

A Localized Study on Reducing Total Dissolved Solids Present in Southern California Tap Water

Bill Wang^{1,*}

¹Redlands East Valley High School, Mentone, 92359, USA

*bbwang211@gmail.com

ABSTRACT

This study, based in San Bernardino County, Southern California, explores the feasibility of adopting non-industrial equipment and methods to reduce water hardness in local tap water. We have utilized water boiling, activated carbon and sodium bicarbonate additives, as well as electrolysis methods to investigate how water quality could be improved. The results of this study show that when water is heated to a temperature around 50°C (122°F), there is a maximum decrease in water hardness as well as its TDS levels. When water is left to boil for more than 10 minutes, there is a significant increase in TDS, making the water unfavorable for drinking. Activated carbon is unable to lower TDS, because it is unable to bind to any impurities present in the water. However, adding less than 4mg/L of sodium bicarbonate will further eliminate water hardness by reacting with magnesium ions and improve taste, while increasing the pH. Electrolysis is one of the methods that are successful in eliminating TDS, resulting in a direct proportion from an increasing electrical current and duration of time lowering the amount of TDS. These results will help residents determine safer and more effective ways to lower their water hardness and control mineral levels for their health and nutritional benefits.

Introduction

TDS, or total dissolved solids present in water, is one of the most significant factors in giving water taste and providing the consumer with necessary minerals such as calcium, magnesium, potassium, and sodium¹⁻³. However, water with higher TDS measurements usually indicates contamination by human activities, such as soil and agricultural runoff caused by irrigation, unregulated animal grazing, slash and burn agriculture, and the overuse of nitrate-based fertilizer⁴. Water that flows through natural springs and waterways with high concentrations of organic salts, or groundwater that originates from wells with high salt concentration will also result in higher particle measurements⁵.

Water sources can be contaminated by substances and ions such as nitrate, lead, arsenic, and copper^{4,6} and may result in many health problems, especially in developing countries who struggle to provide the necessities required for water treatment^{7,8}. However, water treatment plants and US secondary regulations mandate that water hardness should be below 500 mg/L², which is below the WHO recommendation of below 600 mg/L and an absolute maximum of less than 1,000 mg/L³. These substances also form calcium or magnesium scales within water boilers, heaters, and pipes, causing excess buildup and drain problems^{9,10}. Furthermore, most people do not tolerate or prefer water with high hardness or chlorine additives¹¹, as the taste changes tremendously and becomes unpreferable. Even so, TDS levels are not accounted for in mandatory water regulations^{2,12}, because the essential removal of harmful toxins and metals is what matters the most in water safety. Because of this, water hardness is mostly disregarded and is not as well treated as commercial water bottling companies¹².

In Southern California, water quality is clearly not as well maintained than the northern counties as the most treatment plants in violation of a water standard are located in Central-Southern California^{13,14}, with southern counties having the largest number of people affected¹⁴. This study is focused on the Redlands area, which has had no state code violations within the last decade¹⁵. However, despite the well-regulated water treatment process, people prefer bottled water instead of tap water because of the taste and hardness of tap water¹⁶. Although water standards and tests are documented regularly, the taste of the water is not a factor to be accounted for in city water supplies¹⁵, and neither is the residue left behind after boiling water. The residue can build up over time and cause appliance damage or clogs in drainage pipes⁹.

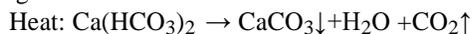
In this study, we review several methods that are said to lower TDS: boiling and heating tapwater with and without NaHCO₃¹⁰, absorption by food-grade activated carbon^{17,18}, and battery electrolysis¹⁹⁻²¹. By obtaining water samples and determining the difference in TDS before and after the listed experiments, we can determine the effectiveness of lowering water hardness. The results of this study will provide options for residents and water treatment plants to find ways to maintain the general taste of the tap water, but also preserve the lifespan of accessories and pipelines. By determining a better way to treat water hardness, water standards can be updated to include the TDS level as a mandatory measurement.

Results

Physical Experiments

Heating Water to Various Temperatures Until The Boiling Point.

The goal for this test was to use heat to reduce the amount of dissolved oxygen and carbon dioxide within the water:



This would reduce ions of calcium bicarbonate down to calcium carbonate.

- Patterns and Trends in Decreasing Temperatures

The following trend lines are based on temperature drops obtained from the test results and used as Figure 1.

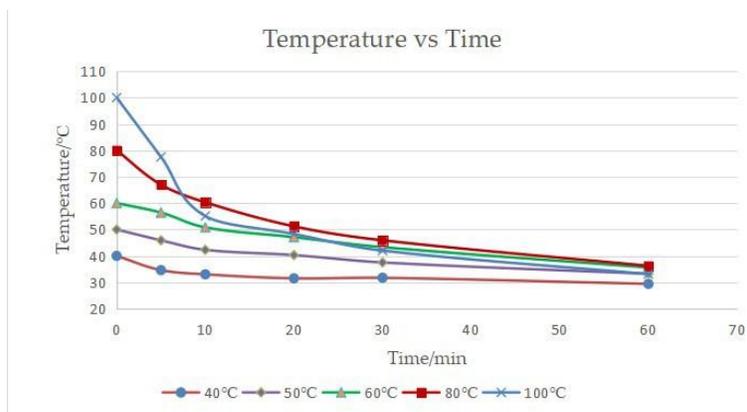


Figure 1. Temperature Change With the Water Heating Temperature and Time

To predict the precise temperature measurements of the tap water at 26.9°C, the fitting curves were created. The fitting equations are in the format, $y = ae^{bx}$. The coefficients, R^2 values, and time stamps are located in Table 1.

Heating Temperature (°C)	a	b	R^2	Time to Reach 26.9°C (min)	Calculated Temperature (°C)
40	36.07	-0.004	0.6798	73.3	26.90
50	46.978	-0.006	0.9175	92.9	26.91
60	57.43	-0.008	0.9639	94.8	26.90
80	71.066	-0.012	0.9175	80.95	26.90
100	78.163	-0.017	0.8101	62.75	26.90

Table 1. Calculated Residence Times for reaching 26.9°C

- Change in TDS as Temperature Decreases

To predict the TDS values when the temperature reaches 26.9°C, the fitting curves were graphed for Figure 1, and the coefficients are located within Table 2.

Heating Temperature (°C)	a	b	R^2	Time to reach 26.9°C (min)	Calculated TDS(ppm)
40	170.4	-0.002	0.9363	73.3	147.17
50	193.65	-0.004	0.8687	92.9	133.55
60	193.46	-0.003	0.7675	94.8	145.58
80	186.86	-0.002	0.9628	80.95	158.93
100	190.2	-0.002	0.849	62.7	167.77

Table 2. Calculated TDS at Temperature 26.9°C

Figure 2 was obtained by using the TDS results with different temperatures and times.

Based the columns of heating temperature and calculated TDS in Table 2, the Fitting curves is generated as Figure 3.

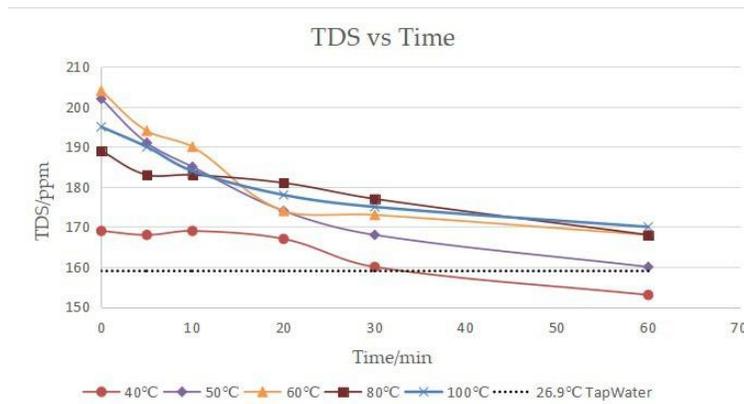


Figure 2. TDS Change with the Water Heating Temperature and Time

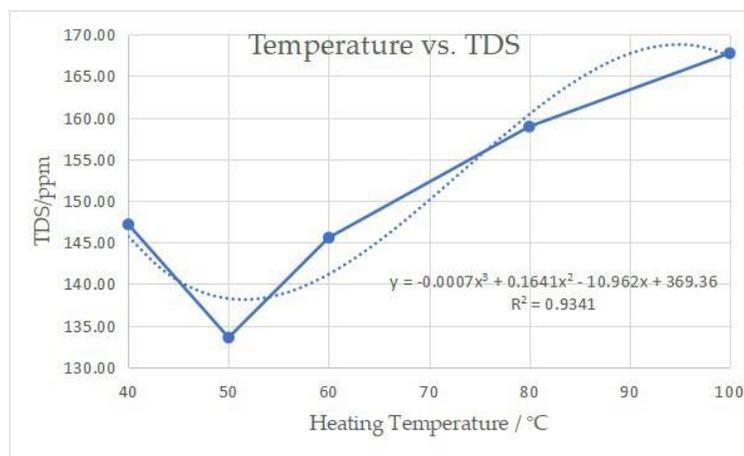


Figure 3. TDS Changes as Temperature Rises

In Figure 1, a direct relationship is shown in the rate of cooling. As the initial temperature rises, the water cools more within the first five minutes and starts to follow a more linear slope. However, the 100°C water cools quicker than the 80°C and eventually cools even faster than the 60°C graph. As shown in Figure 2, all TDS values decrease as the temperature starts to cool to room temperature, demonstrating a proportional relationship. When 50°C is reached, the TDS drops at its fastest rate from an initial value of 202 ppm to 160 ppm after 60 minutes of settling and cooling. When the water reaches 60°C, the TDS reaches a maximum of 204 ppm. However, an interesting phenomenon to point out is that the water does not hit a new maximum at 100°C. meaning that TDS reaches a plateau at 60°C. Also, the rate of decrease in TDS begins to slow down after 20 minutes, showing that something - not yet determined - is affecting the rate of decrease. It is also hypothesized that the increase in data between the 5-20 minute range is caused by the settling of the water, where the temperature starts to decrease at a more gradual and constant rate. In Table 2, when water is heated to less than or equal to 80°C and let cool until room temperature at 26.9°C, the test with 50°C water has the largest drop in TDS, with a final value of 134ppm, a 16 percent drop from the initial measurement of 159 ppm. This means that it is most effective when water is heated between temperatures of 40-60°C when it comes to lowering TDS, with a difference of 7-16 percent. When water is heated to temperatures greater than 80°C, the water begins to evaporate, increasing the concentration of the ions, causing the TDS to increase substantially when cooled to room temperature. Finally, in Figure 3, a line of best fit of function $f(x) = -0.0007x^3 + 0.1641x^2 - 10.962x + 369.36$ is used with $R^2 = 0.9341$. Using this function, the local minimum of the graph would be reached at 48.4°C. This data shows that heating water at low temperatures (i.e. 40-50°C) may be more beneficial than heating water to higher temperatures.

- Scatter Plot for the Effect of Temperature on TDS

After taking all of the different measurements obtained during TDS testing, and compiling the data onto this plot, Figure 4 is created with a corresponding line of best fit.

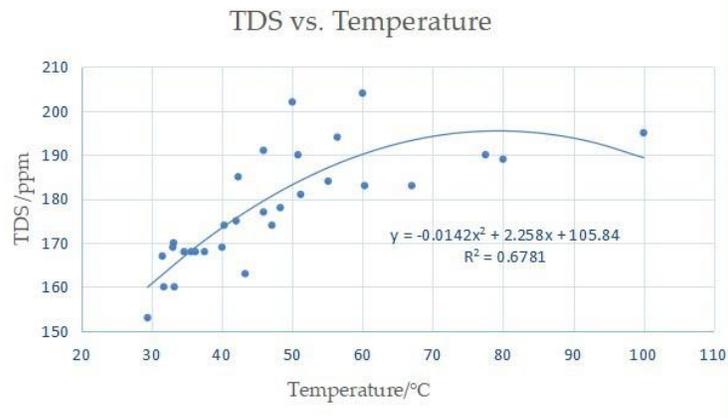


Figure 4. Scatterplot of TDS Under Different Temperatures

In Figure 4, it can be observed that the relationship between the temperature of the water and its relative TDS value is not a linear but a parabolic graph. As the temperature increases, the TDS begins to decrease after the steep incline at 50-60°C. The line of best fit is of function $f(x) = -0.0142x^2 + 2.258x + 105.84$. $R^2 = 0.6781$. Because the R^2 value is less than expected, it is most likely due to undetermined factors such as the time spent settling, the reactivity of the ions, etc. To determine the specifics within this experiment, deeper research and prolonged studies with highly accurate analyses must be utilized to solve this problem.

Boiling water for various amounts of time.

- Trend of Boiling Duration and Rate of Cooling

Using the same methods to create the figures and tables for the first section, Figure 5 depicts how the duration of time spent boiling water affects how fast the water cools.

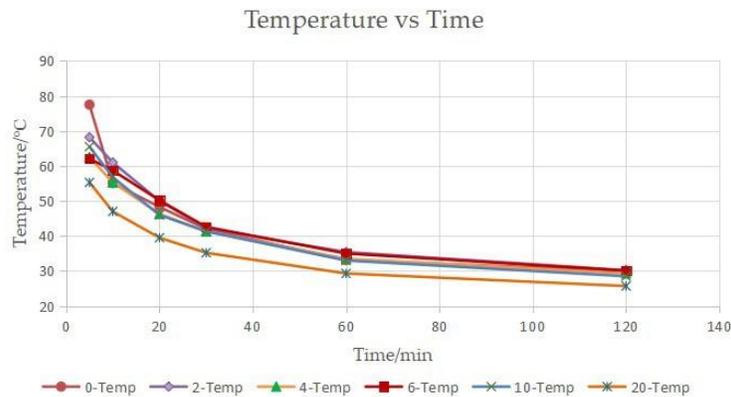


Figure 5. Water Temperature Changes With The Residence Time Under The Different Boiling Time

As seen in Figure 5, within the first 10 minutes of the cooling time, five lines are entwined with each other, seeming to follow a unique pattern of cooling that all lines follow. However, the line showing 20 minutes of boiling is much lower than the rest, showing a faster rate of cooling. This is most likely represented by a relationship where the longer the boil, the faster it cools. This also shows that the first 5 minutes of cooling have the largest deviance compared to any other time frame. The cooling pattern is hypothesized by possible changes in the orderly structure of the hydrogen bonds in the water molecules, or the decreased heat capacity of water due to the increasing concentration of TDS.

- Effect on TDS as Boiling Duration Increases

In Figure 6, for each line boiled for 0, 2, 4, 6, 10, and 20 minutes, each TDS measurement done at the 5 minute mark are 190, 193, 188, 184, 181, and 304. By excluding the last measurement temporarily due to it being an outlier, we have

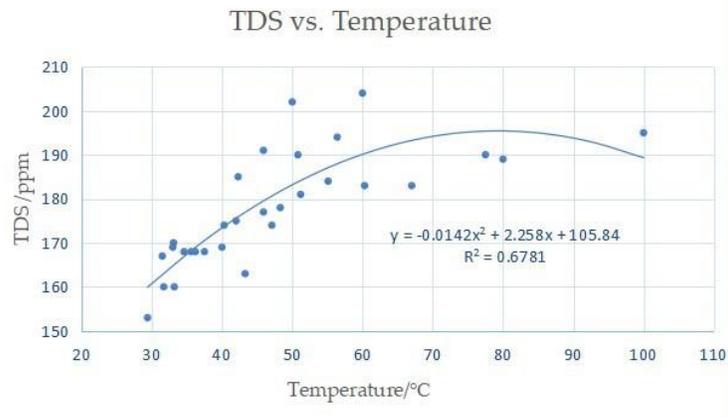


Figure 6. TDS changes with the water boiling and residence time

observed that the difference between the initial and final TDS value of each test decreases. Despite following a similar trend of an increase in TDS at the start of the tests and a slow decrease overtime, this experiment had an interesting result, with the final test measuring nearly twice the amount of particles compared to any previous tests at 310 ppm, as shown in Figure 6. It is confirmed that the long boiling time caused a significant amount of water to evaporate, causing the minerals to be more concentrated, thus resulting in a 300 ppm reading. Figure 6 follows the same trend as Figure 2, except the TDS reading veers away when the boiling duration reaches 20 minutes. Also, with the long duration of heating, the water has reached a point of an unfavorable taste from intense concentrations of CaCO_3 . This also causes a buildup of a thick crust of CaCO_3 and other impurities around the container when the flasks were cleaned afterwards. This finding is in accordance with the introductory statement of hot boiling water causing mineral buildups within pipes and appliances⁹. However, an important thing to point out here is that the cooling rate of the water increases as the time spent boiling increases. This is predicted to be from the increased concentration of dissolved solids, which lowers the volume of water, which has a high specific heat capacity. This means that a method can be derived to measure TDS using the heat capacity of a tap water mixture and volume, in addition to current methods of using the electrical conductivity of aqueous ions.

Adding Food-grade Active Carbon To Untreated Tap Water

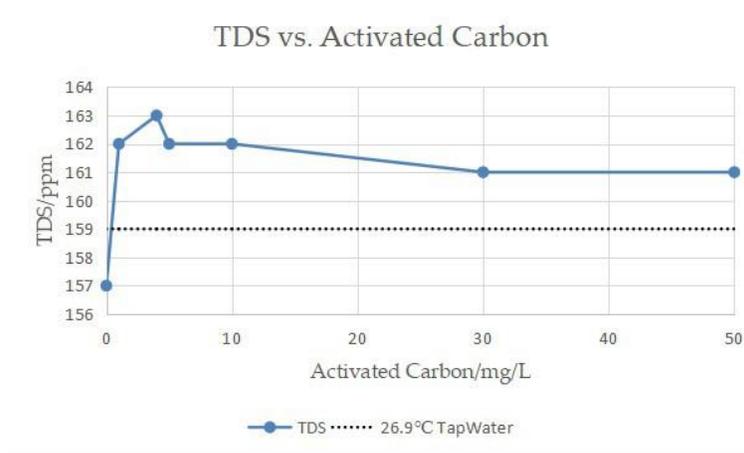


Figure 7. Trend for the effect of activated carbon on TDS.

Figure 7 presents a line graph with little to no change in TDS, with an initial spike from 157 to 163 ppm. The insoluble carbon remains in the water and shows no benefit. The food-grade activated carbon proved no benefit to removing TDS from tap water, and instead added around 5-7ppm extra, which settled down to around +4 ppm at 120 minutes. The carbon, which is not 100 percent pure from inorganic compounds and materials present in the carbon, can dissolve into the water, as it is not industrial grade. Furthermore, ready-to-use tap water has already been treated in processing facilities using a variety of filters, including carbon, so household charcoal filters are not effective in further reducing dissolved solids¹⁸.

Chemical Method: Adding Sodium Bicarbonate Solution to Boiled Tap Water

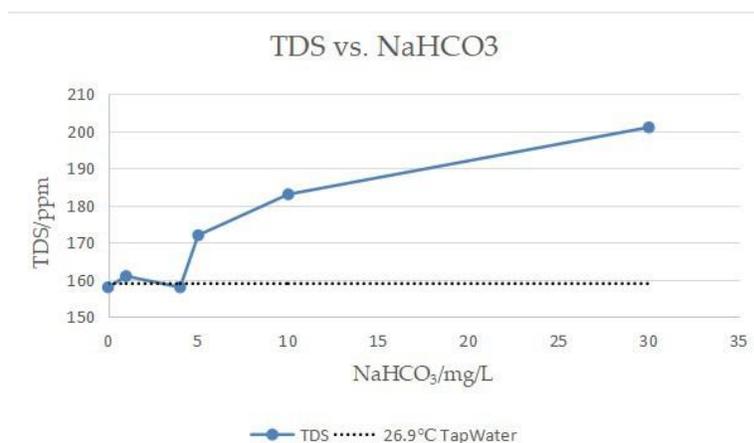


Figure 8. Trend for the effect of NaHCO₃ on Tap Water TDS

As seen in Figure 8, after adding 1mg in, the TDS rises to 161 ppm, showing a minuscule increase. When 4mg was added, the TDS drops down to 158 ppm. Then, when 5 mg was added, a sudden spike to 172 ppm was observed. This means that NaHCO₃ is able to eliminate some Ca²⁺ and Mg²⁺ ions, but also adds Na⁺ back into the water. This means that adding NaHCO₃ has little to no effect on TDS, with 4 mg being the upper limit of effectiveness. To examine whether or not the temperature plays a role in the effectiveness in adding NaHCO₃, a boiling experiment was performed and graphed in Figure 9.

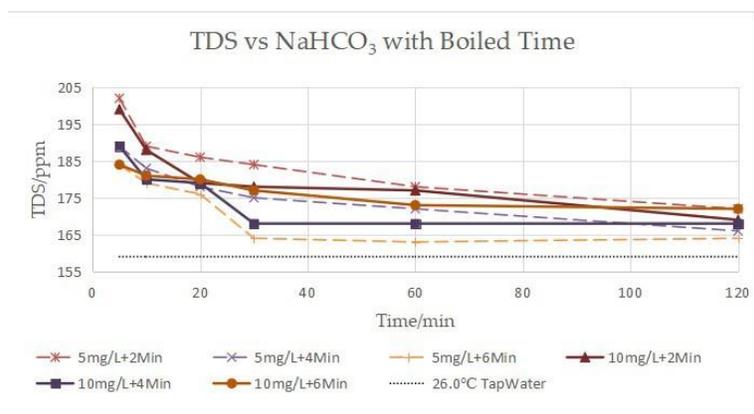


Figure 9. Trend for the Effect of NaHCO₃ on Boiling Water TDS

Figure 9 presents the relationship between the amount of common baking soda (NaHCO₃) added in milligrams to each liter of water and the resulting TDS measurements. After boiling each flask for designated amounts of time, the results showed a downward trend line from a spike but does not reach a TDS value significantly lower than the initial sample. It is apparent that the NaHCO₃ has not lowered the TDS of the boiling water, but instead adds some minerals raising the final value. This additive does not contribute to the lowering of the hardness of the tapwater. However, tests boiled with 5mg/L of baking soda maintained a downward pattern as the water was boiled for an increasing amount of time, compared to the pattern-less graphs of boiling with 10 mg/L. In some households, however, people often add NaHCO₃ to increase the pH for taste and health benefits. However, as shown in the test results, it is not an effective way of reducing TDS levels in the water^{11, 10}, but instead raises the pH, determined by the concentration added. Even under boiling conditions, the water continues to follow the trend of high growth in TDS, of +25-43ppm right after boiling and the slow drop in TDS (but maintaining a high concentration) as the particles settle to the bottom. Utilizing the experimental results, we can summarize that after adding small batches of NaHCO₃ and waiting up to 5 minutes will reduce water hardness making it less prone to crystallizing within household appliances such as water brewers. Also, this process raises the pH, which is used more within commercial water companies. However, the cost comes at increasing TDS.

Electrochemical Method: Using Electrolysis in Tap Water

The process of electrolysis in this experiment was not to split water into hydrogen and oxygen gas, but to separate the water sample into three designated areas: the anode, cathode, and an area of clean water between the two nodes¹⁹. The anions in the water such as OH^- , SO_4^{2-} , HCO_3^- move to the anode, while the cations such as H^+ , Ca^{2+} , Mg^{2+} , Na^+ move to the cathode. The middle area would then be left as an area with less ions, with Figure 10 proving this.

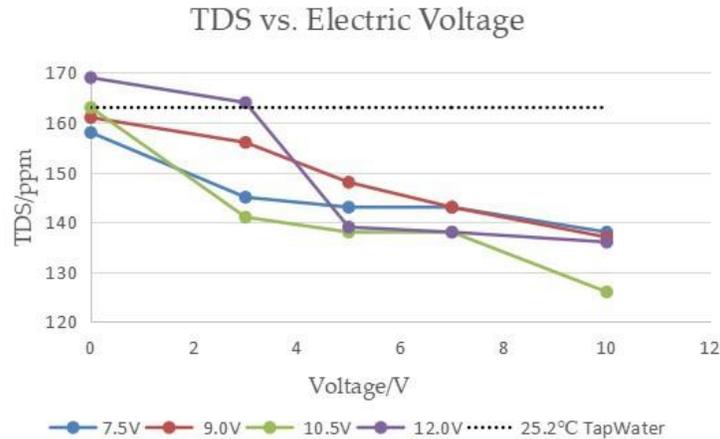


Figure 10. TDS Changes with Different Electrical Voltages

As shown in Figure 10, electrolysis is effective in lowering the TDS within tap water. Despite the lines being extremely tangled and unpredictable, the general trend was a larger decrease with a longer duration of time. At 10 minutes, all lines except 10.5 V are approaching the same value, meaning that the deviation was most likely caused by disturbances to the water during measurement from the low volume of water. This experiment concludes that electrolysis is effective in lowering TDS, with the possibility to improve this process by further experimentation, development of a water cleaning system utilizing this cathode-anode setup to process water. This system would be a more specific and limited version of a reverse osmosis system by taking away ions through attraction, rather than a filter.

Discussion

To lower TDS and water hardness, many conventional methods such as boiling and filtration are ineffective, because commercial water companies have already successfully produced safe drinking water that has removed the harmful toxins. However, the disregard for TDS as a category by these companies means that the quality of the water may be improved, and this is possible by using electrolysis. The Southern Californian tap water supply maintains a value of less than 200 ppm without any personal treatment, a value under the United States drinking water standards of less than or equal to 500 ppm. However, crystalline scale buildup in household appliances is a major issue as it is hard to clean and eliminate. To easily improve the taste, safety, and quality of tap water at home as well as eliminating the formation of scales, the following methods were demonstrated as viable:

1. By heating water to around 50°C (122°F), TDS and water hardness will decrease the most. Also, the boiling process is effective in killing bacteria, microbes, and other ill-inducing organisms and matter. This cannot surpass 10 minutes, as the concentration of the ions in the water becomes unfit for drinking, which is not beneficial for human health.
2. Activated carbon is ineffective in absorbing TDS, but filters can be used to eradicate other matter.
3. By adding 4 mg/L of NaHCO_3 , the water hardness is lowered, which improves the taste of water. Large additions of baking soda will raise the pH, but will not lower TDS, boiled or not.
4. Electrolysis is one of the most effective methods of eliminating TDS. Experiments have proven that increased current and duration of time helps lower TDS. However, this method has yet to be implemented into conventional commercial water filtration systems.

Also, some observations made in these experiments could not be explained, and require further research and experimentation to resolve these problems:

1. TDS and increasing water temperature maintains a parabolic relationship, with a maximum being reached at 80°C, followed by a gradual decrease.
2. When water is boiled for an increasing duration of time, the rate of cooling also increases.

This experiment utilized non-professional scientific equipment which are prone to mistakes and less precise. These results may deviate from professionally derived data, and will require further study using more advanced equipment to prove these findings.

Methods

All experiments utilized tap water sourced from Redlands homes. This water is partially supplied from the Mill Creek (Henry Tate) and Santa Ana (Hinckley) Water Sheds/Treatment Plants, as well as local groundwater pumps. Water sampling and sourcing were done from 1-2 pm when temperatures were relatively stable at 26.9°C (80.42°F). For each test, all procedures were done indoors under conditions with controlled temperature, water was obtained from kitchen faucets (preferred source for tap water drinking), and 20 L of fresh water was retrieved for the tests. Water samples were taken before each experimental set and measured for TDS and temperature, and all tools and containers were rinsed with purified water before and after each measurement.

Physical Methods

Heating/Boiling Water for Various Lengths of Time

Four flasks of 1 L of tap water were heated separately to intervals within 40-80°C (104-176°F), while the temperature was observed and measured by a laser thermometer. The heated water was then left to cool and measurements were made at the 5, 10, 20, 30, and 60-minute marks. For the boiling experiments, five flasks of 1 L of tap water were heated to the boiling point 100°C (212°F). Each flask, which was labeled corresponding to its boiling duration, was marked with 2, 4, 6, 10, and 20 minutes, was boiled for its designated time, left to cool under open air, and measurements were made at the 5, 10, 20, 30, 60, and 120-minute marks. The reason that the boiling experiment was extended to 120 minutes was for the water to cool down to room temperature.

Activated Carbon as a Water Purification Additive

Food-grade activated carbon powder was measured using a milligram scale and separated into batches of 1, 2, 4, 5, 10, 30, and 50mg. One batch of the aforementioned activated carbon would be added and stirred five minutes and left to settle for another five minutes. TDS measurements were recorded after the water settled.

Chemical Method: Common Baking Soda as a Water Purification Additive

To lower scale error and increase experimental accuracy, a concentration of 200 mg/L NaHCO₃ solution was made with purified water and pure NaHCO₃. For each part, an initial TDS measurement was taken before each experiment. In separate flasks of 1 L tap water each labeled 1, 2, 4, 5, 10, and 30 mg of NaHCO₃, a batch was added to and stirred for 5 minutes to ensure everything dissolved. Measurements were taken after the water was left to settle for another 5 minutes. 6 flasks of 1 L tap water were labeled, with 5 mg (25 mL solution) of NaHCO₃ added to three flasks and 10 mg (50 mL solution) of NaHCO₃ added to the remaining three. One flask from each concentration of NaHCO₃ was boiled for 2 mins., 4 mins., or 6 mins., and then left to cool. A TDS measurement was taken at the 5, 10, 20, 30, 60, and 120-minute marks after removal from heat.

Electrochemical Method: Electrolysis Under Low Voltages

Two 18 cm long (pencil-length) graphite pieces were connected via copper wiring to a group of batteries, with each end of the graphite pieces submerged in a beaker of tap water, 3 cm apart. Using groups of 1.5 V double-A batteries, 4 beakers with 40mL of tap water were each treated with either 7.5, 9.0, 10.5, and 12.0 V of current. Electrolysis was observed to be present by the bubbling of the water each test, and measurements were taken at the 3, 5, 7, and 10 minute marks.

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Author contributions statement

B.W. prepared, conducted, and selected the experiments, and analysed the results. The author reviewed the manuscript and has revised it.

Additional information

Competing interests (The author declares no competing interests.).