in the control group and the vacuum cleaned panel group

Statistical evaluations were performed to verify if the composition of the tempered glass sample is significant different from the dust composition found in the control group and the vacuum cleaner group. In addition, statistical tests were also used to verify if the composition of the dust found in control group is significantly different from the dust found on the vacuum cleaner group.

Table 15-17 presents the results from running the t-tests for sodium, aluminum, silicon, potassium, and oxygen elements. It states the mean of each compound, their corresponding variances, degrees of freedom Df, t-statistics, and then t-critical and P-values for one-tailed and two-tailed tests.

Table 15. T-test results to verify if the composition of the tempered glass sample is significant different from the dust composition found in the control group

Element	**Na**	**Al**	**Si**	**K**	**O**
Mean	4.37	5.24	32.60	12.16	45.63
Variance	1.79	0.13	0.51	0.35	0.46
df	53	83	80	83	79
t Stat	2.26	4.36	6.48	10.04	0.93
P(T<=t) one-tail	0.01	0	0	0	0.18
t Critical one-tail	1.67	1.66	1.66	1.66	1.66
P(T<=t) two-tail	0.03	0	0	0	0.36
t Critical two-tail	2.01	1.99	1.99	1.99	1.99

Table 16. T-test results to verify if the composition of the tempered glass sample is significant different from the dust composition found in the vacuum cleaner group

Element	**Na**	**Al**	**Si**	**K**	**O**
Mean	4.37	5.24	32.60	12.16	45.63
Variance	1.79	0.13	0.51	0.35	0.46
df	32	72	68	72	68
t Stat	2.09	6.68	4.10	9.92	1.65
P(T<=t) one-tail	0.02	0	0	0	0.05
t Critical one-tail	1.69	1.67	1.67	1.67	1.67
P(T<=t) two-tail	0.04	0	0	0	0.10
t Critical two-tail	2.04	1.99	2.00	1.99	2.00

Table 17. T-test results to verify if the composition of the dust on the control group is significant different from the dust composition on the vacuum cleaner group

Element	***Na***	***Al***	***Si***	***K***	***O***
Mean	2.16	2.65	19.64	3.45	43.36
Variance	54.78	26	306.54	54.76	463.19
df	137	138	142	143	137
t Stat	-0.50	0.70	-1.65	-0.87	0.26
P(T<=t) one-tail	0.31	0.24	0.05	0.19	0.40
t Critical one-tail	1.66	1.66	1.66	1.66	1.66
P(T<=t) two-tail	0.62	0.48	0.10	0.39	0.80
t Critical two-tail	1.98	1.98	1.98	1.98	1.98

The two-tailed test has to be used when the hypothesis states that there exists some difference between the elements in the glass sample and the control group or vacuum group but does not state the direction. Table 15 and 16 showed that only oxygen had a t Stat lower than the t Critical, and that the P-value was not lower than 0.05, which is the significance level. For this element, the hypothesis cannot be rejected. For sodium, aluminum, silicon, and potassium we can reject the null hypothesis. Thus, the composition of these compounds is significantly different from the composition found in the control group and in the vacuum cleaner group.

Since Table 17 showed that all compounds had a t Stat lower than the t Critical, and that the P-value was not lower than 0.05, we cannot reject the null hypothesis. Then, there is no difference between the composition of the dust found in the control group and the dust found on the vacuum cleaner group.

5.2 Metals in the Different Types of Wash Water

Figure 34 shows the mean trace concentration of 21 metals from the second to the eighth panel washes. Cadmium and selenium were not identified at detection limits of 0.001 and 0.025 mg/L, respectively. Table 18 shows the mean trace concentration of 21 metals for the wash water before washing the PV panels.

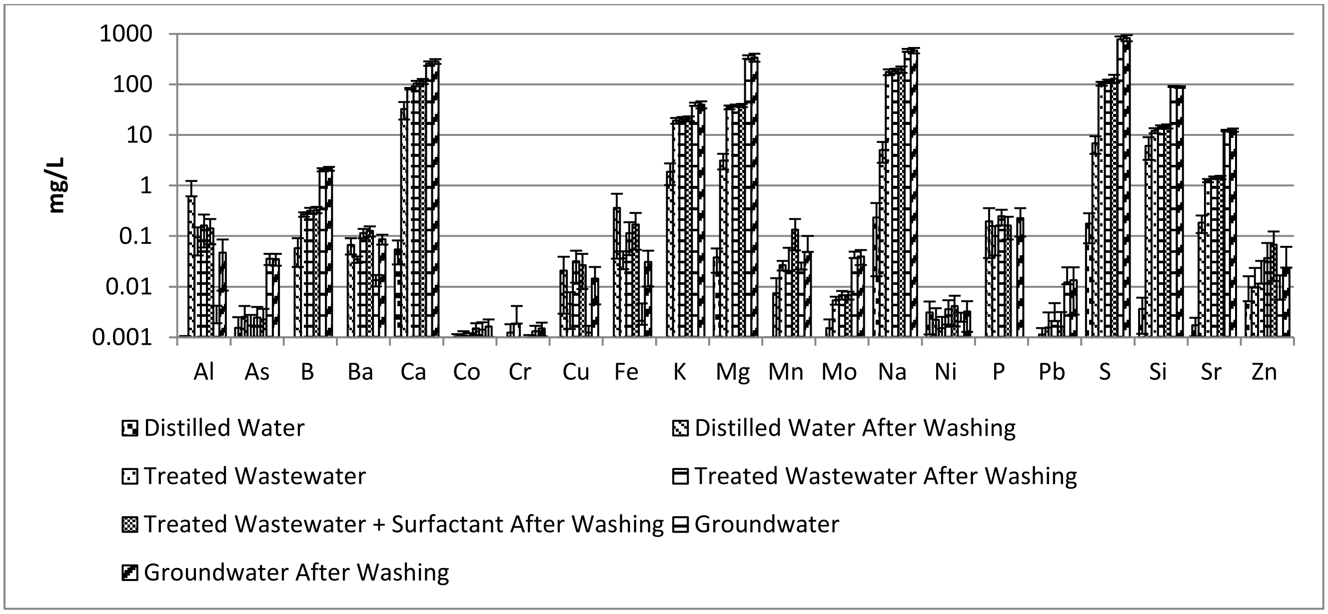


Figure 34. Mean trace concentration of 21 metals from the second to the eighth panel washes

Table 18. Mean trace concentration of 21 metals (mg/L) for the wash water before washing the PV panels

Metal	Al	As	B	Ba	Ca	Co	Cr	Cu	Fe	K	Mg
Distilled Water	0.001	0.001	0	0	0.054	0	0	0	0	0	0.037
Treated Wastewater	0.095	0.001	0.26	0.034	81.84	0.001	0.001	0.004	0.036	19.1	35.06
Groundwater	0.001	0.035	2.05	0.013	256.9	0.001	0.001	0.001	0.002	37.4	320.8

Metal	Mn	Mo	Na	Ni	P	Pb	S	Si	Sr	Zn
Distilled Water	0.001	0	0.234	0.003	0	0	0.1774	0.0036	0.0017	0.0051
Treated Wastewater	0.027	0.005	175.6	0.0015	0.1	0.0016	102.51	12.16	1.25	0.0116
Groundwater	0.022	0.036	440.8	0.002	0	0.0122	774.23	88.7	11.81	0.0056

The results revealed high amount of metals present in the treated wastewater and groundwater even before washing the surface of the panels. The wastewater used contains high levels of calcium, magnesium, potassium, sodium, and sulfur. The groundwater used contains high levels of calcium, potassium, magnesium, sodium, sulfur, and silicon. The presence of these elements on the cleaning water types may have affected the power output as explained in the previous chapter.

The best water to compare the presence of metals was the distilled water (cleaner water). After washing the panels with distilled water, a significant amount of Ca, K, Mg, Na, S, Si, Al, and Fe was detected. Same compounds were identified in this study with the Scanning Electron Microscopy coupled with an Energy Dispersive Spectrometer (SEM-EDS). These results support the conclusion that the dust deposited on the panels came from the ground.

Sylva (2017) studied the same solar panels located at the West Yard of the City of Las Vegas and compared the composition of the dirt in the surrounding area of the panels with that of the dust accumulated on the panel surface. His studies have identified the presence of calcium, magnesium, sodium, iron, aluminum, potassium, and sulfur. He found only slight difference between the composition from the ground and the dirt accumulated on the panels.

Furthermore, local minerals such as dolomite ($CaMg(CO_3)_2$), carbonate($CO_3{-}_2$), rutile (TiO_2), quartz (SiO_2), gypsum ($CaSO_4 \cdot 2H_2O$), and anatase (TiO_2) were identified in his study.

The City of Las Vegas West Maintenance Yard solar site is located close to the W Cheyenne Ave and N Buffalo Dr. Trace of contaminating elements such as zinc, copper, nickel, and chromium can be explained by the light vehicular traffic in the urban area. The contamination sources contributing to these elements may be related to the resuspension of road dust particles, vehicle fleet exhaust, brake and tire wear (Javed et al., 2017).

5.3 Anions in the Wash Water

The anions analyzed in this research were chloride, fluoride, nitrate, sulfate, bromide, and phosphate. Figure 35 presents the anion concentration from the fourth to the eighth wash. These samples showed a variation on the anions concentration for each time the surface of the panels was cleaned. This variation can be described by the prior presence of anions in some types of water such as the treated wastewater or groundwater. Another relevant reason could be related with the quantity of dirt accumulated on the panels, influenced by the wind, rainfalls or the cleaning process.

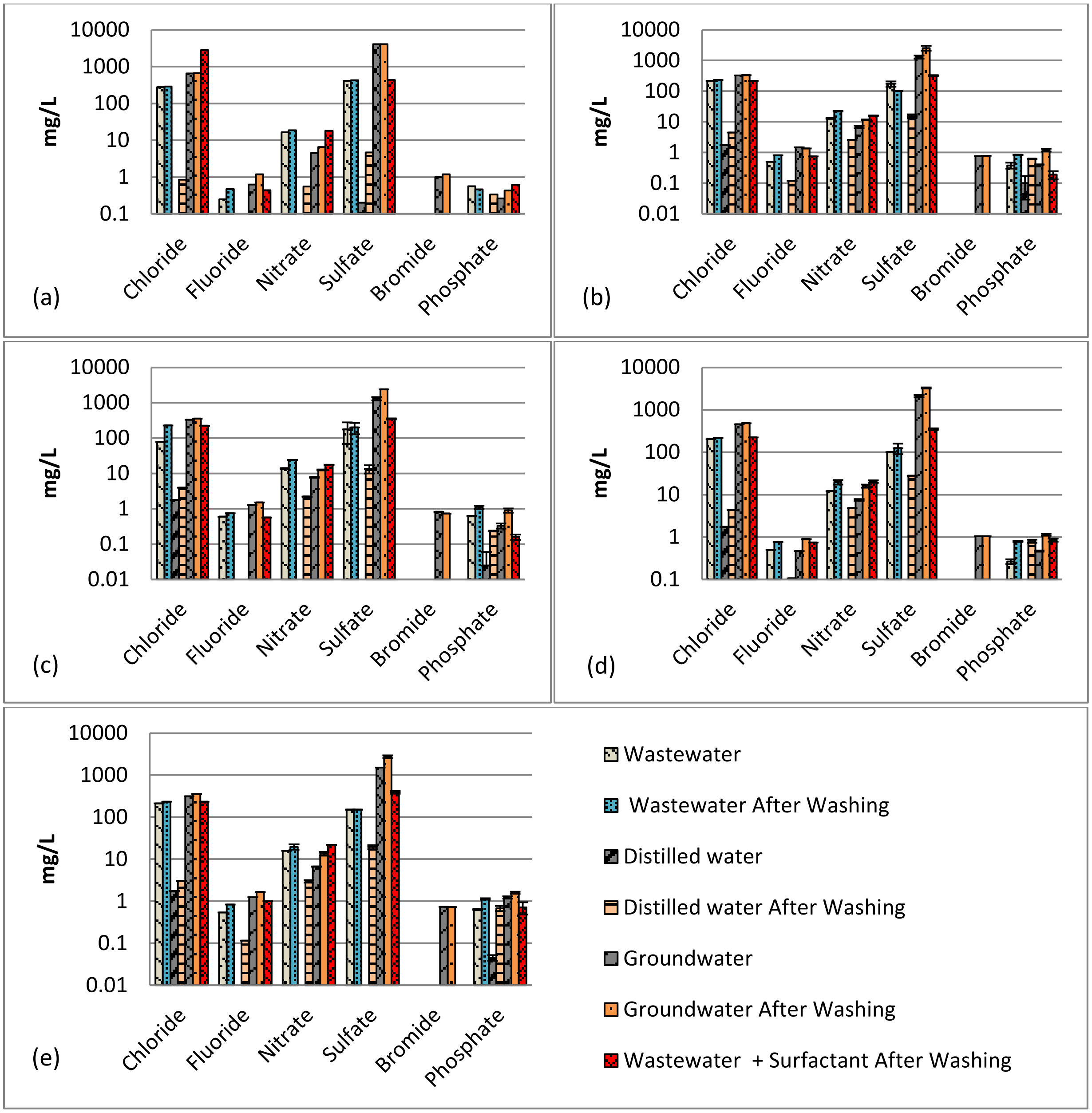


Figure 35. Anions (a) 4th wash (b) 5th wash (c) 6th wash (d) 7th wash (e) 8th wash

The mean anion concentration and the standard deviation for each type of water are shown in Figure 36. The wastewater and groundwater used contain high levels of chloride and sulfate even before washing the solar panels. After washing the panels with treated wastewater and groundwater higher levels of these anions were observed in both types of wash water, except for sulfate that had similar levels in the wastewater.

Bromide was only observed in the groundwater and in similar amounts before and after washing the PV panels. As expected, the distilled water was the wash water with the smaller presence of anions. However, after washing the solar panels with this type of water, significant amounts of fluoride, nitrate, sulfate, and phosphate were observed.

Sylva (2017) studied the same PV panels as mentioned before and his research revealed that the presence of phosphorus may be attributing to the nearby park that may use fertilizers in the area.

Since total phosphate was performed in the fourth wash, it was not included in the mean of orthophosphate (fifth, sixth, seventh, and eight wash) represented in Figure 34.

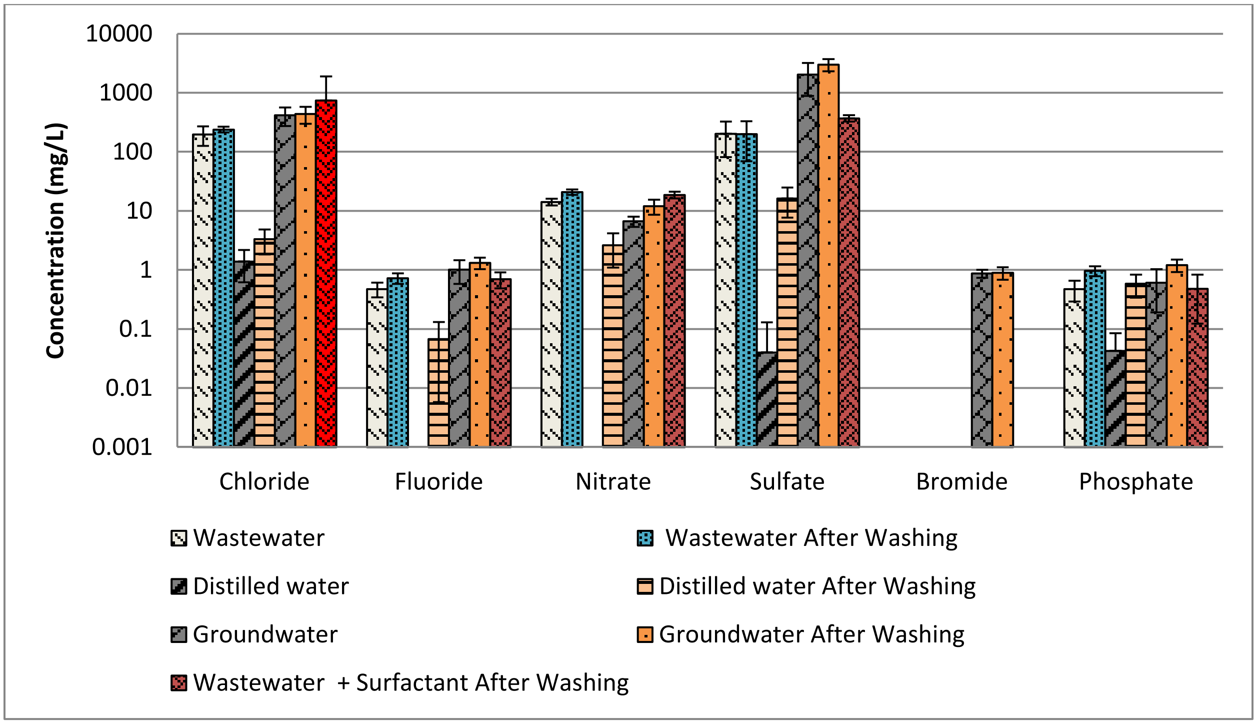


Figure 36. Mean anion concentration (mg/L) for each type of wash water

5.4 Organic Composition of the Dust

GC-MS was used to compare the total ion chromatograms (TIC) (Appendix C) from the second to the eighth wash for each group of panels. Table 19 shows the organic compounds identified on the surface of the solar panels. These organic compounds are related to the local suspended soil and pollen. Furthermore, vaporized cooking oils may have contributed under some circumstances. Same results were revealed by Sylva (2017).

Table 19. Organic compounds identification

Peak	Identification
1	Hexadecanoic acid, methyl ester
2	9-Octadecenoic acid (Z)-, methyl ester
3	Octadecenoic acid, methyl ester
4	Nonadecanoic acid
5	Fatty Acid Methyl Ester Isomers
6	1,6-Octadien-3-ol, 3,7-dimethyl

The presence of the organic 1,6-octadien-3-ol (mostly known as linalool) can be associated with flowers and plants, but also, it can be correlated with cleaning agents, pest controls, and repellents.

The different groups of solar panels presented similar organic compounds. Similarly, the same group of panels presented a similar composition before and after washing the PV panels, which means that even after cleaning the surface of the panels remaining organic compounds can be found.

Chapter 6 – Conclusions, Implications and Recommendation for Further Research

6.1 Conclusion

The objectives of this research were to evaluate the impacts of waters of low quality on solar panel washing; determine if the use of waters of low quality promotes the deposition of any substances on the solar panel surface that can be detrimental to their performance; and to examine the chemical composition of the dust accumulated on the panels of the solar system where the research is being performed. The following conclusions can be drawn from this research:

6.1.1 Regarding the Impact of Water Source on Panel Washing

It was found that accumulation of dust on the solar panels caused an overall decrease of 1.88% in energy generation efficiency. The solar panels did not get as dirty as expected because the solar plant studied is located on a site with compacted soil that is covered with small rocks to abate dust.

Cleaning the solar panels with distilled water was the most effective way to recover the normalized efficiency of the system. During the cleaning schedule period (8 total) the distilled water recovered a mean normalized efficiency of around 1.32%, followed by the treated wastewater (0.92%), treated wastewater with surfactant (0.73%), vacuum cleaner (0.27%), and groundwater (0.24%). The cleaning with treated wastewater alone was more effective when compared with the treated wastewater with surfactant addition.

After starting the cleaning schedule (8 total) the highest normalized mean efficiency was also observed in panels washed with the distilled water (11.79%), followed by the treated wastewater (11.74%), treated wastewater with surfactant (11.72%), vacuum cleaner (11.67%), groundwater (11.66%), and the control group (11.64%). However, the expected efficiency was varying from 14.31 to 14.61%.

For the solar panels studies, even a light rain (0.254 mm) was sufficient to remove most of the soiling accumulated. The removal of bird droppings was the most time consuming part in the cleaning schedule. The vacuum cleaner and the rainfall events were not able to totally remove the bird droppings, which contributed to the low mean normalized solar output efficiency.

Although all set of panels investigated was operating under similar conditions the difference between the power outputs from each group of panels can be also be impacted by differences in manufacturing. The spread in the energy efficiency data can also be attributed to errors in the normalization process and error in each of the measurements.

Although the goal of cleaning was to remove particulates from the panels, some of the water types used contained particulates and contributed to more solids in the resulting wash water. The presence of solids in the water can affect the system efficiency because residues remain on the panels.

6.1.2 Regarding the Accumulation of Dust or Residues on the Surface of the Solar Panels

The dust composition analysis performed by the Scanning Electron Microscopy coupled with an energy dispersive spectrometer (SEM-EDS) and the Thermo iCAP 6300 – ICP-OES Spectrometer revealed that the dust deposited on the surface of the PV panels came from the ground. Furthermore, the City of Las Vegas West Maintenance Yard solar site is located nearby to an urban area and trace of contaminating elements such as zinc, copper, nickel, and chromium can be explained by the light vehicular traffic in this location.

The anions found in the dust composition were chloride, fluoride, nitrate, sulfate, and phosphate. These compounds can be identified in the local soil. Atmospheric pollution can also have contributed for the presence of these compounds. Moreover, the presence of phosphorus may be attributing to the nearby park that may use fertilizers in the area. Bromide was only identified in the groundwater, and was not found in the dust.

Pyrolysis-GC/MS identified that the presence of organic compounds on the surface of the PV panels are related to the local suspended soil and pollen. Furthermore, vaporized cooking oils may have contributed organics under some circumstances.

6.2 Implications

For the photovoltaic plant studied, located in the Las Vegas area, weekly or monthly cleaning is not recommended because the dust deposition on the glass of PV modules did not considerably degrade the performance of the PV system. Furthermore, most of the rain events were enough to keep the solar panels clean. Washing with some types of water, such as reuse water or brackish groundwater, can result in less effective cleaning. However, economic evaluation is needed that relate cost of washing, cost of water, and the energy loss incurred.

This research results indicate that for cleaning PV panels, the use of water with low amounts of solids, such as distilled water, provided for better recovery of the panel capacity. On the other hand, water types with high amounts of solids may promote mineral deposits on the surface of the panels. The dissolved minerals present in the wastewater and principally in the groundwater can negatively impact the performance of the system (power output). Again, cost and sustainability evaluations are needed to determine the pros and cons of washing with water of low quality.

The reuse of water in the washing process should be avoided due to the accumulation of particles in the cleaning water. However, wash water could be treated prior to reuse.

6.3 Recommendations for Future Work

One of the significant findings of this work was the identification of which type of water was better to clean the surface of PV panels and consequently recover the power output. It would be also important to evaluate the costs related to water transportation, water storage, labor work, cleaning time needed, field size, and cleaning materials utilized. After this estimation an economical comparison could be made to determine the price and sustainability of cleaning.

Dust accumulation in the plant studied did not show to have a great effect on the PV system studied. Therefore, more studies are needed in plants located in areas of high dust accumulation. Plants located in industrial areas, with higher traffic, and construction activities should be considered in a comparative study.

This research related the difficulty in removing bird droppings from PV panels. For this reason, investigation is needed on effective methods and potential techniques that can be used to remove bird droppings from solar panels.

It would be also be important to characterize the dust accumulation effects in Concentrating Solar Power systems (CSP). According to the literature, this technology is more affected by the dust, atmospheric pollution, dirt, and bird droppings than the photovoltaic technology.

Appendix A

Daily temperature, power output, and solar insolation data.

	C°			**KWh**				**KWh/m^2**
Day	Temp.	Inverter A	Inverter B	Inverter C	Inverter D	Inverter E	Inverter F	Insolation
June 1, 2016	63	31.32	31.63	31.58	31.23	31.46	31.48	3.92
June 2, 2016	64	30.92	31.41	31.27	31.00	31.12	31.13	3.90
June 3, 2016	65	30.76	31.19	30.95	30.73	30.80	30.83	3.89
June 4, 2016	67	30.37	30.73	30.53	30.27	30.45	30.48	3.87
June 5, 2016	62	31.20	31.58	31.27	31.08	31.21	31.22	3.92
June 6, 2016	64	31.11	31.50	31.20	31.01	31.15	31.13	3.93
June 7, 2016	65	30.05	30.38	30.20	29.93	30.07	30.11	3.79
June 11, 2016	59	30.77	31.24	31.08	30.83	30.92	30.89	3.75
June 14, 2016	54	32.52	32.83	32.46	32.30	32.59	32.51	3.92
June 15, 2016	52	33.03	33.38	32.94	32.73	33.11	33.13	3.95
June 16, 2016	54	32.99	33.45	32.97	32.83	33.12	32.98	4.01
June 17, 2016	54	32.57	32.98	32.59	32.46	32.67	32.56	3.94
June 19, 2016	66	29.92	30.39	30.31	29.99	30.19	30.18	3.81
June 20, 2016	68	29.70	30.10	29.89	29.69	29.79	29.80	3.81
June 22, 2016	62	30.24	30.61	30.36	30.18	30.22	30.22	3.79
June 23, 2016	63	30.51	30.87	30.57	30.24	30.47	30.48	3.84
June 24, 2016	64	29.90	30.38	30.14	29.82	30.01	30.01	3.78
June 25, 2016	64	30.51	30.87	30.66	30.45	30.55	30.58	3.86
June 26, 2016	66	29.86	30.22	30.02	29.72	29.86	29.88	3.79
June 27, 2016	66	29.58	29.87	29.77	29.54	29.65	29.62	3.74
June 29, 2016	65	29.84	30.65	29.98	29.70	29.85	29.84	3.78
July 2, 2016	58	30.81	31.17	31.03	30.79	30.88	30.89	3.65
July 4, 2016	61	30.96	31.35	31.06	30.76	30.96	30.89	3.76
July 5, 2016	59	32.02	32.50	32.11	32.04	32.14	32.10	3.89
July 6, 2016	57	32.19	32.49	32.17	31.98	32.26	32.20	3.84
July 7, 2016	58	31.80	32.20	31.81	31.66	31.83	31.81	3.82
July 8, 2016	59	31.81	32.32	31.91	31.81	31.95	31.88	3.84
July 10, 2016	59	31.62	31.94	31.84	31.45	31.79	31.71	3.80
July 12, 2016	59	31.70	32.08	31.82	31.63	31.76	31.74	3.86
July 13, 2016	63	30.95	31.28	31.07	30.82	30.98	30.99	3.82
July 14, 2016	65	30.45	30.91	30.75	30.40	30.60	30.61	3.79
July 15, 2016	65	30.64	31.03	30.79	30.52	30.67	30.67	3.81
July 16, 2016	59	32.01	32.29	32.05	31.67	32.05	32.02	3.88
July 17, 2016	60	31.48	31.74	31.47	31.01	31.46	31.41	3.81
July 18, 2016	58	31.29	31.64	31.38	31.22	31.36	31.32	3.76
July 19, 2016	60	31.06	31.42	31.12	30.95	31.11	31.05	3.75

July 20, 2016	62	30.79	31.19	30.89	30.56	30.81	30.79	3.76
July 21, 2016	64	29.59	30.29	29.77	29.52	29.59	29.59	3.64
July 22, 2016	66	29.82	30.18	30.02	29.60	29.89	29.84	3.71
July 23, 2016	66	30.05	30.47	30.35	30.12	30.21	30.17	3.76
July 24, 2016	62	28.49	28.78	28.56	28.34	28.51	28.45	3.48
July 25, 2016	62	29.91	30.22	30.04	29.85	29.93	29.90	3.69
July 26, 2016	66	29.13	29.48	29.40	29.10	29.25	29.22	3.62
July 27, 2016	68	28.98	29.36	29.30	28.98	29.14	29.10	3.64
August 1, 2016	59	28.59	28.91	28.72	28.54	28.64	28.62	3.49
August 2, 2016	62	29.54	29.95	29.73	29.62	29.64	29.69	3.63
August 3, 2016	62	29.56	29.88	29.75	29.60	29.66	29.65	3.64
August 5, 2016	59	30.81	31.17	30.98	30.74	30.85	30.88	3.71
August 7, 2016	59	31.93	32.34	31.98	31.75	32.06	32.04	3.87
August 8, 2016	60	31.47	31.76	31.98	31.28	31.54	31.53	3.82
August 9, 2016	57	32.82	33.21	33.02	32.85	32.96	32.40	3.97
August 10, 2016	57	32.10	32.58	32.19	32.09	32.28	32.22	3.85
August 11, 2016	62	31.36	31.80	31.59	31.37	31.57	31.55	3.85
August 12, 2016	65	30.99	31.40	31.25	30.93	31.16	31.18	3.86
August 13, 2016	68	30.76	31.10	31.09	30.80	30.96	30.94	3.87
August 14, 2016	66	30.73	31.26	31.06	30.79	30.90	30.90	3.87
August 15, 2016	62	31.78	32.00	31.95	31.48	31.85	31.76	3.89
August 16, 2016	63	32.02	32.38	32.14	31.90	32.10	32.13	3.98
August 23, 2016	56	31.59	31.99	31.81	31.53	31.64	31.64	3.73
August 24, 2016	63	30.53	30.94	30.77	30.42	30.68	30.72	3.74
August 25, 2016	59	31.63	31.99	31.75	31.56	31.85	31.82	3.82
August 28, 2016	60	31.78	32.26	237.36	31.95	32.04	32.06	3.84
August 29, 2016	66	30.98	31.39	31.34	30.93	31.23	31.23	3.85
August 30, 2016	65	31.12	31.50	31.39	31.16	31.25	31.27	3.86
September 2, 2016	59	32.16	32.53	32.32	32.36	32.55	32.29	3.89
September 3, 2016	60	32.87	33.23	33.09	32.76	33.07	33.01	3.99
September 4, 2016	56	32.75	33.26	32.98	32.83	32.95	32.89	3.92
September 5, 2016	60	32.84	33.28	33.11	32.88	33.03	33.42	4.01
September 6, 2016	60	33.00	33.49	33.35	33.10	33.19	33.24	4.06
September 7, 2016	62	32.33	32.79	32.61	32.32	32.54	32.56	3.98
September 8, 2016	62	31.44	31.85	31.77	31.51	31.67	31.70	3.86
September 9, 2016	63	31.35	31.86	31.70	31.48	31.61	31.64	3.87
September 11, 2016	63	32.32	32.65	32.54	32.25	32.50	32.51	4.00
September 13, 2016	49	34.72	35.18	34.77	34.66	34.97	34.95	4.01
September 14, 2016	58	33.16	33.76	33.71	33.42	33.58	33.56	4.00
September 15, 2016	60	32.88	33.33	33.27	32.99	33.19	33.21	4.00
September 16, 2016	62	32.47	32.95	32.88	32.50	32.71	32.82	3.98

September 17, 2016	63	32.25	32.70	32.59	32.29	32.49	32.53	3.98
September 18, 2016	63	32.42	32.88	32.77	32.50	32.64	32.68	4.04
September 22, 2016	48	34.69	34.95	34.73	34.44	34.82	34.79	3.99
September 23, 2016	45	35.33	35.97	36.01	35.70	35.97	35.97	4.01
September 26, 2016	61	32.25	32.75	32.65	32.38	32.62	32.61	3.92
September 27, 2016	60	32.15	32.57	32.46	32.23	32.40	32.42	3.90
September 29, 2016	57	32.17	32.67	32.47	32.29	31.63	32.38	3.85
September 30, 2016	58	31.86	32.25	32.12	31.87	31.99	32.00	3.81
October 2, 2016	51	34.44	34.66	34.50	34.13	34.59	34.62	4.00
October 4, 2016	54	33.31	33.89	33.77	33.48	33.66	33.65	3.91
October 5, 2016	55	33.15	33.92	33.97	33.63	33.89	33.88	3.95
October 6, 2016	53	33.61	34.43	34.59	34.24	34.47	34.46	3.95
October 9, 2016	56	31.73	32.33	32.25	32.03	32.08	32.12	3.78
October 11, 2016	58	31.83	32.48	32.44	32.11	32.32	29.76	3.82
October 15, 2016	49	32.97	33.59	33.27	33.02	33.33	33.35	3.76
October 17, 2016	53	31.86	32.71	32.76	32.56	32.67	32.67	3.70
October 18, 2016	55	31.71	32.26	32.30	31.98	32.26	32.16	3.73
October 19, 2016	49	33.57	34.39	34.51	34.21	34.38	34.37	3.84
October 21, 2016	53	32.48	33.18	32.86	32.63	32.74	32.72	3.79
October 22, 2016	55	31.88	32.50	32.35	32.11	2105.98	32.24	3.78
October 26, 2016	53	31.64	32.11	31.99	31.85	31.97	31.95	3.67
October 31, 2016	49	32.31	32.96	33.04	32.87	33.00	33.01	3.69
December 3, 2016	31	32.66	33.23	33.51	33.06	33.16	33.10	3.47
December 4, 2016	40	30.95	31.28	31.18	30.93	31.04	31.03	3.37
December 17, 2016	24	34.09	34.59	34.59	34.31	34.52	34.55	3.53
December 18, 2016	28	33.63	34.18	34.18	33.91	34.09	34.07	3.49
December 19, 2016	36	32.59	33.03	33.01	32.70	32.90	32.84	3.48
December 20, 2016	39	32.21	32.57	32.46	32.13	32.29	32.27	3.47
December 27, 2016	34	31.76	32.22	32.24	32.02	32.18	32.13	3.32
December 28, 2016	38	31.51	31.84	31.78	31.46	31.64	31.63	3.34
December 29, 2016	41	31.28	31.74	31.67	31.36	31.54	31.53	3.34
January 1, 2017	39	30.95	31.26	31.18	30.96	31.04	31.01	3.26
January 6, 2017	30	33.27	33.68	33.58	33.38	33.48	33.49	3.47
January 11, 2017	33	33.60	33.84	33.76	33.40	33.68	33.62	3.46
January 15, 2017	34	32.88	33.38	33.37	33.12	33.22	33.18	3.40
January 16, 2017	30	34.50	35.07	35.05	34.72	34.97	35.03	3.53
January 17, 2017	37	33.65	34.15	34.15	33.93	34.01	33.98	3.52
January 21, 2017	33	34.45	34.94	34.94	34.53	34.88	34.89	3.52
January 24, 2017	29	35.54	36.08	36.11	35.74	36.07	36.07	3.60
January 25, 2017	31	35.40	36.05	36.01	35.64	35.94	35.95	3.61
January 26, 2017	37	34.09	34.52	34.52	34.21	34.40	34.38	3.56

January 27, 2017	26	36.04	36.59	36.57	36.22	36.52	36.57	3.63
January 28, 2017	36	34.52	35.02	34.99	34.75	34.85	34.82	3.62
January 29, 2017	42	33.55	33.91	33.82	33.41	33.66	33.67	3.58
February 1, 2017	41	33.55	33.96	33.88	33.68	33.75	33.78	3.59
February 14, 2017	43	34.70	35.33	35.39	35.16	35.28	35.23	3.76
February 15, 2017	46	34.19	34.74	34.74	34.37	34.46	34.52	3.75
February 22, 2017	45	35.89	36.33	36.32	35.94	36.24	36.35	3.85
February 24, 2017	35	36.41	36.86	37.38	37.17	36.92	36.80	3.94
February 26, 2017	41	36.01	36.38	36.21	36.12	36.12	36.08	3.86
February 28, 2017	36	37.67	38.30	38.35	38.10	38.34	38.34	3.98
March 1, 2017	42	36.36	36.85	36.84	36.67	36.75	36.73	3.96
March 2, 2017	48	35.50	36.09	36.01	35.77	35.94	35.95	3.97
March 3, 2017	47	35.80	36.20	36.06	35.87	35.91	35.92	4.00
March 4, 2017	41	32.07	32.21	31.98	32.01	32.24	32.16	3.47
March 5, 2017	35	37.88	37.81	37.71	37.38	37.68	37.69	3.86
March 6, 2017	42	36.68	37.20	37.10	36.86	36.91	36.96	3.99
March 7, 2017	46	35.77	36.17	35.97	35.73	35.78	35.83	3.90
March 8, 2017	49	32.05	32.49	32.37	32.18	32.28	32.38	3.65
March 9, 2017	54	33.77	34.26	34.18	33.86	34.07	33.32	3.88
March 11, 2017	52	33.35	33.84	33.78	33.53	33.63	33.72	3.85
March 12, 2017	53	32.10	32.58	32.45	32.31	32.41	32.52	3.76
March 13, 2017	56	32.63	33.05	32.91	32.54	32.74	32.82	3.85
March 14, 2017	56	33.26	33.71	33.58	33.29	33.42	33.51	3.95
March 17, 2017	55	32.83	33.23	33.04	32.85	32.86	32.96	3.85
March 18, 2017	55	31.96	32.40	32.22	32.12	32.08	32.17	3.78
March 24, 2017	48	34.96	35.44	35.20	35.05	34.98	35.10	3.96
March 28, 2017	38	37.47	37.89	37.76	37.48	37.83	37.94	4.09
April 2, 2017	55	33.46	33.97	33.69	33.54	33.59	33.85	3.98
April 8, 2017	40	37.20	37.46	37.25	36.84	37.22	37.04	4.14
April 9, 2017	45	33.43	33.90	33.65	33.65	33.85	33.66	3.80
April 10, 2017	52	35.24	35.81	35.62	35.52	35.56	35.61	4.15
April 12, 2017	52	34.89	35.31	35.03	35.06	35.16	35.13	4.07
April 13, 2017	45	36.44	36.69	36.40	36.01	36.44	36.30	4.13
April 14, 2017	50	35.04	35.63	35.46	35.33	35.47	35.41	4.05
April 15, 2017	53	34.84	35.26	35.24	35.11	34.91	35.03	4.09
April 18, 2017	49	35.35	35.71	35.50	35.14	35.45	35.29	4.02
April 19, 2017	54	34.36	34.94	34.88	34.62	34.89	34.81	4.04
April 20, 2017	53	34.68	35.28	35.22	34.88	35.21	35.25	4.07
April 21, 2017	45	35.64	36.31	36.24	35.87	36.17	36.06	4.04
April 22, 2017	54	34.42	34.86	34.54	34.36	34.50	34.57	4.07
April 28, 2017	41	37.13	37.75	37.66	37.26	37.63	37.48	4.15

April 29, 2017	43	36.75	37.29	37.23	36.79	37.17	2.28	4.12
April 30, 2017	54	34.42	34.85	34.53	34.28	34.46	34.56	4.05
May 1, 2017	51	34.68	35.50	35.45	35.04	35.38	35.29	4.03
May 2, 2017	58	33.12	33.56	33.44	33.17	33.37	33.27	3.96
May 3, 2017	59	32.76	33.25	33.03	32.75	32.93	32.90	3.93
May 4, 2017	63	32.48	32.97	32.86	32.42	32.73	32.71	3.97
May 9, 2017	50	33.90	34.41	34.01	34.02	34.05	34.00	3.89
May 10, 2017	49	32.60	33.16	32.73	32.71	32.78	32.75	3.71
May 11, 2017	54	32.80	33.28	32.97	32.86	32.94	32.96	3.83
May 12, 2017	52	34.17	34.66	34.13	34.10	34.36	34.29	3.98
May 13, 2017	52	34.48	35.00	34.84	34.50	34.86	34.82	4.02
May 14, 2017	48	35.46	35.91	35.45	35.15	35.64	35.53	4.09
May 16, 2017	51	33.39	33.92	33.47	33.47	33.61	33.61	3.87
May 18, 2017	50	34.61	35.30	35.09	35.02	35.08	34.94	3.99
May 19, 2017	52	33.92	34.58	34.20	34.17	34.21	34.21	3.94
May 20, 2017	57	32.86	33.33	33.02	32.85	33.00	33.02	3.89
May 21, 2017	60	31.98	32.40	32.12	31.95	32.13	32.14	3.86
May 23, 2017	62	31.60	31.92	32.13	31.55	31.68	31.70	3.85
May 25, 2017	57	32.37	32.73	32.55	32.34	32.52	32.39	3.86
May 26, 2017	57	32.59	32.94	32.65	32.44	32.65	32.47	3.87
May 27, 2017	58	32.10	32.58	32.37	32.18	32.36	32.23	3.83
May 28, 2017	60	32.10	32.47	32.22	31.95	32.16	31.99	3.88
May 29, 2017	61	31.56	31.93	31.78	31.57	31.75	31.57	3.84
June 1, 2017	55	32.32	32.66	32.34	32.27	32.36	32.25	3.80
June 2, 2017	62	31.24	31.64	31.33	31.13	31.34	31.26	3.79
June 3, 2017	62	30.54	30.82	30.64	30.46	30.52	30.44	3.73
June 4, 2017	59	31.45	31.63	31.42	31.09	31.43	31.29	3.76
June 5, 2017	60	31.80	32.12	31.72	31.50	31.82	31.70	3.84
June 6, 2017	60	30.82	31.15	30.91	30.79	30.86	30.76	3.74
June 7, 2017	59	31.53	30.51	31.58	31.54	31.56	31.44	3.83
June 9, 2017	51	33.04	33.19	32.89	32.63	33.06	32.92	3.80
June 11, 2017	48	34.08	34.39	33.98	33.83	34.11	33.89	3.87
June 12, 2017	52	33.13	33.55	33.22	32.98	33.24	33.15	3.83
June 13, 2017	57	32.29	32.72	32.56	32.24	32.50	32.37	3.83
June 14, 2017	60	31.69	32.04	31.84	31.61	31.76	31.67	3.83
June 15, 2017	63	31.10	31.47	31.14	30.98	31.08	31.05	3.81
June 16, 2017	66	30.71	31.12	30.81	30.55	30.77	30.70	3.80
June 17, 2017	66	30.40	30.72	30.29	30.12	30.34	30.23	3.73
June 18, 2017	67	29.61	30.00	29.75	29.60	29.83	29.73	3.64
June 19, 2017	69	29.28	29.59	29.15	29.10	29.30	29.22	3.62
June 20, 2017	68	29.24	29.58	29.14	29.05	29.18	29.11	3.62

June 21, 2017	63	30.57	30.88	30.36	30.37	30.51	30.43	3.72
June 22, 2017	69	30.10	30.39	29.91	29.84	30.03	29.97	3.74
June 23, 2017	67	29.62	29.98	29.62	29.45	29.63	29.59	3.66
June 25, 2017	65	30.14	30.47	30.09	30.01	30.08	30.04	3.70
June 26, 2017	59	32.06	32.26	31.85	31.61	31.97	31.86	3.85
June 27, 2017	65	30.64	30.91	30.59	30.37	30.59	30.58	3.74
June 28, 2017	64	30.94	31.32	30.91	30.81	30.95	30.94	3.78
June 29, 2017	64	30.81	31.13	30.82	30.63	30.77	30.77	3.78
June 30, 2017	65	30.49	30.75	30.50	30.30	30.50	30.49	3.73
July 1, 2017	64	30.31	30.74	30.36	30.31	30.34	30.33	3.72
July 2, 2017	59	30.81	31.09	30.78	30.74	30.74	30.69	3.68
July 3, 2017	63	30.89	31.18	30.73	30.67	30.78	30.78	3.74
July 4, 2017	65	30.93	31.39	31.07	30.98	31.06	31.05	3.82
July 6, 2017	68	29.20	29.49	29.23	29.08	29.20	29.19	3.61
July 7, 2017	69	28.04	28.26	27.99	27.81	28.02	27.97	3.48
July 12, 2017	64	29.14	29.51	29.25	29.20	29.25	29.32	3.55
July 13, 2017	64	29.58	29.88	29.52	29.48	29.49	29.55	3.60
July 14, 2017	66	29.46	29.81	29.46	29.39	29.47	29.53	3.62
July 15, 2017	67	29.22	29.47	29.19	29.11	29.15	29.20	3.61
July 16, 2017	64	28.96	29.29	28.92	28.89	28.89	28.95	3.53
July 18, 2017	61	29.58	29.82	29.61	29.56	29.58	29.54	3.58
July 21, 2017	62	30.34	30.68	30.33	30.21	30.30	30.28	3.66
July 22, 2017	66	29.91	30.27	30.01	29.76	29.92	29.88	3.69
July 23, 2017	66	29.84	30.10	29.83	219.23	29.79	29.76	3.66
July 26, 2017	60	30.48	30.88	30.63	30.46	30.55	30.51	3.66
July 27, 2017	64	30.09	30.44	30.20	29.96	30.13	30.11	3.68
July 28, 2017	64	30.45	30.84	30.56	30.41	30.45	28.70	3.72
July 29, 2017	64	30.10	30.37	30.23	30.01	30.13	30.14	3.66
August 1, 2017	67	29.81	30.05	29.75	29.54	29.78	29.75	3.68
August 2, 2017	65	29.88	30.26	30.01	29.74	29.96	29.95	3.65
August 5, 2017	60	30.66	31.05	31.48	30.57	30.68	30.68	3.66
August 6, 2017	63	30.63	31.01	30.81	30.60	30.77	30.77	3.70
August 8, 2017	63	31.28	31.67	31.43	31.19	31.36	31.36	3.80
August 9, 2017	63	31.21	31.59	31.30	31.14	31.25	31.27	3.79
August 10, 2017	62	31.43	31.73	31.47	31.35	31.42	31.39	3.79
August 12, 2017	63	31.21	31.59	31.27	31.12	31.22	31.19	3.79
August 13, 2017	60	32.33	32.67	32.25	32.18	32.38	32.31	3.87
August 14, 2017	56	33.43	33.89	33.36	33.42	33.59	33.47	3.94
August 15, 2017	59	32.01	32.48	32.40	32.19	32.37	32.30	3.80
August 16, 2017	62	31.76	32.11	31.94	31.78	31.93	31.92	3.83
August 17, 2017	64	31.35	31.75	31.50	31.28	31.46	31.45	3.81

August 18, 2017	65	31.32	31.79	31.50	31.20	31.44	31.40	3.83
August 19, 2017	62	32.09	32.41	32.20	31.97	32.12	32.11	3.89
August 20, 2017	61	31.98	32.40	32.13	32.06	32.06	32.03	3.86
August 22, 2017	63	31.85	32.18	31.96	31.66	31.90	31.90	3.85
August 25, 2017	64	31.56	31.96	31.78	31.48	31.70	31.70	3.82
August 26, 2017	67	31.22	31.63	31.44	31.13	31.37	31.36	3.85
August 28, 2017	67	30.93	31.39	31.20	30.95	31.16	31.15	3.81
August 30, 2017	60	32.07	32.62	32.54	32.15	32.60	32.56	3.84
September 1, 2017	65	31.11	31.61	31.54	31.27	31.51	31.46	3.80
September 2, 2017	66	30.80	31.17	30.97	30.83	30.92	30.89	3.78
September 10, 2017	61	31.94	32.33	32.23	32.09	32.21	32.20	3.81
September 11, 2017	64	31.36	31.74	31.59	31.40	31.50	31.50	3.81
September 14, 2017	58	33.36	33.76	33.59	33.35	33.54	33.52	3.96
September 15, 2017	59	32.43	32.79	32.61	32.46	32.71	32.61	3.84
September 16, 2017	58	32.83	33.21	33.13	32.98	33.21	33.08	3.87
September 17, 2017	59	32.77	33.15	32.95	32.90	33.01	32.91	3.90
September 18, 2017	55	33.58	33.98	33.68	33.63	33.80	33.64	3.92
September 20, 2017	56	33.46	33.84	33.59	33.41	33.59	33.52	3.91
September 21, 2017	47	35.23	35.40	35.17	34.85	35.19	35.17	3.94
September 22, 2017	51	34.92	35.60	35.50	35.15	35.52	35.54	4.00
September 24, 2017	49	35.65	36.37	36.41	36.16	36.34	36.37	4.06
September 25, 2017	50	35.13	35.78	35.86	35.60	35.76	35.80	4.01
September 27, 2017	54	33.68	34.24	34.28	34.03	34.21	34.18	3.92
September 28, 2017	57	33.22	33.61	33.45	33.20	33.27	33.40	3.90
September 29, 2017	59	32.49	32.82	32.78	32.56	32.67	32.71	3.87
September 30, 2017	55	33.33	33.59	33.42	33.08	33.38	33.39	3.89
October 1, 2017	60	32.31	32.55	32.41	32.10	32.37	32.44	3.85
October 2, 2017	47	35.57	36.16	36.13	35.84	36.07	36.22	4.03
October 3, 2017	50	34.58	35.10	34.83	34.84	34.74	34.84	3.96
October 4, 2017	52	33.83	34.28	34.36	34.15	34.29	34.36	3.93
October 5, 2017	56	33.54	33.98	33.96	33.67	33.88	33.95	3.95
October 6, 2017	52	34.52	35.27	35.34	34.97	35.15	35.35	3.99
October 7, 2017	59	33.32	33.65	33.65	33.39	33.47	33.60	3.98
October 8, 2017	58	32.94	33.33	33.16	32.86	32.98	33.12	3.92
October 9, 2017	46	35.87	36.44	36.47	36.20	36.28	36.49	4.05
October 10, 2017	51	34.60	35.12	35.01	34.82	34.78	34.96	4.00
October 11, 2017	51	34.07	34.63	34.50	34.33	34.21	34.37	3.94
October 12, 2017	53	33.05	33.63	33.71	33.58	33.59	33.69	3.85
October 13, 2017	55	32.89	33.14	33.08	32.89	32.92	33.04	3.87
October 14, 2017	43	35.67	36.16	36.18	35.87	35.98	36.26	3.99
October 15, 2017	54	33.95	34.39	34.39	34.09	34.18	34.41	3.99

October 16, 2017	57	33.00	33.25	33.21	32.92	33.01	33.21	3.93
October 17, 2017	57	32.24	32.61	32.51	32.28	32.29	32.50	3.84
October 19, 2017	55	31.93	32.26	32.20	32.00	31.95	32.16	3.74
October 21, 2017	47	34.58	35.07	34.93	34.91	34.84	34.96	3.86
October 22, 2017	56	32.58	32.97	32.77	32.68	32.74	32.79	3.77
October 23, 2017	52	32.79	33.54	33.38	33.31	33.39	33.49	3.74
October 24, 2017	52	33.11	33.74	33.65	33.71	33.69	33.77	3.80
October 25, 2017	56	31.95	32.26	32.09	31.97	32.06	32.11	3.73
October 26, 2017	57	32.06	32.42	32.17	32.05	32.14	32.24	3.76
October 27, 2017	53	32.41	32.95	32.71	32.73	32.69	32.79	3.74
October 28, 2017	56	31.65	32.05	31.90	31.79	31.90	31.95	3.68
October 29, 2017	54	31.83	32.22	31.95	31.86	31.86	32.00	3.68
October 31, 2017	51	31.54	31.87	31.64	31.65	31.59	31.71	3.58
November 1, 2017	50	31.05	31.43	31.21	31.21	31.21	31.33	3.50
November 2, 2017	46	32.00	32.27	32.02	32.10	32.02	32.12	3.56
November 4, 2017	43	33.24	33.43	32.89	33.13	33.28	33.37	3.60
November 5, 2017	49	31.37	31.77	31.53	31.64	31.73	31.80	3.59
November 7, 2017	50	31.44	31.77	31.53	31.62	31.68	31.79	3.64
November 8, 2017	45	32.01	32.37	32.01	32.17	32.10	32.26	3.64
November 9, 2017	45	31.91	32.22	31.88	32.07	31.97	32.10	3.61
November 10, 2017	49	31.22	31.50	31.25	31.35	31.41	31.55	3.60
November 11, 2017	49	30.93	31.24	31.00	31.07	31.12	31.28	3.60
November 18, 2017	43	32.66	32.90	32.50	32.69	32.68	32.79	3.68
November 19, 2017	45	32.28	32.47	32.01	32.17	32.19	32.30	3.65
November 22, 2017	52	29.35	29.52	29.15	29.23	29.42	29.51	3.39
November 23, 2017	52	28.90	29.17	28.76	28.82	29.07	29.07	3.42
November 25, 2017	48	29.36	29.53	29.10	29.26	29.33	29.32	3.36
November 26, 2017	48	29.61	29.85	29.31	29.53	29.63	29.67	3.39
November 28, 2017	41	31.31	31.46	31.12	31.20	31.14	31.39	3.48
November 29, 2017	45	30.41	30.54	30.23	30.35	30.28	30.56	3.40
December 1, 2017	45	30.06	30.19	29.90	29.92	29.98	30.12	3.35
December 2, 2017	42	29.39	29.44	28.97	29.37	29.29	29.33	3.30
December 5, 2017	30	33.25	33.48	33.19	33.32	33.44	33.61	3.53
December 6, 2017	33	32.34	32.56	32.29	32.42	32.50	32.65	3.44
December 7, 2017	38	32.10	32.34	32.07	32.25	32.23	31.83	3.45

Appendix B

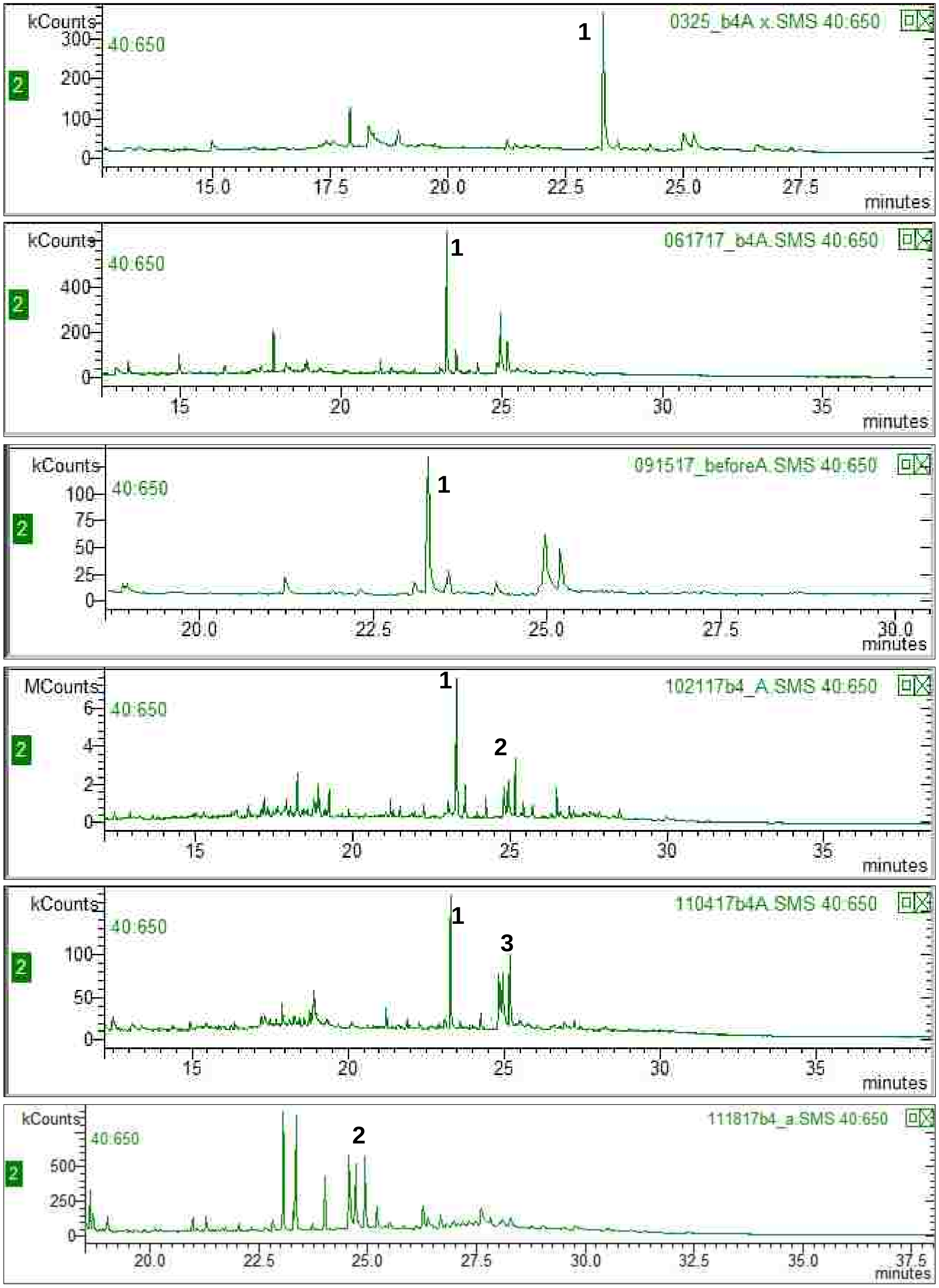
List of rainy days and cleaning schedule.

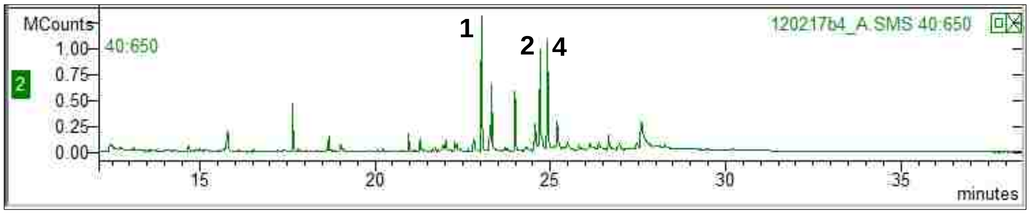
Date	**Event**	**Classification (mm)**
11-Jun-16	Rain	0.76
1-Jul-16	Rain	2.79
2-Jul-16	Rain	0.76
29-Jul-16	Rain	0.25
3-Aug-16	Rain	0.25
22-Aug-16	Rain	5.08
23-Aug-16	Rain	0.25
27-Aug-16	Rain	2.54
4-Sep-16	Rain	19.89
23-Oct-16	Rain	0.50
24-Oct-16	Rain	3.55
16-Dec-16	Rain	1.52
22-Dec-16	Rain	10.41
24-Dec-16	Rain	7.62
1-Jan-17	Rain	0.25
12-Jan-17	Rain	2.29
13-Jan-17	Rain	2.79
20-Jan-17	Rain	8.38
22-Jan-17	Rain	19.3
23-Jan-17	Rain	1.78
11-Feb-17	Rain	6.09
17-Feb-17	Rain	1.52
18-Feb-17	Rain	19.81
24-Feb-17	Cleaning	NA
25-Mar-17	Cleaning	NA
3-Apr-17	Rain	4.06
7-May-17	Rain	0.25
17-Jun-17	Cleaning	NA
4-Aug-17	Rain	1.77
5-Aug-17	Rain	1.52
21-Aug-17	Rain	0.50
24-Aug-17	Rain	6.35
30-Aug-17	Rain	0.25
7-Sep-17	Rain	0.25
8-Sep-17	Rain	5.33
9-Sep-17	Rain	1.01
13-Sep-17	Rain	0.5

15-Sep-17	Cleaning	NA
21-Oct-17	Cleaning	NA
4-Nov-17	Cleaning	NA
18-Nov-17	Cleaning	NA
2-Dec-17	Cleaning	NA

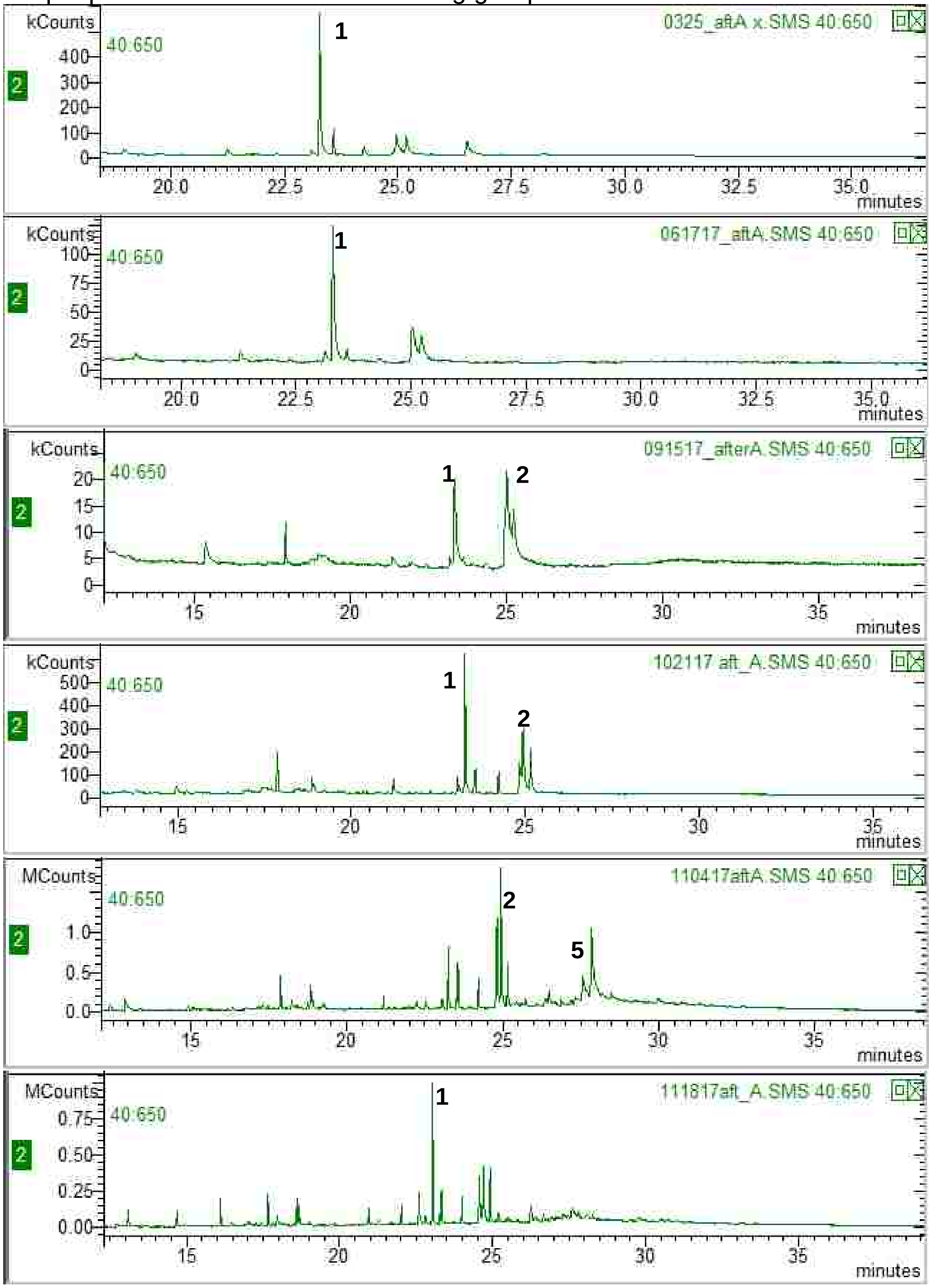
Appendix C

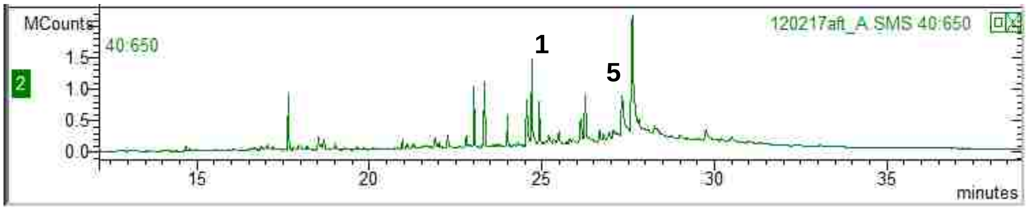
GC/MS sample peak identification before washing group A



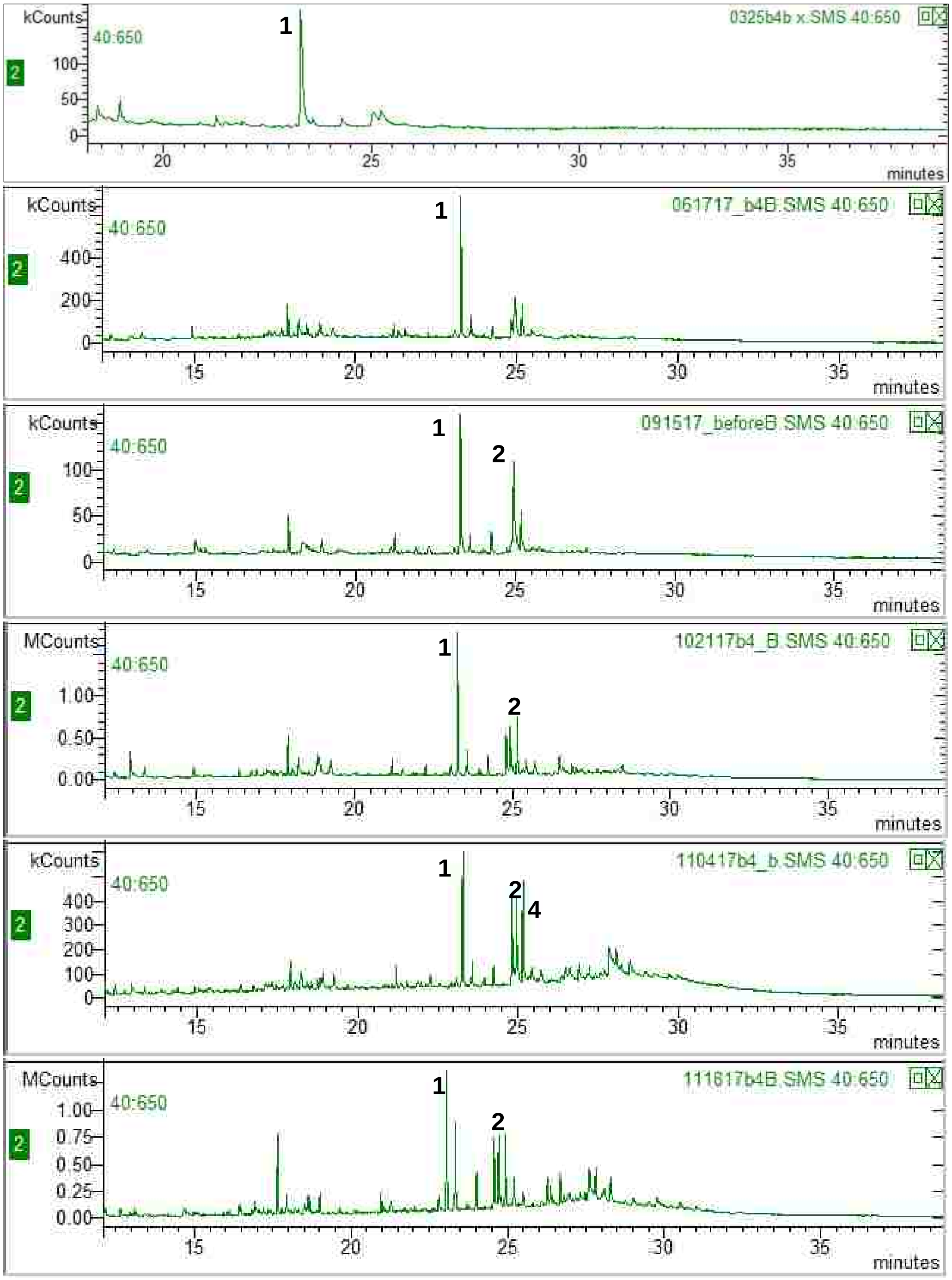


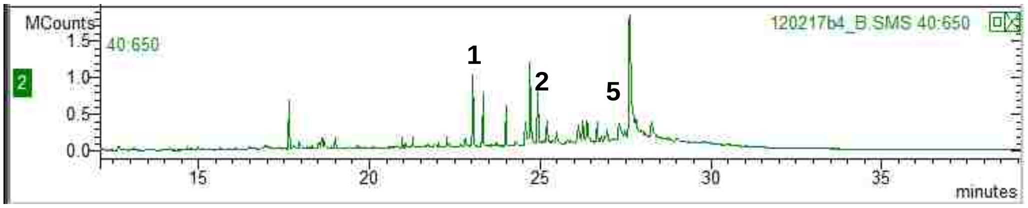
GC/MS sample peak identification after washing group A



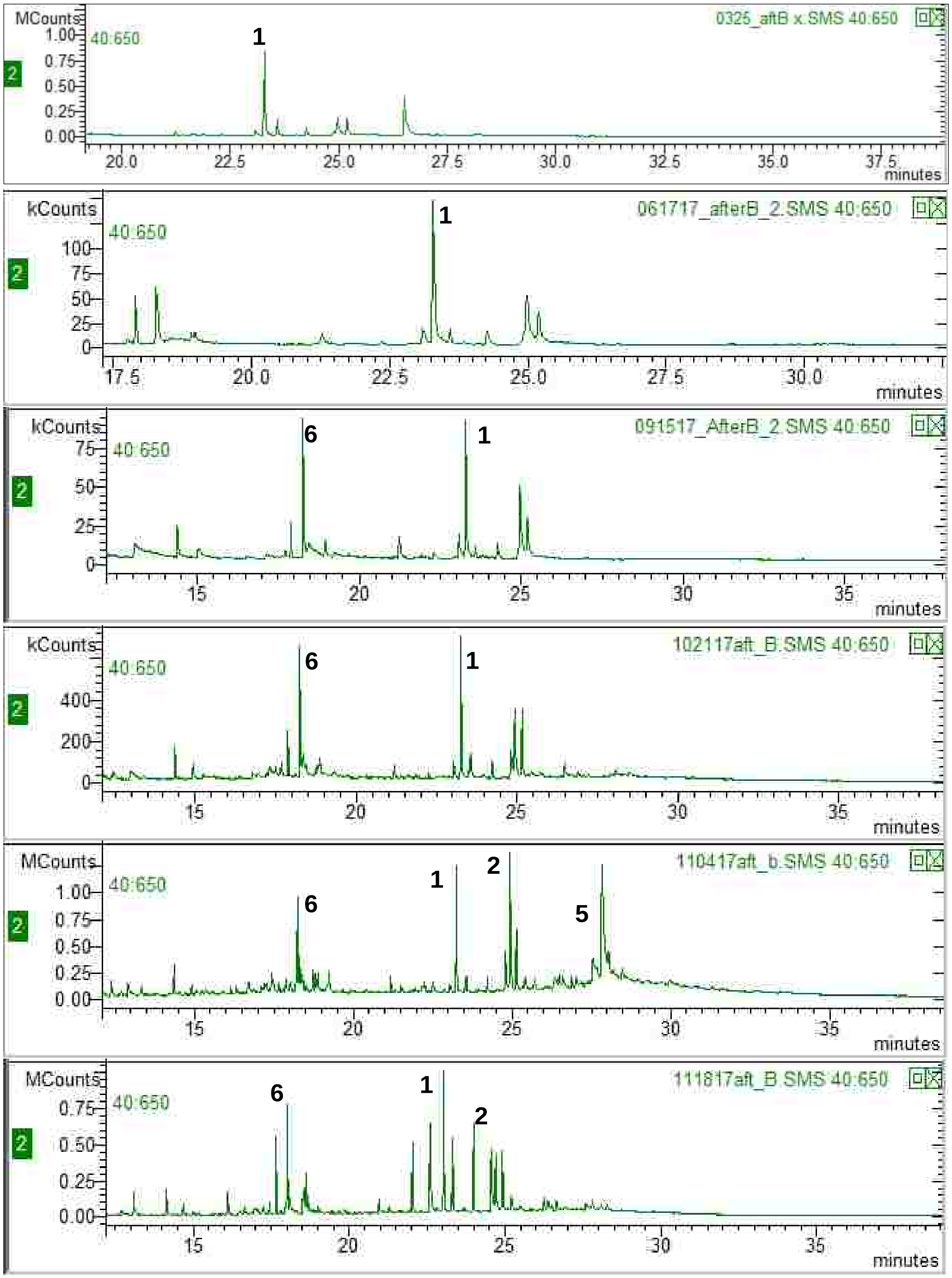


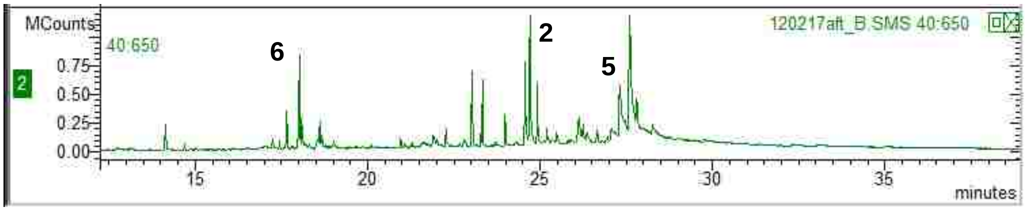
GC/MS sample peak identification before washing group B



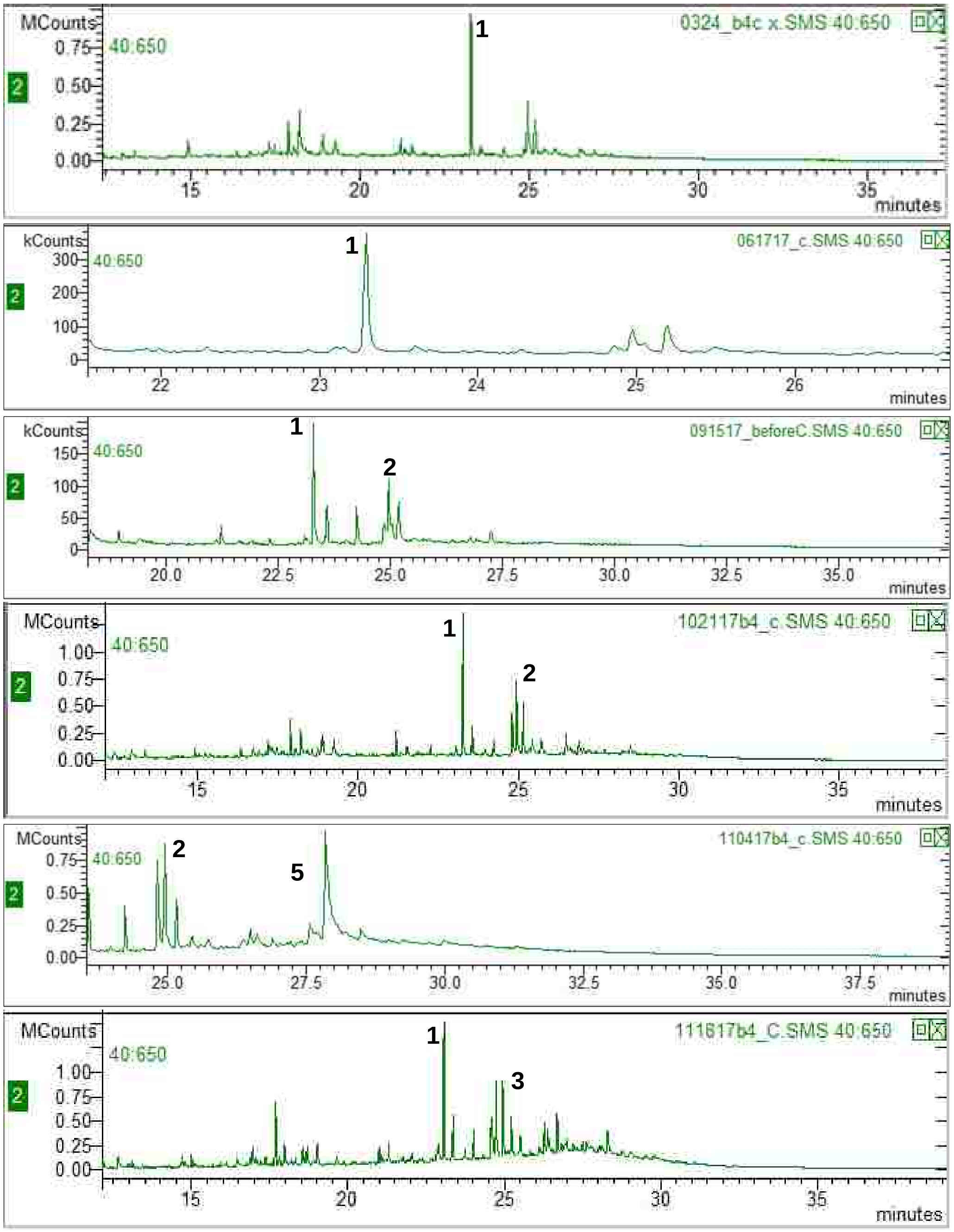


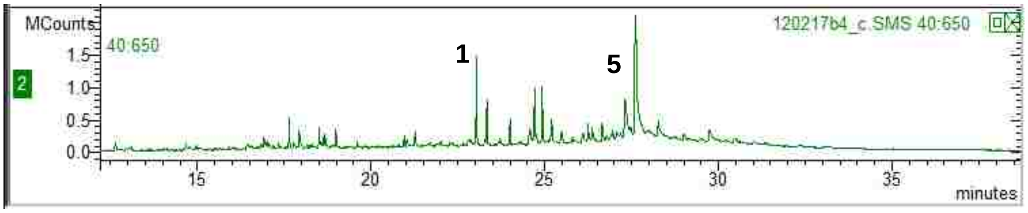
GC/MS sample peak identification after washing group B



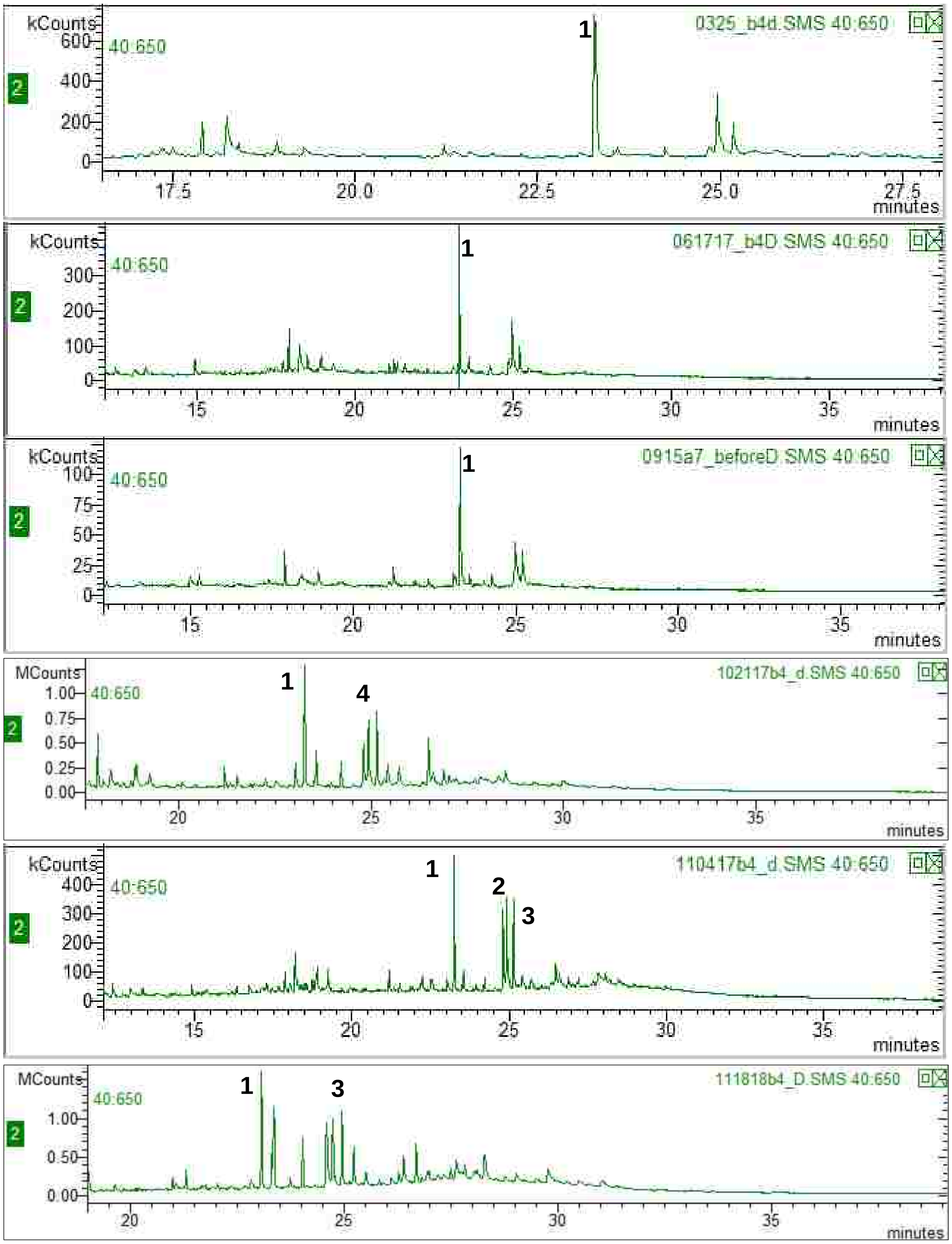


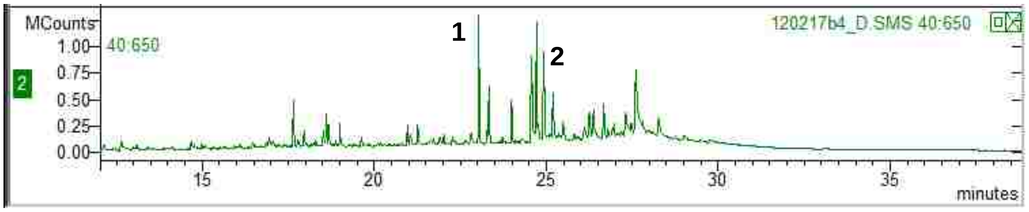
GC/MS sample peak identification for the control group C



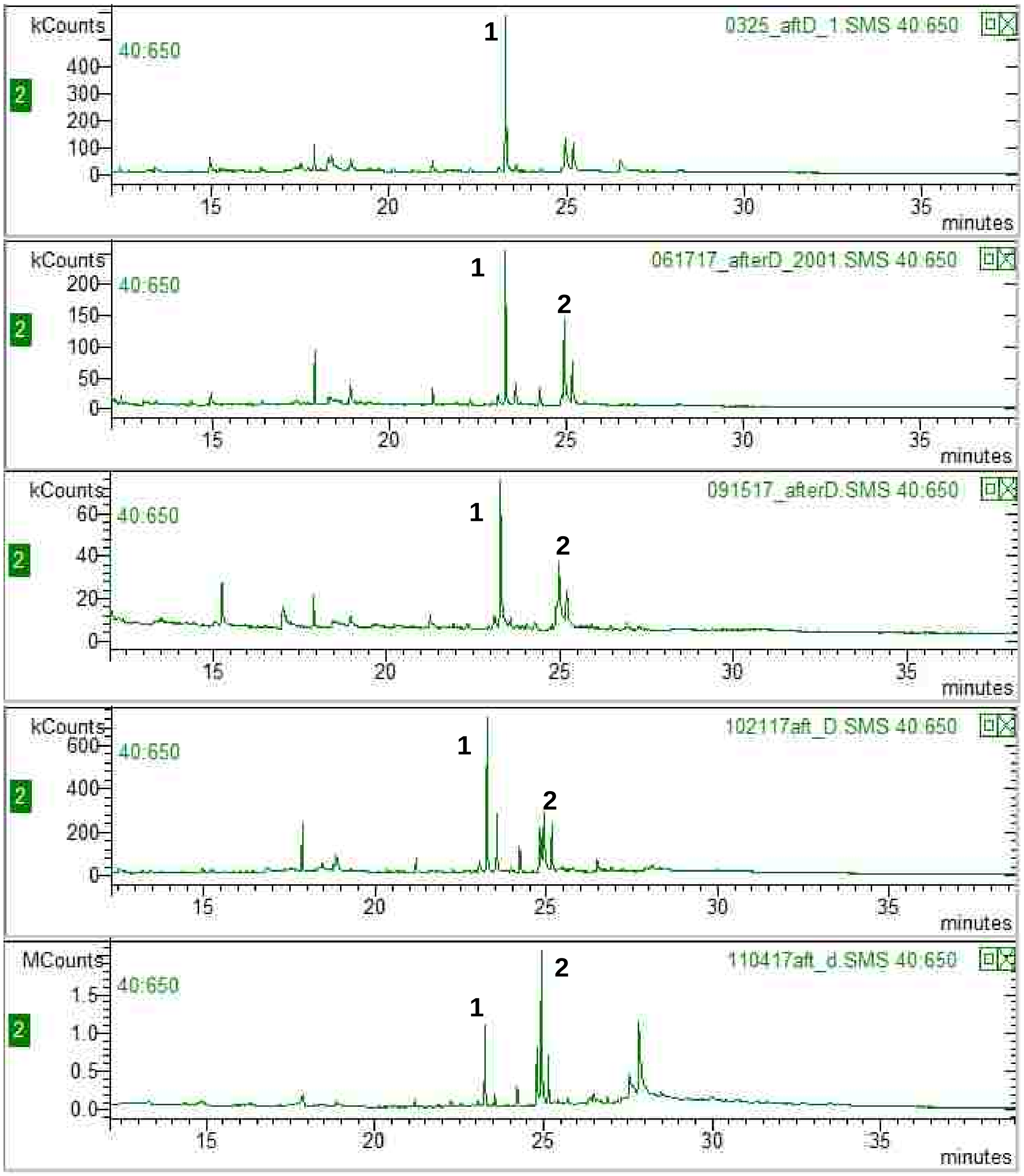


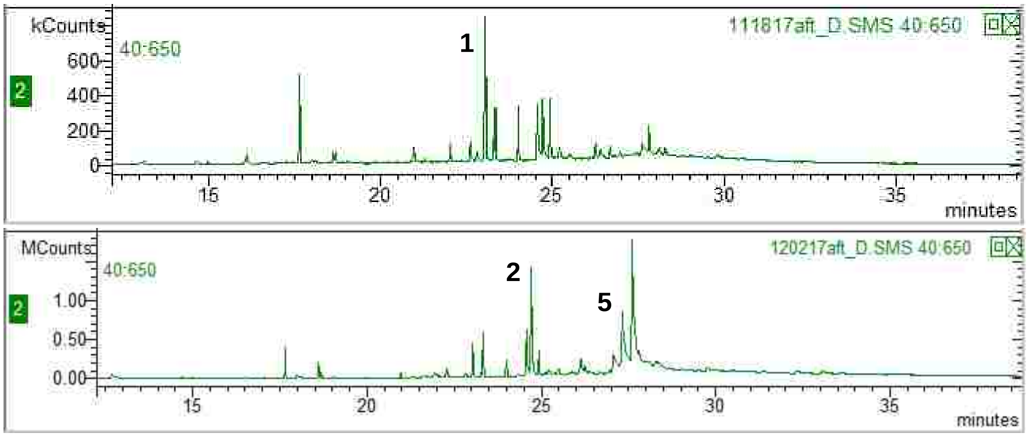
GC/MS sample peak identification before washing group D



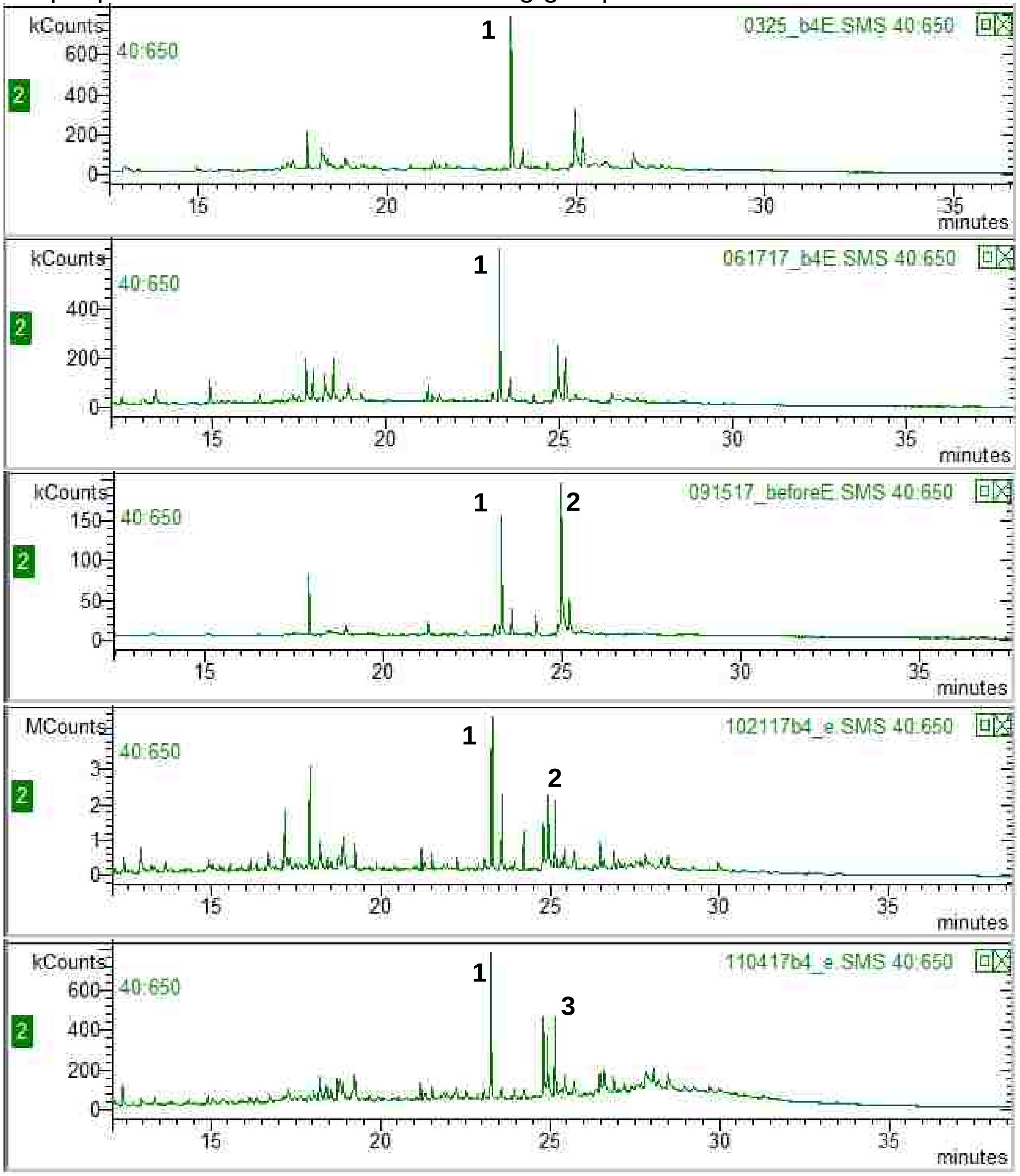


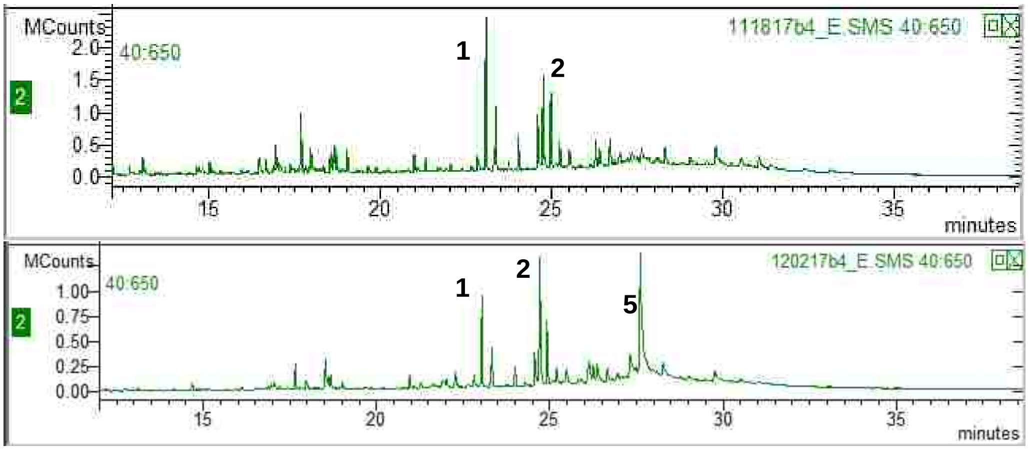
GC/MS sample peak identification after washing group D



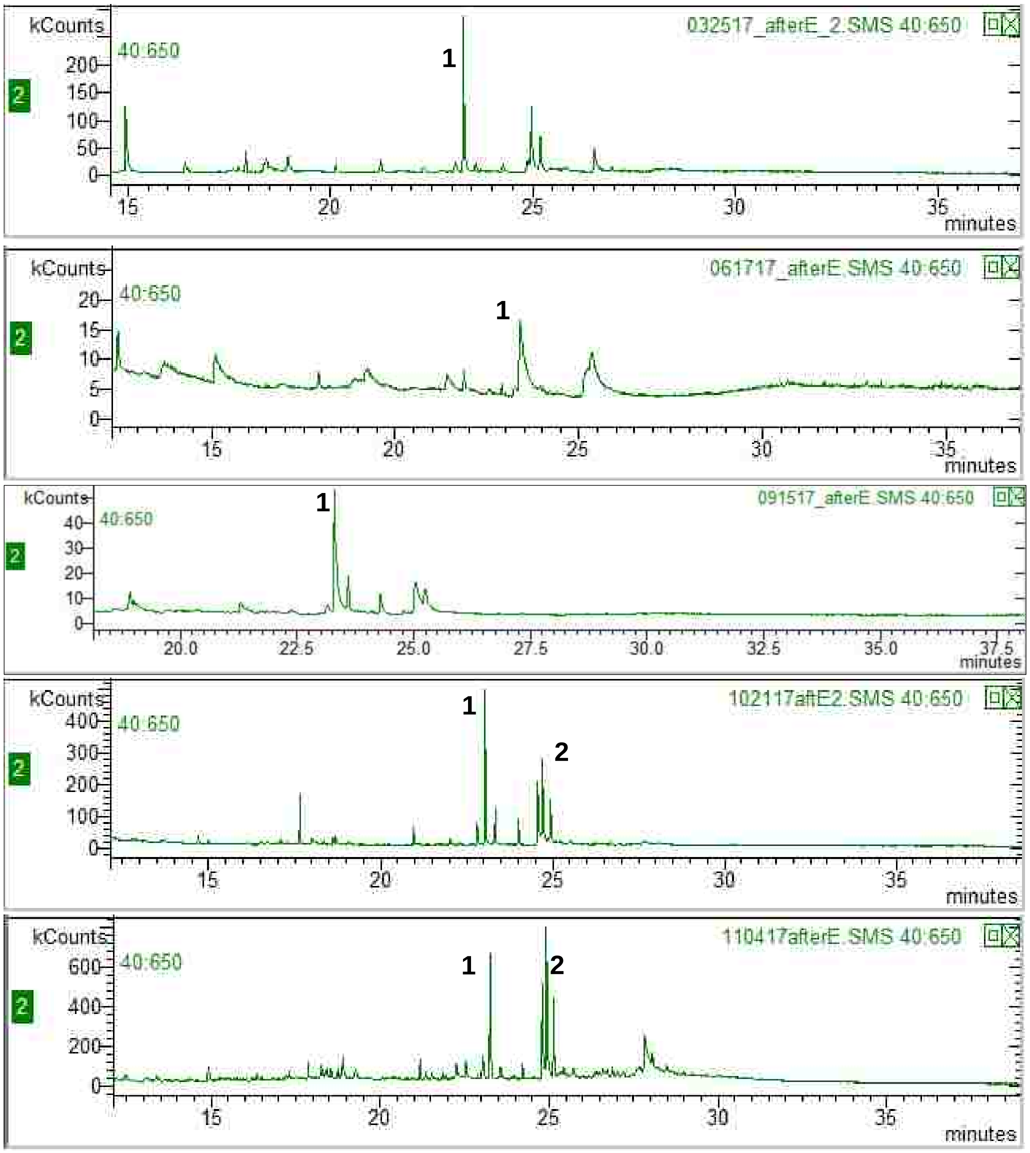


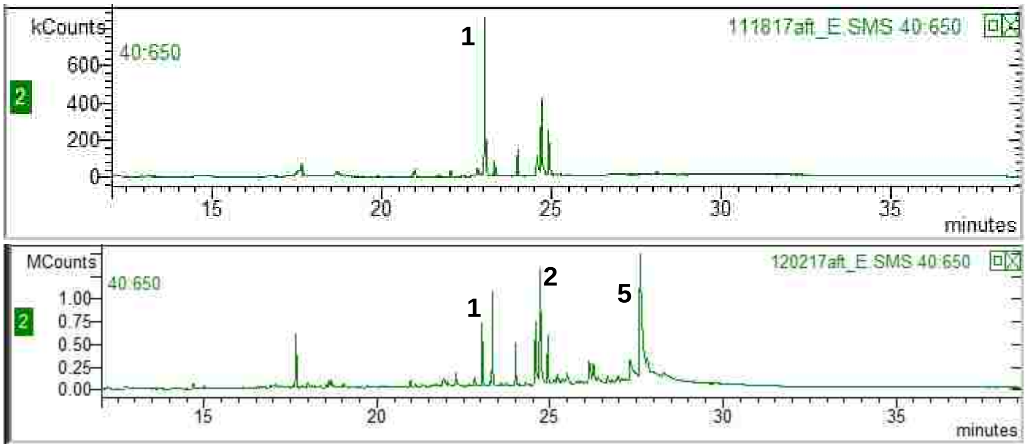
GC/MS sample peak identification before washing group E



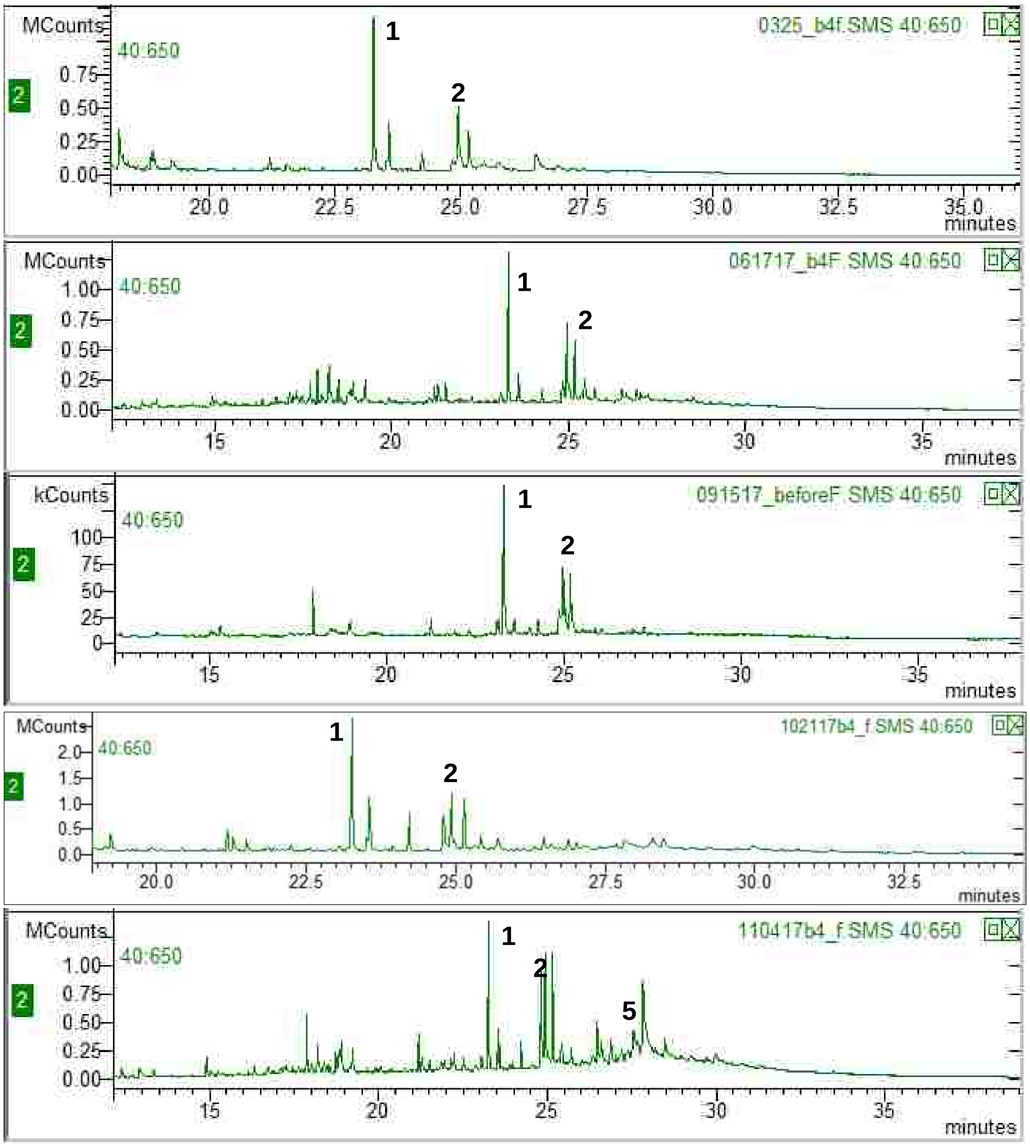


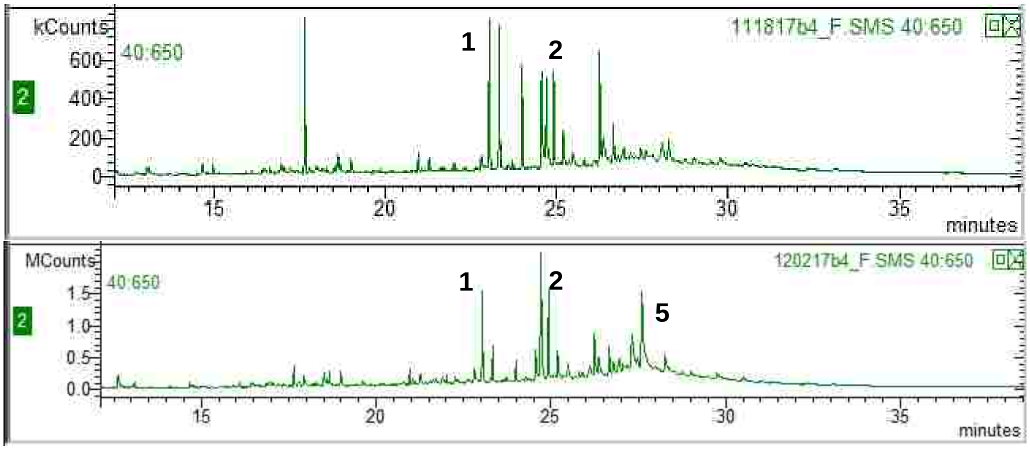
GC/MS sample peak identification after washing group E



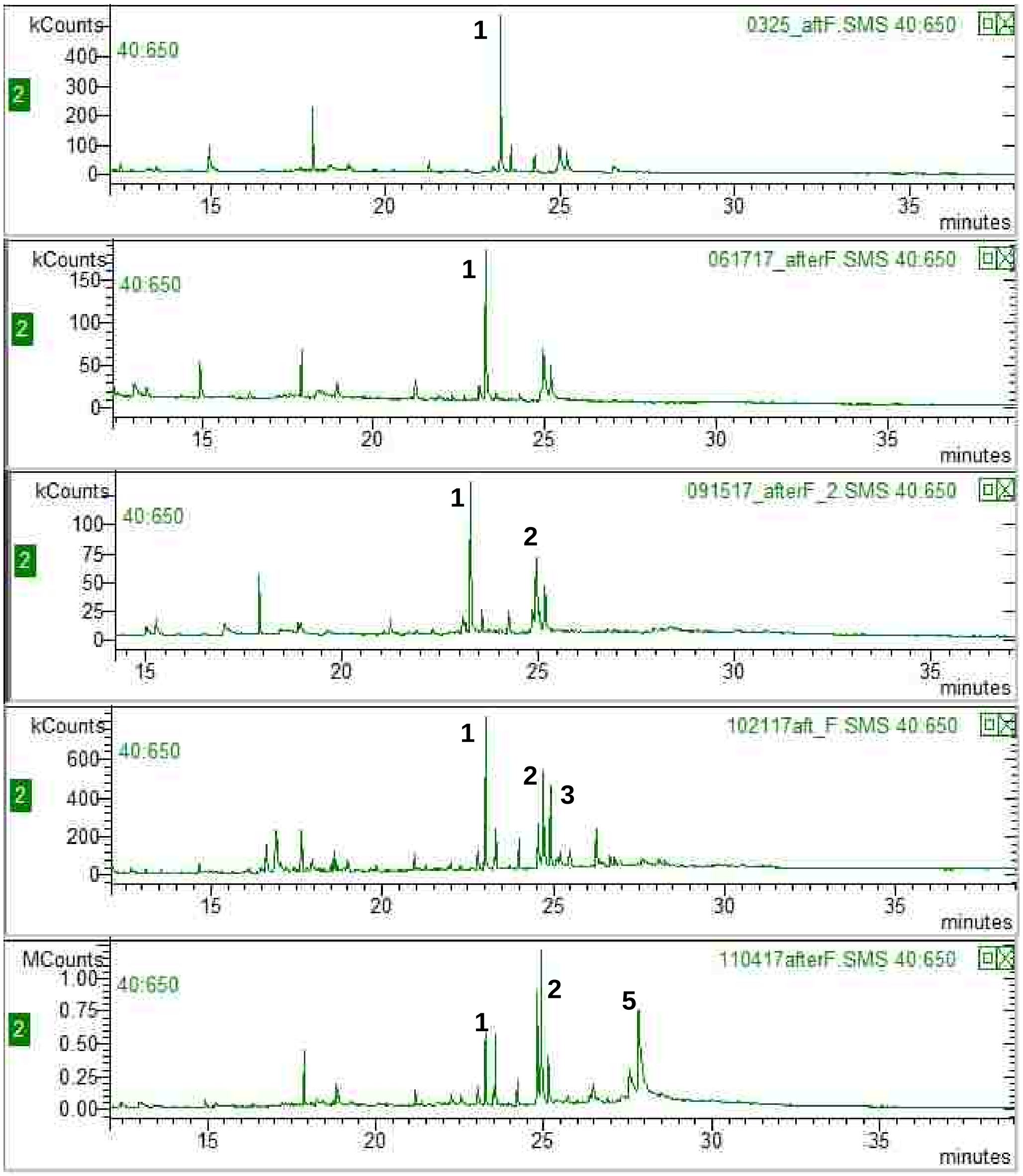


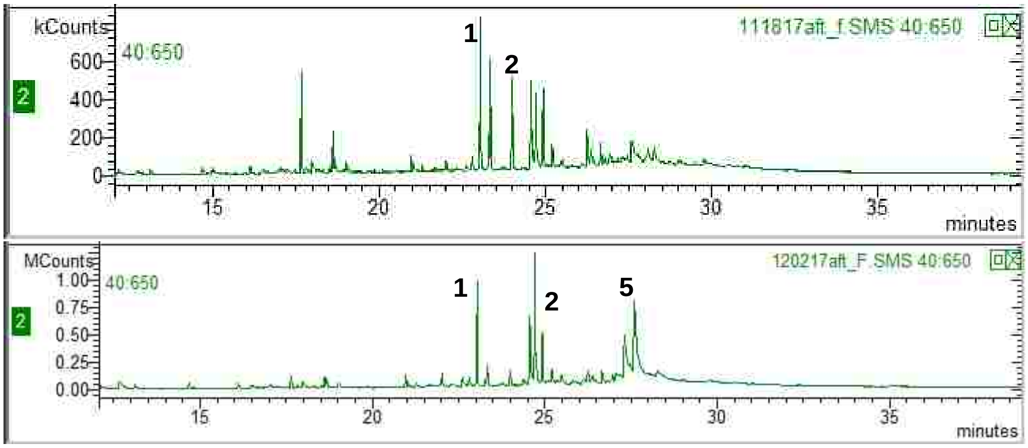
GC/MS sample peak identification before washing group F





GC/MS sample peak identification after washing group F

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2
5
15
20
25
30
35
minutes

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