12th World Bamboo Congress

Taiwan, 18-22 April, 2024

www.worldbamboo.net

Bamboo activated carbon as a material for designing multi-layered simple water filter

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Abstract

Nearly 800 million people around the world lack clean and safe drinking water for daily use. Providing more clean drinking water through simple water filtration equipment, and locally available filter materials are possible to decrease the diseases. This study used bamboo activated carbon (BAC) as the material used in the design of Multi-Layered Simple Water Filter (MSWF). The BACs were prepared by using easily available bamboo. The difference pore characteristics of BAC with adsorption and/or filtration functions was used as the feasibility of obtaining clean drinking water. Depending on the activation duration for 60, 90 and 150 min, the BACs with different pore characteristics were prepared. By using a multi-layer filtration to process-purified water, the BACs showed the range of iodine index from 362 to 891 mg/g, and the turbidity, total hardness, nitrite nitrogen, coliform, and total bacterial count of the treated water was 1.30 NTU, 89.02 mg/L, 0.05 mg/L, 0.00 CFU/mL, and 26.00 CFU/mL, respectively, all of them reached drinking water quality standards in Taiwan. In the Ames tests, the residual bacteria rate of the cytotoxicity for the treated water was higher than 80% of the control, indicating a lack of cytotoxicity. The mutagenicity of both was not over spontaneous revertants of the control group by more than two times, signifying no mutagenicity. The BACs with different pore characteristics offer the potential development of water quality purification, and can be widely used in places lacking clean water. Especially in poor African regions, every 2 minutes is more children die of disease due to lack of clean drinking water. Based on above results, the bamboo enables to prepare the adsorption filters. The BACs with different pore characteristics combined for the MSWF designed in this study can achieve the accessibility of clean drinking water needs.

Keywords Bamboo activated carbon; Multi-Layered Simple Water Filter; Adsorption Filter Function; Drinking Water; Product Design

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1. Introduction

Bamboo charcoal (BC) has a particular pore structure, surface functional group, chemical stability, mechanical strength, acid resistance, alkali resistance and heat resistance, and can provide strong adsorption characteristics (Lin et al. 2003). In general, activated carbon (AC) is a good adsorbent for gaseous and liquid adsorption and is widely applied in the purification, de-colorization, and removal of toxic substances, as well as the treatment of wastewater (Manocha 2003; Yorgun et al. 2009; Sun and Jiang 2010). Hence, the BC, after being refined by activation, becomes bamboo activated carbon (BAC) that retains the charcoal's characteristics, and its absorption capacity is higher than that of BC (Weng 2010). The advantage lies in sourcing carbon materials locally, enabling the replacement of filter carbon at any time for long-term use. Access to safe water can transform challenges into opportunities, leading to improved health, economic growth, expanded educational access, and poverty alleviation. Previous work (Lin et al. 2014) has established that the iodine value-886 to 1068 mg/g of BAC, refined from BC, is higher than that-141 to 623 mg/g of BC. The true density-2.11 g/cm^3 and BET surface area-791.22 m^2/g of BAC are obviously higher than those-1.68 g/cm^3 and 138.70 m^2/g of BC. Moreover, BAC belongs to the micro/mesopore multi-structure because the average pore diameter is 2.22 nm. Lee et al (2014); Weng (2010) reported that the BET specific surface area of BAC, prepared by using the method of physical activation, can reach commercial AC, normally ranging from 500 to 1500m^2/g (Huang 2002). According to the Brunauer-Deming-Deming-Teller (BDDT) classification, the nitrogen adsorption-desorption isotherms of the BAC are classified as type IV with the hysteresis loop, presenting the possibility of adsorption-desorption porosity; in addition, BAC can be used as functional water purifying material (Liu 1998; Lin et al. 2014; 2015). The extensive use of chemical substances, their environmental accumulation, and chemical reactions contribute to environmental pollution and pose significant risks to human health. Mutagenicity refers to alterations in the genetic characteristics during the DNA replication process, where genetic information is stored in biological cells, resulting from exposure to toxic chemicals. When source water is heavily polluted, it may exhibit mutagenic properties, thereby increasing the likelihood of cellular mutations. Additionally, an excessive dosage of chlorine in the source water can lead to a heightened carcinogenic risk. The genetic mutations induced by chemical substances can be assessed through the Ames test (Ames et al. 1975; Maron and Maron 1983). BAC derived from bamboo via steam activation with various activated conditions, and was utilized to purify source water employing the self-design of Multi-Layered Simple Water Filter (MSWF), meaning a multi-layer filtration system. Both the untreated water and water treated with the prepared BAC in MSWF were subjected to cytotoxicity assessments and mutagenicity evaluations using the Ames test. This integration of a straightforward product structure and design aims to enhance user convenience and facilitate the acquisition of clean water from natural sources, particularly in remote mountainous regions and post-disaster scenarios, such as: the poor African regions.

2. Materials and methods

2.1. Multi-Layered Simple Water Filter

In the field of product semantics, there exists a cyclic relationship between the product's appearance and the user. This cycle encompasses various stages, starting from needs analysis, design concept generation, prototype testing, modification, and optimization, and continuing through production and release, culminating in user feedback and product improvement. Krippendorff (1996) has previously proposed that artifacts possess two primary aspects in the realm of product semantics: "form" and "meaning." Users understand the purpose of an object through its form and meaning. The study utilizes the concept of this cycle with a focus on functional design to ensure that a product's appearance effectively conveys the required meaning and functionality, thereby reducing user uncertainties during the utilization process.

The design of Multi-Layered Simple Water Filter (MSWF) was included a fine mesh sieve, polypropylene, a plastic injection process, and filter paper. The product featured a safety and easy-to-open closure with a durable shell. It utilized BC and BAC that effectively absorb residual chlorine, colloids, heavy metal elements, and various organic substances. Additionally, it efficiently removes peculiar colors and odors, ensuring that the filtered water is not only safe but also pleasant to drink. This water filtration system offered a comprehensive solution to ensure the purity of your drinking water. It effectively filtered out a wide range of impurities, including suspended solids such as rust, worm eggs, and cysts. The ultrafiltration membrane further enhanced its capabilities by removing harmful bacteria and viruses. BC and BAC played a pivotal role in this filtration process, as its primary function was to adsorb substance. The MSWF with BC and BAC filtered with temperatures reaching 800 to 1000ºC in a low-oxygen environment (Lin et al. 2014, 2015) was prepared as follow.

2.2. Bamboo charcoal

The bamboo charcoal (BC) was Moso bamboo (*Phyllostachys heterocycla* Milf), manufactured in earth kilns at a temperature of 700-800ºC (Hung 2004; Lin and Hwang 2006) as the precursor; it was ground and sieved to the size of 10-40 mesh, and then dried in a vacuum oven overnight at 105ºC.

2.2.1. Preparation of bamboo charcoal carbon

The prepared bamboo activated carbon (BAC) used the physical activation method. The precursor, 30 g of oven dried BC, was activated in a closed container of super-high temperature vacuum carbonization activation equipment (Chi-How Heating Co. Ltd.). Nitrogen (N_2 gas) was added to make the container oxygen free. The heating rate was set at 10ºC/min to carbonization temperature in the range of 700, 800 and 900ºC. The steam activation was carried out at 700, 800, and 900ºC with the activation duration for 60, 90 and 150 min, respectively. The flow rate of steam was maintained at 200 mL/min. The BACs were then cooled by N_2 gas to a normal temperature and taken out (Chang et al. 1998; Juang et al. 2000; Tseng et al. 2007; Lee et al. 2014; Lin et al. 2014; 2015). The equation for the BAC yield (Y) is Y (%) = (bone dry weight of BAC / absolute dry weight of BC) × 100.

2.2.2. Characterization of BC and BAC

pH value: BC and BAC were determined according to CNS 697 (1965).

Iodine value: according to JIS K 1474 (1991).

True density: by the Ultrapycnometer 1000 (Quantachrome Instrument Co.Ltd.) (Hwang et al., 2013).

Characterization measurements: the nitrogen adsorption-desorption isotherms measured using a Micromeritics ASAP 2020. The BET specific surface area (SBET), and Barret-Joyner-Halenda (BJH) (Barrett et al. 1951) were used to measure (Hu and Srinivasan 1999).

2.3 Water tests

2.3.1. Physical item: The turbidity was tested by the water turbidity detection method-turbidimetric method (NIEA W219.52C 2005). The total hardness was tested by the in water total hardness detection method-EDTA (Ethylenediaminetetraacetic acid) titration (NIEA W208.51A 2006).

2.3.2. Chemical item

2.3.2.1. pH value: by the in-water hydrogen ion concentration measuring method-electrode method (NIEA W424.52A 2008).

2.3.2.2. Nitrite nitrogen: by the in-water nitrite nitrogen detection method-spectrophotometry (NIEA W418.52C 2013b).

2.3.3. Biological item

2.3.3.1. The coliform: by the commercial quick test method; namely, Chromocult coliform.

2. 3.3.2. The total bacterial count: by the total bacterial count detection method-mixed dilution method (NIEA E204.55B 2013a).

2.4. Ames tests

The *Salmonella typhimurium* (*S. typhimurium*) TA98 and TA100 were used as test strains (Mortelmans and Zeiger 2000).

2.4.1. The cytotoxicity testing: the residual bacterial count (Survival, %) has to be higher than 80% of the residual bacterial count of the Control, meaning that the specimen has no toxic response to cells (Waleh *et al*., 1982). Survival (%) = [(the bacterial count of the tested water / the bacterial count of the Control)] × 100.

2.4.2. The mutagenicity test: if the specimen induced by spontaneous revertants is two times higher than the Control's, i.e. mutagenicity ratio (MR) above 2.0, it means the specimen has mutagenicity (Ames *et al*., 1975). MR = induced revertants per plate/spontaneous revertants per plate (Control).

2.5. Statistical analysis

The results are represented by mean (standard deviation). The statistical analysis was conducted using SPSS 12 (Statistical Product and Service Solutions) and Duncan's multiple range test (ρ<0.05). Different letters represent significant difference, while the same letter (same subset) represents no significant difference.

3. Results and discussion

3.1. Multi-Layered Simple Water Filter

The MSWF, shown in Fig. 1., has been developed using the polypropylene. The BAC and BAC based on particle size and porosity characterization, placed in the MSWF. Utilizing the force of gravity, water specimen was filtered from top to bottom. The first layer consists of a fine mesh sieve to filter out larger particles BC with a lower activated temperature (60^{o}C), followed by the second layer of BAC with the 90^{o}C of activated temperature for water treatment. Finally, the multi-layered filtration process was completed by the Self-designed filter paper (Lin and Fujimoto 2017; Lin et al. 2017), ensuring the quality of the filtered water. The design prioritizes functionality with a circular appearance, reducing the risk of container damage from transportation or collisions. The exterior was molded using the polypropylene from a plastic injection process for minimizing mold and manufacturing costs, reducing production waste significantly. This was considered to a single-material usage allows for direct recycling and reuse after damage.

The product featured a safety and easy-to-open closure with a durable shell. It utilized BC and BAC that effectively absorb residual chlorine, colloids, heavy metal elements, and various organic substances that can be harmful to the human body. Additionally, it efficiently removes peculiar colors and odors, ensuring that the filtered water is not only safe but also pleasant to drink. This water filtration system-MSWF offered a comprehensive solution to ensure the purity of drinking water. It effectively filtered out a wide range of impurities, including suspended solids such as rust, worm eggs, and cysts. The ultrafiltration membrane further enhanced its capabilities by removing harmful bacteria and viruses, guaranteeing that water was safe to consume. BC and BAC played a pivotal role in this filtration process, as its primary function was to adsorb substance. The MSWF with BC and BAC filtered with temperatures reaching 800 to 1000ºC in a low-oxygen environment (Lin et al. 2014) was prepared as follow.

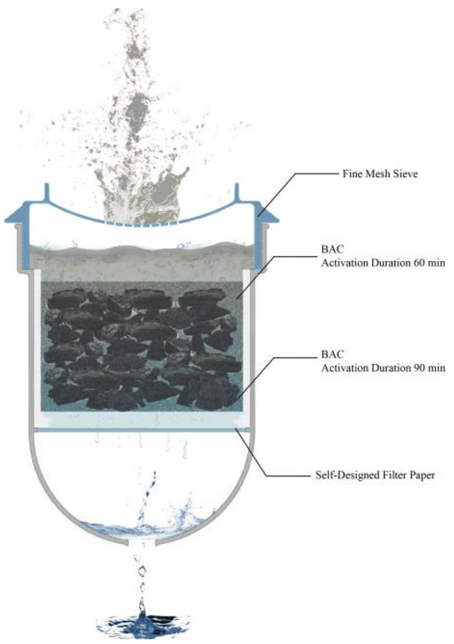

Figure 1. Illustrations of Multi-Layered Simple Water Filter

3.2. Characterization of BC and BAC

The yield of BAC was from 58.02 to 90.59%, using steam activation at activation temperatures of 700, 800 and 900ºC and activation duration of 60, 90 and 150 min, respectively. The characterizations of AC are dependent on the activation temperature and duration (Chang et al. 1998, 2003; Zhang et al. 2004; Tseng et al. 2007; Huang et al. 2010; Wu et al. 2010; Peng et al. 2010). The pH value of BC was 7.87. When the activation temperature and duration increased, the BAC became alkaline, 9.87-11.10%. This is because the AC prepared from precursor contains abundant natural mineral substances of Ca, Mg, Fe, K, Mn, and P metal ions, and the different compounds are generated and dis- charged. A higher temperature is required for the reaction to form oxides, which may be because its pH is alkaline (Gundale and Deluca 2006; Neary et al. 1999). The iodine value of BAC was 362.17-933.45 mg/g, which was higher than the value of BC, 277.55 mg/g. The iodine value of BAC prepared with duration at 90 min at 800ºC and 900ºC for over 90 min was the highest range, 870.43-933.45 mg/g. This indicates that a higher temperature and duration results in expansion on micropores or a burn–off on the carbonaceous surface because of uneven activation; that is, the micropores' neighbor is ruined and its pore scale is expanded (Zhou et al. 2003; Aworn et al. 2008).

The true density of BAC was from 1.90 to 2.02 (g/cm^3). Salvador and Jiménez (1999) report that true density is the density of the solid material, excluding the volume of any open and closed pores. The SBET, Sex and Vtot of the selected BAC increased as the activation temperature increased. The percentage of Vmi/Vtot for BAC had some micropores over 86%, but physical activation has pore– drilling and expansion effects at 800ºC, producing multiple micropores (Lua and Guo,2000; Yun et al. 2001). The average pore diameters of BAC were from 1.94 to 2.18 nm. According to the BDDT classification, the selected BAC was Type IV, indicating the micro-mesopore content of the adsorbents, and was H4 type hysteresis loops with most of the microporous structures in accordance with the International Union of Pure and Applied Chemistry (IUPAC). The formation of mesopores is known to be enhanced by an increase in the activation temperature or the flow rate of steam (Zhou 2003; Aworn et al. 2008).

3.3. Water purification

The turbidity and total hardness of the source water was 2.39 NTU and 243.62 mg/L, respectively. The source water purified separately by prepared BC and BAC with the standing and filtration methods for the turbidity and total hardness were 16.29 to 40.20 NTU and 9.37 to 224.99 mg/L, respectively. However, the turbidity was higher than the standard at 2 NTU. This study used the multi-layer filtration method to retry the source water purification. As shown in Table 1, the turbidity was 1.30 to 1.86 NTU with the flow velocity of 10 mL/min, meeting the quality standard for drinking water, with about 22.18 to 45.16 percent removal (PR), but with the 5 mL/min it was 1.85 to 2.18 NTU after filtration. This is indicated that the decrease of turbidity is influenced by the multi-layer filtration method at a flow velocity of 10 mL/min. The total hardness decreased after filtration. In other words, the hard water or moderately hard water would become soft water, with Ca^{2+}, Mg^{2+}, Sr^{2+} and Fe^{2+} removed by treatment with AC or/and BAC (Lin et al. 2015, 2017).

The pH value and the nitrite nitrogen concentration of source water were 7.26 and 0.08 mg/L, respectively. After the use of the BC and BAC standing and filtration methods, the pH value increased to 8.10-10.14 and the nitrite nitrogen decreased to 0.02-0.08 mg/L. The pH value and the nitrite nitro- gen concentration of the treated water, purified by the multi-layer filtration method, were 8.84-9.80 and 0.05-0.08 mg/L, respectively, with different flow velocity. The pH value increases because AC becomes alkaline by means of the Lewis Bases-like effect (Zhu et al. 2012), and AC surface produces more basic functional groups with a higher activation temperature (over 800ºC) (Park and Kim, 2001; Zhu et al. 2012). For the decrease of the nitrite nitrogen concentration, the basic alkaline functional group of AC can adsorb nitrite nitrogen (Cabal et al. 2009; Nunell et al. 2012).

Table 1. Turbidity and total hardness [1] and its percent removal of water specimens after treating by the multi–layer filtration method

Purification method, water specimen and flow velocity			Turbidity (NTU)	PR (%) [2]	Total hardness (mg/L)	PR (%)
Source water			2.39 (0.73) b3)	-	243.62 (13.25)d	-
Multi-layer filtration method	T700 [4]	5 mL/min	2.18 (0.16) b	8.79	193.98 (2.99) c	20.38
		10 mL/min	1.86 (0.07) ab	22.18	200.08 (9.13) c	17.87
	T800	5 mL/min	2.03 (0.12) b	15.06	89.02 (6.63) a	63.46
		10 mL/min	1.30 (0.17) a	45.61	121.81 (0.00) a	50.00
	T900	5 mL/min	1.85 (0.08) ab	22.59	121.81(13.25) a	50.00
		10 mL/min	1.81 (0.12) ab	24.27	117.13 (6.63) a	51.92

1) Turbidity and total hardness of water quality standard for drinking water source is 2 NTU and 300 mg/L (reached drinking water quality standards in Taiwan)

2) Percent removal (PR, %) = [(turbidity (or total hardness) of blank – turbidity (or total hardness) of water specimen after treating with BAC) / turbidity of blank] × 100

3) Mean (standard deviation) with the different superscripts are significantly different ($\rho<0.05$) by Duncan's

multiple range test

4) Bamboo activated carbon (activation temperature)

The AC with the strongly alkaline solution condition can cause bacterial death and/or the bacteria to be adsorbed (Uraki et al. 2008). As shown in Table 2., the coliform of the source water was 158.50 CFU/mL, and the treated water after purifying with the multi-layer filtration method was 1.50-10.50 CFU/mL with the flow velocity of 5 mL/min, not meeting the quality standard for drinking water (0.06 CFU/mL); even the PR was about 95.58 to 99.05%. With BAC prepared in 900ºC of activation temperature at the multi-layer filtration with 10 mL/min of flow velocity, it met the quality standard for drinking water, and the PR was 100% (0.00 CFU/mL). For the total bacterial count, the source water was 1688.18 CFU/mL. The PR (total bacterial count) for water specimens reached 90.46-92.54% (161.00-124.52 CFU/mL), but it was higher than the quality standard for drinking water, 100 CFU/mL. The total bacterial count of the treated water was 26-73 CFU/mL because the total bacterial count in water effectively decreases as the AC characterizations increase (Ogawa et al. 2011).

Table 2. Coliform and total bacterial count [1] and its percent removal of water specimens after treating by the multi–layer filtration method

Purification method, water specimen and flow velocity			Coliform (CFU/mL)	PR (%) [2]	Total bacterial count(CFU/mL)	PR (%)
Source water			158.50 (61.5) [b3)]	-	1688.18 (9.09) [f]	-
Multi-layer filtration method	T700[4)]	5 mL/min	7.00 (0.00) [a]	95.58	144.00 (16.00) [cd]	91.47
		10 mL/min	4.00 (1.00) [a]	97.48	161.00 (9.00) [d]	90.46
	T800	5 mL/min	10.50 (2.50)[a]	93.38	124.52 (9.98) [c]	92.54
		10 mL/min	5.00 (4.00) [a]	96.85	145.00 (3.00) [cd]	91.31
	T900	5 mL/min	1.50 (0.50) [a]	99.05	26.00 (1.00) [a]	98.44
		10 mL/min	0.00 (0.00) [a]	100.00	73.25 (1.25) [b]	95.63

[1)] Coliform and total bacterial count of water quality standard for drinking water source is 0.06 CFU/mL and 100 CFU/mL (Environmental Protection Administration, 2013c)

[2), 4)] See the Table 2 [2), 4)]

[3)] See the Table 1 [3)]

3.4. Ames test

The cytotoxicity of the source water and the treated water after the multilayer filtration method at the flow velocity of 5 and 10 mL/min for *S. typhimurium* TA98 and TA100 strains are shown that the bacterial count of the Control without S9 mixture was 2673 in TA98, and 1290 in TA100; the TA98 with S9 mixture was 1790, and TA100 was 2530. The bacterial count of source water and water specimens without the S9 mixture was 2140-3527 in TA98 and 1437-1717 in TA100, and Survival was 80-133%. The TA98 and TA100 with the S9 mixture were 2437-3040 and 2237-2763, respectively, and Survival was 88-169%. The source and the treated waters had no cytotoxicity. It is said that that if the Survival of the source and the treated waters in TA98 and TA100 strain tests is higher than 80% of the Control; the mutagenicity can be carried out (Waleh et al. 1982). The mutagenicity are shown in Table 3. The revertants of *S. typhimurium* TA98 and TA100 induced by source water, purifying with the multi–layer filtration method at the flow velocity of 5 and 10 mL/min with and without the S9 mixture, had not exceeded double the spontaneous revertants of the Control, meaning they had no mutagenicity (Ames et al. 1975). It indicated that that the source water before and after purification had no mutagenicity toward *S. typhimurium* TA98 and TA100.

Table 3. Mutagenicity of source water and water specimens after treating with bamboo activated carbon by multi–layer filtration meth- od toward *Salmonella typhimurium* TA98, TA100 without (-S9) or with S9 (+S9) mixture

Water specimen	TA98				TA100			
	–S9	MR [1)]	+S9	MR	–S9	MR [1)]	+S9	MR
Control [2)]	290 (111) [3)]	1.0	174 (15)	1.0	176 (6)	1.0	208 (12)	1.0
Source water	154 (35)	0.5	271 (6)	1.6	154 (5)	0.9	274 (18)	1.3
5 mL/min [4)]	46 (5)	0.2	199 (21)	1.1	40 (4)	0.2	64 (15)	0.3
10 mL/min	184 (60)	0.6	243 (87)	1.4	57 (1)	0.3	69 (3)	0.3

[1)] MR (Mutagenicity ratio) = induced revertants per plate/spontaneous revertants per plate (Control)

[2] Control: only with 0.1 mL phosphate buffer saline

[3] Mean (standard deviation)

[4] Flow velocity

Conclusions

This study evaluated BC and the BAC with the MSWF for purifying source water, and performed the Ames test to ensure the preliminary safety of water quality before and after purification. The turbidity, total hardness, nitrite nitrogen, colifandm group and total bacterial count of purified source water were 16.29 NTU, 28.11 mg/L, 0.02 mg/L, 0.00 CFU/mL and 151.00 CFU/mL, respectively. Meanwhile, after treating by MSWF with the BAC prepared from BC at 900ºC and 90 min of activated duration with 10 mL/min of flow rate, the treated water turbidity was 1.81 NTU; the pH value in water was increased in solution; The total hardness was 117 mg/L; The nitrite nitrogen concentration could be reduced, and the total bacterial count in water was removed by 95.63%.The bacterial survival rate of cytotoxicity testing for source water before and after purification was higher than 80% of the Control, meaning there was no cytotoxicity. The mutagenicity results showed that two times, indicating no mutagenicity did not exceed the spontaneous revertants of the source and the treated water. Combining a simple water filtration device-MSWF, it can be widely distributed in impoverished areas, meeting the basic need for clean drinking water for more people. Notably, the use of BC and BAC allowed for easy replacement, ensuring long-term and sustainable use of the filtration system. Access to safe water has the potential to address various challenges, including improved health, economic development, enhanced educational opportunities, and poverty reduction.

Conflict of interest

Authors declare there is no conflict of interest.

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