Environmental Sciences Proceedings

MDPI

*Proceedings*

# Hexavalent Chromium Removal from Groundwater—A Low-Tech Approach †

**Samiotis Georgios, Lefteri Lefteris, Mavromatidou Charoula, Tsioptsias Costas, Trikilidou Eleni, Batsi Anna and Amanatidou Elisavet ***

Environmental Chemistry and Water & Wastewater Treatment Research Laboratory, University of Western Macedonia, Koila University Campus, 50100 Kozani, Greece; samiotis1982@hotmail.com (S.G.); lefteris1194@gmail.com (L.L.); xaroulam73@gmail.com (M.C.); ktsiopts@gmail.com (T.C.); etrikilido@yahoo.com (T.E.); annampatsi@gmail.com (B.A.)

* Correspondence: eamanatidou@uowm.gr; Tel.: +30-24610-68015

† Presented at the 4th EWaS International Conference: Valuing the Water, Carbon, Ecological Footprints of Human Activities, Online, 24–27 June 2020.

Published: 14 August 2020

**Table 1.** Materials used for experimental setups.

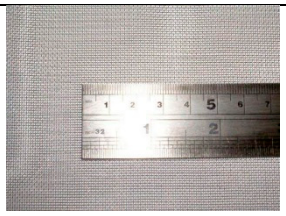
| Iron wool | Iron wire | Iron screen |
|---|---|---|
|  |  |  |
| ***Specifications:*** *Wire diameter (mm) = 0,06* *Specific weight (g/m) = 0,0076* *Specific surface area ($m^2/m$) = 0,00038* | ***Specifications:*** *Wire diameter (mm) = 1* *Specific weight (g/m) = 0,0076* *Specific surface area ($m^2/m$) = 0,00314* | **Specifications:** *Wire diameter (mm) = 0,1* *Specific weight ($kg/m^2$) = 0,255488* *Specific surface area ($m^2/m^2$) = 0,00041867* |
| **Scrap Iron chips** | **Scrap Iron fillings** | **Activated carbon** |
|  |  |  |
| ***Specifications:*** *Wire diameter (mm) = 1* *Specific weight (g/m) = 0,0076* *Specific surface area ($m^2/m$) = 0,031557* | ***Specifications:*** *Mesh (mm) = 0,6 – 1,6 & <0,6* *Specific weight (kg/L) = 1884 & 1271,25 respectively* *Specific surface area ($m^2/kg$) = 80,7 & 111,2 respectively* | ***Specifications:*** *Mesh (mm) = 1,6-3,15 & <0,6* *Specific weight (kg/L) = 1875 respectively* *Specific surface area ($m^2/kg$) =* 235,5 & 84,78 *respectively* |

**Table 2.** Short description of the experimental setups and their results regarding Cr(VI) removal & important data for the evaluation of each experiment.

| Experiment series | Experiment code | Short description | Contact time | Agitation | Cr(VI) removal efficiency (%) | Comments |
|---|---|---|---|---|---|---|
| 1st series (vessel vs wire) | 1-1 | 1,5 L vessel with 1m of folded non-galvanized iron wire of 1mm diameter | 10 seconds to 1,5 hours | Slow, continuous manual agitation (inversion of vessel every 3 seconds approximately) | Min – Max: 1,5 – 42,0 | - |
| | 1-2 | 1,5 L vessel with 100 pieces of non-galvanized iron wire (approximately 1 cm each, to a total length of 1 m) of 1mm diameter | 10 seconds to 20 hours | Slow, continuous manual agitation (inversion of vessel every 3 seconds approximately) for the first 10 minutes | Min – Max: 1,7 - 100,0 | - |
| | 1-3 | 1,5 L vessel with 4m of folded non-galvanized iron wire of 1mm diameter | 10 seconds to 20 hours | Slow, continuous manual agitation (inversion of vessel every 3 seconds approximately) for the first 10 minutes | Min – Max: 6,4 - 100,0 | - |
| 2nd series (first column experiments) | 2-1 | 47,1 g / 25 ml scrap iron fillings (mixed galvanized, oxidized and non-galvanized grains of 0,6 mm to 1,6 mm diameter) mixed with 25ml fine limestone sand in 100 ml cylinder (Hight = 25 cm, Diameter – 2,75 cm) | 1,2 seconds* | No agitation | 44,0 | First use (day 1)<br>Flow = 100ml/30 seconds |

| Experiment series | Experiment code | Short description | Contact time | Agitation | Cr(VI) removal efficiency (%) | Comments |
|---|---|---|---|---|---|---|
| | 2-2 | 30,0 g / 16 ml scrap iron fillings (mixed galvanized, oxidized and non-galvanized grains of 0,6 mm to 1,6 mm diameter) in 100 ml cylinder (Hight = 25 cm, Diameter – 2,75 cm) | 0,80 seconds* | No agitation | 3,4 | Second use 1 day later (day 2)<br>Flow = 100ml/20 seconds |
| | 2-3 | 30,0 g / 16 ml scrap iron fillings (mixed galvanized, oxidized and non-galvanized grains of 0,6 mm to 1,6 mm diameter) mixed with 16 ml fine limestone sand in 100 ml cylinder (Hight = 25 cm, Diameter – 2,75 cm) | 0,92 seconds* | No agitation | 0,0 | Third use 1 day later (day 2)<br>Flow = 100ml/23 seconds |
| | 2-4 | 30,0 g / 16 ml scrap iron fillings (mixed galvanized, oxidized and non-galvanized grains of 0,6 mm to 1,6 mm diameter) mixed with 16 ml fine limestone sand and 16 ml (30g) of activated carbon (grains of 1,6 mm to 1,5 mm diameter) in 100 ml cylinder (Hight = 25 cm, Diameter – 2,75 cm) | 2,31 seconds* (1,32 with iron fillings & 0,99 with Act. Carbon) | No agitation | 27,1 | Fourth use 1 day later (day 2)<br>Flow = 100ml/33 seconds |
| | 2-5 | 30,0 g / 16 ml of activated carbon (grains of 1,6 mm to 1,5 mm diameter) in 100 ml cylinder (Hight = 25 cm, Diameter – 2,75 cm) | 2,10 seconds* | No agitation | 13,5 | First use<br>Flow = 100ml/42 seconds |
| | 2-6 | 30,0 g / 16 ml of activated carbon (grains of 0,6 mm to 1,5 mm diameter) in 100 ml cylinder (Hight = 25 cm, Diameter – 2,75 cm) | 7,30 seconds* | No agitation | 18,7 | First use<br>Flow = 100ml/146 seconds |
| | 2-7 | 30,0 g / 16 ml of activated carbon (grains of 0,6 mm to 1,5 mm diameter) in 100 ml cylinder (Hight = 25 cm, Diameter – 2,75 cm) | 15,00 seconds* | No agitation | 23,7 | First use<br>Flow = 100ml/300 seconds |
| 3rd series (vessel vs scrap iron fillings) | 3-1 | 250 ml vessel (100 ml standard solution) with 1g of scrap iron fillings (mixed galvanized, oxidized and non-galvanized grains of < 0,6 mm diameter) | 10 seconds | Continuous manual orbital stirring | 2,1 | First use |
| | 3-2 | 250 ml vessel (100 ml standard solution) with 2g of scrap iron fillings (mixed galvanized, oxidized and non-galvanized grains of < 0,6 mm diameter) | 10 seconds | Continuous manual orbital stirring | 3,2 | Addition of 1 g scrap iron fillings (first use) |

| Experiment series | Experiment code | Short description | Contact time | Agitation | Cr(VI) removal efficiency (%) | Comments |
|---|---|---|---|---|---|---|
| | 3-3 | 250 ml vessel (100 ml standard solution) with 3g of scrap iron fillings (mixed galvanized, oxidized and non-galvanized grains of < 0,6 mm diameter) | 10 seconds | Continuous manual orbital stirring | 5,4 | Addition of 1 g scrap iron fillings (first use) |
| | 3-4 | 250 ml vessel (100 ml standard solution) with 4g of scrap iron fillings (mixed galvanized, oxidized and non-galvanized grains of < 0,6 mm diameter) | 10 seconds | Continuous manual orbital stirring | 3,9 | Addition of 1 g scrap iron fillings (first use) |
| | 3-5 | 250 ml vessel (100 ml standard solution) with 5g of scrap iron fillings (mixed galvanized, oxidized and non-galvanized grains of < 0,6 mm diameter) | 10 seconds | Continuous manual orbital stirring | 5,2 | Addition of 1 g scrap iron fillings (first use) |
| | 3-6 | 250 ml vessel (100 ml standard solution) with 1g of scrap iron fillings (non-galvanized grains of < 0,6 mm diameter) | 10 seconds | Continuous manual orbital stirring | 97,3 | First use |
| | 3-7 | 250 ml vessel (100 ml standard solution) with 2g of scrap iron fillings (non-galvanized grains of < 0,6 mm diameter) | 10 seconds | Continuous manual orbital stirring | 98,6 | Addition of 1 g scrap iron fillings (first use) |
| | 3-8 | 250 ml vessel (100 ml standard solution) with 3g of scrap iron fillings (non-galvanized grains of < 0,6 mm diameter) | 10 seconds | Continuous manual orbital stirring | 96,1 | Addition of 1 g scrap iron fillings (first use) |
| | 3-9 | 250 ml vessel (100 ml standard solution) with 4g of scrap iron fillings (non-galvanized grains of < 0,6 mm diameter) | 10 seconds | Continuous manual orbital stirring | 96,7 | Addition of 1 g scrap iron fillings (first use) |
| | 3-10 | 250 ml vessel (100 ml standard solution) with 5g of scrap iron fillings (non-galvanized grains of < 0,6 mm diameter) | 10 seconds | Continuous manual orbital stirring | 89,0 | Addition of 1 g scrap iron fillings (first use) |
| | 3-11 | 250 ml vessel (100 ml standard solution) with 1g of scrap iron fillings (mixed galvanized, oxidized and non-galvanized grains of 0,6 mm to 1,6 mm diameter) | 10 seconds | Continuous manual orbital stirring | 2,2 | First use |

| Experiment series | Experiment code | Short description | Contact time | Agitation | Cr(VI) removal efficiency (%) | Comments |
|---|---|---|---|---|---|---|
| | 3-12 | 250 ml vessel (100 ml standard solution) with 2g of scrap iron fillings (mixed galvanized, oxidized and non-galvanized grains of 0,6 mm to 1,6 mm diameter) | 10 seconds | Continuous manual orbital stirring | 3,1 | Addition of 1 g scrap iron fillings (first use) |
| | 3-13 | 250 ml vessel (100 ml standard solution) with 3g of scrap iron fillings (mixed galvanized, oxidized and non-galvanized grains of 0,6 mm to 1,6 mm diameter) | 10 seconds | Continuous manual orbital stirring | 5,3 | Addition of 1 g scrap iron fillings (first use) |
| | 3-14 | 250 ml vessel (100 ml standard solution) with 4g of scrap iron fillings (mixed galvanized, oxidized and non-galvanized grains of 0,6 mm to 1,6 mm diameter) | 10 seconds | Continuous manual orbital stirring | 3,8 | Addition of 1 g scrap iron fillings (first use) |
| | 3-15 | 250 ml vessel (100 ml standard solution) with 5g of scrap iron fillings (mixed galvanized, oxidized and non-galvanized grains of 0,6 mm to 1,6 mm diameter) | 10 seconds | Continuous manual orbital stirring | 5,1 | Addition of 1 g scrap iron fillings (first use) |
| | 3-16 | 250 ml vessel (100 ml standard solution) with 1g of scrap iron fillings (non-galvanized grains of < 0,6 mm diameter) | 10 seconds | Continuous manual orbital stirring | 97,1 | First use |
| | 3-17 | 250 ml vessel (100 ml standard solution) with 2g of scrap iron fillings (non-galvanized grains of 0,6 mm to 1,6 mm diameter) | 10 seconds | Continuous manual orbital stirring | 98,7 | Addition of 1 g scrap iron fillings (first use) |
| | 3-18 | 250 ml vessel (100 ml standard solution) with 3g of scrap iron fillings (non-galvanized grains of 0,6 mm to 1,6 mm diameter) | 10 seconds | Continuous manual orbital stirring | 98,0 | Addition of 1 g scrap iron fillings (first use) |
| | 3-19 | 250 ml vessel (100 ml standard solution) with 4g of scrap iron fillings (non-galvanized grains of 0,6 mm to 1,6 mm diameter) | 10 seconds | Continuous manual orbital stirring | 96,9 | Addition of 1 g scrap iron fillings (first use) |
| | 3-20 | 250 ml vessel (100 ml standard solution) with 5g of scrap iron fillings (non-galvanized grains of 0,6 mm to 1,6 mm diameter) | 10 seconds | Continuous manual orbital stirring | 92,5 | Addition of 1 g scrap iron fillings (first use) |

| Experiment series | Experiment code | Short description | Contact time | Agitation | Cr(VI) removal efficiency (%) | Comments |
|---|---|---|---|---|---|---|
| | 3-21 | 250 ml vessel (100 ml standard solution) with 5g of scrap iron fillings (mixed galvanized, oxidized and non-galvanized grains of < 0,6 mm diameter) | 10 seconds each batch | Continuous manual orbital stirring | 1st pass = 81,4%<br>2nd pass = 63,9%<br>3rd pass = 71,2%<br>4th pass = 70,7%<br>5th pass = 64,7% | Five additions of standard solution, each followed by rinsing with ultrapure water |
| | 3-22 | 250 ml vessel (100 ml standard solution) with 5g of scrap iron fillings (non-galvanized grains of < 0,6 mm diameter) | 10 seconds each batch | Continuous manual orbital stirring | 1st pass = 86,1 %<br>2nd pass = 38,9 %<br>3rd pass = 36,8 %<br>4th pass = 24,7 %<br>5th pass = 26,4 % | Five additions of standard solution, each followed by rinsing with ultrapure water |
| | 3-23 | 250 ml vessel (100 ml standard solution) with 5g of scrap iron fillings (mixed galvanized, oxidized and non-galvanized grains of 0,6 mm to 1,6 mm diameter) | 10 seconds each batch | Continuous manual orbital stirring | 1st pass = 81,3%<br>2nd pass = 30,5%<br>3rd pass = 30,6 %<br>4th pass = 22,5%<br>5th pass = 27,6% | Five additions of standard solution, each followed by rinsing with ultrapure water |
| | 3-24 | 250 ml vessel (100 ml standard solution) with 5g of scrap iron fillings (non-galvanized grains of 0,6 mm to 1,6 mm diameter) | 10 seconds each batch | Continuous manual orbital stirring | 1st pass = 93,2%<br>2nd pass = 24,9%<br>3rd pass = 20,9%<br>4th pass = 19,1%<br>5th pass = 16,4% | Five additions of standard solution, each followed by rinsing with ultrapure water |
| 4th series (second | 4-1 | 2 iron screen sheets (9cm X 83cm each), with wire diameter of 100 µm, square pore side's size of 750 µm non galvanized (500 ml standard solution) in 750 ml cylinder (Hight = 22 cm, Diameter –7 cm) | 5 seconds | No agitation | 94,0 | One passing |

| Experiment series | Experiment code | Short description | Contact time | Agitation | Cr(VI) removal efficiency (%) | Comments |
|---|---|---|---|---|---|---|
| column experiments) | 4-2 | 2 iron screen sheets (9cm X 83cm each), with wire diameter of 100 μm, square pore side's size of 750 μm non-galvanized and oxidized (500 ml standard solution) in 750 ml cylinder (Hight = 22 cm, Diameter –7 cm) | 5 seconds | No agitation | 1st pass = 43,0%<br>2nd pass = 39,1%<br>3rd pass = 91,4 % | Three passings of standard solution (before the third passing, a mild mechanical removal of oxides from iron screens was performed) |
| | 4-3 | Iron wool with fiber diameter of 60 μm, specific density of 0,0076 g/m or 131,154 m/g non-galvanized (100 ml standard solution) | 5 seconds | No agitation | 89,6 | One passing |
| | 4-4 | Iron wool with fiber diameter of 60 μm, specific density of 0,0076 g/m or 131,154 m/g non-galvanized and partially oxidized (100 ml standard solution, prepared with mineral water) | 5 seconds | No agitation | 100,0 | One passing |
| | 4-5 | Iron wool with fiber diameter of 60 μm, specific density of 0,0076 g/m or 131,154 m/g non-galvanized (100 ml standard solution, prepared with mineral water)) | 5 seconds | No agitation | 98,9 | One passing |
| 5th series (tube experiments) | 5-1 | Polypropylene tube, length of 1m, diameter of 0,35 cm and volume of 9,61 ml, with 1m non galvanized iron wire of 1mm diameter | 2,91 seconds** | No agitation | 35,7 | Average flow of 3495 ml/h |
| | 5-2 | Polypropylene tube, length of 1m, diameter of 0,75 cm and volume of 44,15 ml, with 1m non galvanized iron wire of 1mm diameter | 19,95 seconds** | No agitation | 26,5 | Average flow of 3495 ml/h |
| | 5-3 | Polypropylene tube, length of 1m, diameter of 1,00 cm and volume of 84,91 ml, with 1m non galvanized iron wire of 1mm diameter | 66,46 seconds** | No agitation | 18,6 | Average flow of 3495 ml/h |
| | 5-4 | Polypropylene tube, length of 1m, diameter of 1,00 cm and volume of 84,91 ml, with 3 non galvanized iron wires of 1m each 1mm diameter) | 66,46 seconds** | No agitation | 43,7 | Average flow of 3495 ml/h |

* Contact time calculated from: $C_t = \frac{V_{pore}}{Q_F}$

Where: $C_t$ is the contact time; $V_{pore}$ is the pore volume of the media that can be occupied by water solution; $Q_F$ is the volumetric feed.

** Contact time = Retention time (hydraulic) calculated from: $HRT = \frac{V_{vessel,active}}{Q_F}$

Where: $HRT$ is the hydraulic retention time in the vessel (tube); $V_{vessel,\ active}$ is the active volume of the vessel; $Q_F$ is the volumetric feed.

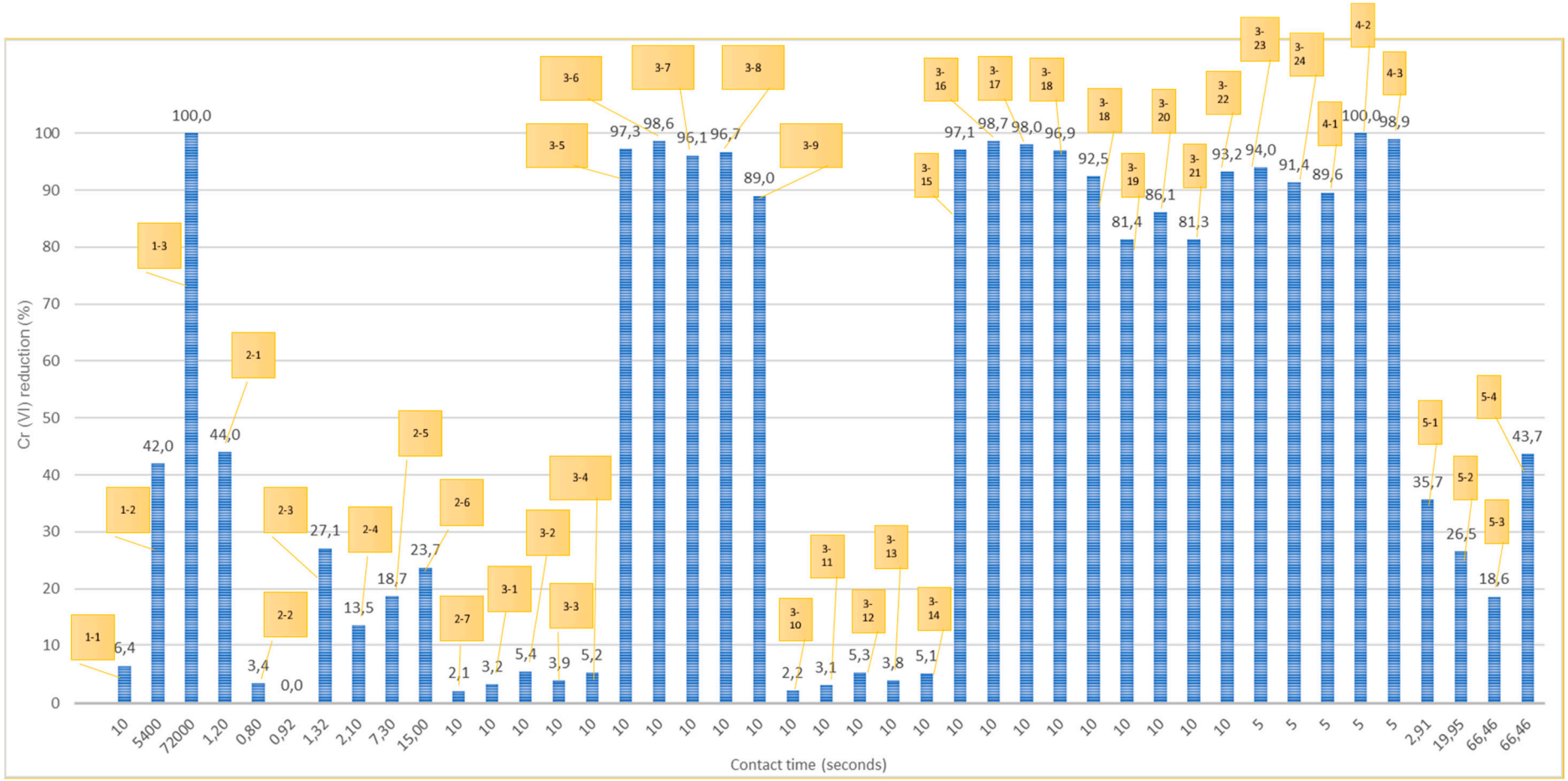



**Figure 1.** Maximum Cr(VI) reduction/removal efficiency (%) in relation to contact time and experimental setups of Table S2.

Environmental Sciences Proceedings