

The innovative simple water filter for producing utility water using activated carbon from rubber tree branches

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Abstract

This study presents the development of a cost effective and an innovative household water filtration system utilizing activated carbon derived from locally sourced rubber tree branches. Aimed at improving tap water quality in the Ban Kut Saeng Community, Sakon Nakhon Province, Thailand, the research promotes sustainable material use and simple technology to enhance the availability of clean water in underdeveloped and developing regions. Activated carbon was produced through a dry activation process using NaOH, yielding high adsorption capacity 687.24 mg I₂/g for iodine and complete (100%) methylene blue removal at 100 ppm. BET surface area analysis indicated a value of 833.06 m²/g, with the pore structure exhibiting both microporous and mesoporous characteristics. The filtration performance was evaluated by comparing raw and treated water quality based on the standards of the American Public Health Association (APHA), American Water Works Association (AWWA), and Water Environment Federation (WEF), covering physical, chemical, heavy metal, and microbiological parameters. The raw water has shown high turbidity and bacterial contamination. Following two-stage filtration, Sample D exhibited the tap water quality standards, with turbidity of 9 NTU, apparent color of 2.1 Pt-Co, total dissolved solids (TDS) of 151 ppm, pH of 6.8, total hardness of 30 ppm as CaCO₃, and chloride ion concentration of 9.8 ppm. Total coliforms and *E. coli* counts were observed below the detectable limits (<1.1 CFU/100 mL), and heavy metals or other harmful ions found to be absent. The results have confirmed the system's high efficiency in contaminant removal and water quality improvement, underscoring its potential as a low-cost, community-driven solution for household water treatment in the resource-limited areas.

Key words: Innovative simple water filter, Utility water, Activated carbon, Rubber tree branches, Absorbent, Innovative simple biomass incinerator

1. Introduction

Water is essential for human life; globally, in which about 70% of freshwater consumption has been used for agriculture, 22% for industry, and 8% for domestic purposes, with only a small fraction allocated to recreational activities [1, 2]. Despite its vital role, freshwater represents only 3.46% of the Earth's total water resources, and nearly 99% of that is inaccessible, being stored mainly in glaciers and deep groundwater reserves [3-6]. Therefore the availability of clean and safe water remains as a critical global challenge, especially in the developing countries. This issue is explicitly addressed in the United Nations Sustainable Development Goals (SDGs), particularly Goal 6, which promotes the sustainable water management and access to safe drinking water by 2030 [7, 8]. Hence, achieving these targets has led to the need of innovative, cost-effective, and locally adaptable water treatment technologies.

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Activated carbon is widely recognized as an effective material for water purification due to its high adsorption capacity, large specific surface area, and relatively low production cost [9-12]. The activated carbon produced through either chemical or physical activation typically exhibits surface areas of 600–2400 m²/g and pore volumes of 0.20–1.00 cm³/g, enabling an efficient removal of organic contaminants, microorganisms, and other undesirable compounds from water [13-17]. Among the available methods, chemical activation using agents such as KOH, NaOH, and ZnCl₂ is particularly attractive because it allows pore development at lower temperatures and facilitates the formation of well-developed porous structures [13, 18-21]. Numerous studies have demonstrated the successful production of high-performance activated carbon from biomass sources such as bamboo, coconut shells, and oil palm residues, confirming both technical feasibility and economic advantages [13, 22, 23].

Beyond freshwater scarcity, surface water sources are increasingly contaminated by suspended solids, nutrients, pathogenic microorganisms, heavy metals, and emerging contaminants, including pharmaceuticals and personal care products (PPCPs). These pollutants originate mainly from domestic wastewater, agricultural runoff, hospital effluents, and inadequately treated sewage. Recent studies have reported the widespread occurrence of pharmaceutical residues in surface waters in Southeast Asia. For example, Al-Qaim et al. detected caffeine in surface water using solid-phase extraction coupled with high-performance liquid chromatography, highlighting the persistence of pharmaceutical contaminants in natural water bodies [24]. In addition, the various therapeutic classes of pharmaceuticals from hospitals and wastewater treatment plants into surface waters has been documented, underscoring the limitations of conventional treatment systems in removing such micropollutants [25]. Due to their biological activity and resistance to degradation, these contaminants can pose potential risks to human health and aquatic ecosystems. In this context, adsorption-based treatment methods—especially those employing activated carbon—are considered as the practical and effective solutions for decentralized and community-level water treatment systems.

In recent years, the research has been focused towards the production of activated carbon from plant-based and agricultural waste materials, driven by sustainability concerns, abundant resource availability, and waste valorization. Biomass precursors such as leaves, fruit peels, seed shells, wood residues, and damaged or fallen agricultural products have been successfully converted into activated carbon with well-developed porous structures that are appropriate for filtration and adsorption applications. Several studies have confirmed the effectiveness of plant-derived activated carbon for pollutant removal. For example, activated carbons prepared from grape leaves and fig leaves have demonstrated high adsorption efficiencies for methylene blue, highlighting the importance of surface modification and pore development in enhancing the adsorption performance [26, 27]. The agricultural residues such as walnut shells have also been identified as the suitable precursors, yielding activated carbon with excellent dye removal capacity [28].

Leelatam et al. [18] demonstrated a simple and scalable method for producing activated carbon from agricultural residues using an innovative biomass incinerator, emphasizing low cost and community applicability. Likewise, Roschat et al. [29] successfully investigated the activated carbon derived from Krabok (*Irvingia malayana*) seed shells to purify crude glycerol from biodiesel production, confirming the effectiveness of agricultural waste-based activated carbon in purification processes. These studies have provided a strong scientific foundation and highlighted the potential of locally available biomass as a sustainable carbon precursor. Building on this established knowledge, the present research focuses on the utilization of rubber tree branch waste, a locally abundant agricultural by-product, as a precursor for activated carbon production. Rather than emphasizing adsorption kinetics or advanced process optimization, this study has prioritized the material preparation, physicochemical characterization, and practical implementation in a community-scale water filtration system. The proposed approach aims to develop a low-cost, locally reproducible, and sustainable water treatment solution tailored to rural communities, thereby supporting the self-reliance and long-term water security.

In the rural region of Thailand, limited budgets have constrained the water supply development, as observed in Ban Kut Saeng, Wattana Subdistrict, Song Dao District, Sakon Nakhon Province. The village peoples have been facing persistent challenges in securing the sufficient clean water. Although wells drilled to depths of 10–30 meters can provide freshwater, the yield is insufficient. Deeper wells at 30–60 meters produce brackish water unsuitable for consumption or agriculture. The village depends on Nong Kut Saeng, a water body approximately with 300 meters long, 20 meters wide, and 3–5 meters deep, has been its main water source. In 2015, Wattana Municipality constructed a water filtration plant at a cost of 355,000 baht, which was later managed by the community. However, flood in 2017 and inadequate maintenance, were largely due to limited knowledge of water system management, rendering the facility ineffective. As a result, households now rely on untreated water containing sediment and pathogens, as shown in Figure 1. Villagers have been purchasing the water at 12 baht per 20-liter tank for drinking and cooking purpose, which costs each household approximately 144–240 baht per week or 6,912–11,520 baht per year. For 80 households, this amounts to roughly 552,960–921,600 baht annually, creating a substantial financial burden. In addition, households pay about 50–100 baht per month for village tap water used for bathing and washing. The development of filtration system could reduce household expenses, strengthen local water management, and potentially generate community income while improving overall well-being. The health concerns were also reported, particularly skin irritation and itching associated with the use of unclean water. It is observed that these problems have been more common during the rainy season, when flooding at Nong Kut Saeng increases the turbidity and sediment accumulation.

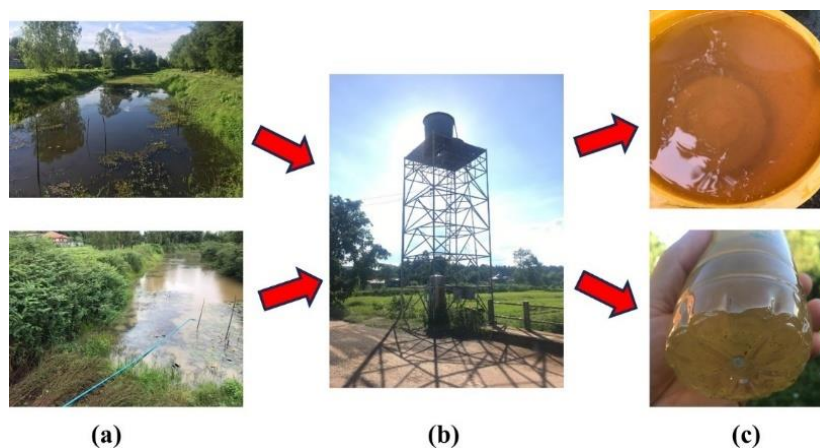


Figure 1 (a) Example image of the Nong Kut Saeng water source, (b) image of the damaged Ban Kut Saeng water supply system, and (c) characteristics of the tap water used by Ban Kut Saeng villagers for consumption.

Therefore, this research aims to develop a prototype water filter using activated carbon derived from local waste materials and a high-energy biomass stove to address water quality concerns. By enabling local production of clean water, the project seeks to reduce the financial burden of purchased water and promote self-reliance, in line with the economy requirements. The project adopts the concept of “Producing clean water that meets standards by the community, for the community,” integrating scientific and technological solutions for long-term sustainability. The research consists of three parts, as shown in Figure 2. First, activated carbon will be prepared from rubber tree branch waste and characterized using XRD, FT-IR, SEM, TEM, EDS, and BET, with adsorption efficiency evaluated by iodine number and methylene blue adsorption in accordance with TIS 900-2547 of the Ministry of Industry of Thailand. Second, a simple and cost-effective water filter will be designed for community use. Third, a comparative study will evaluate water properties before and after filtration using the prototype, following the Standard Methods for the Examination of Water and Wastewater of APHA, AWWA, and WEF, as well as the 2020 water quality standards of the Ministry of Public Health, Thailand [30, 31].

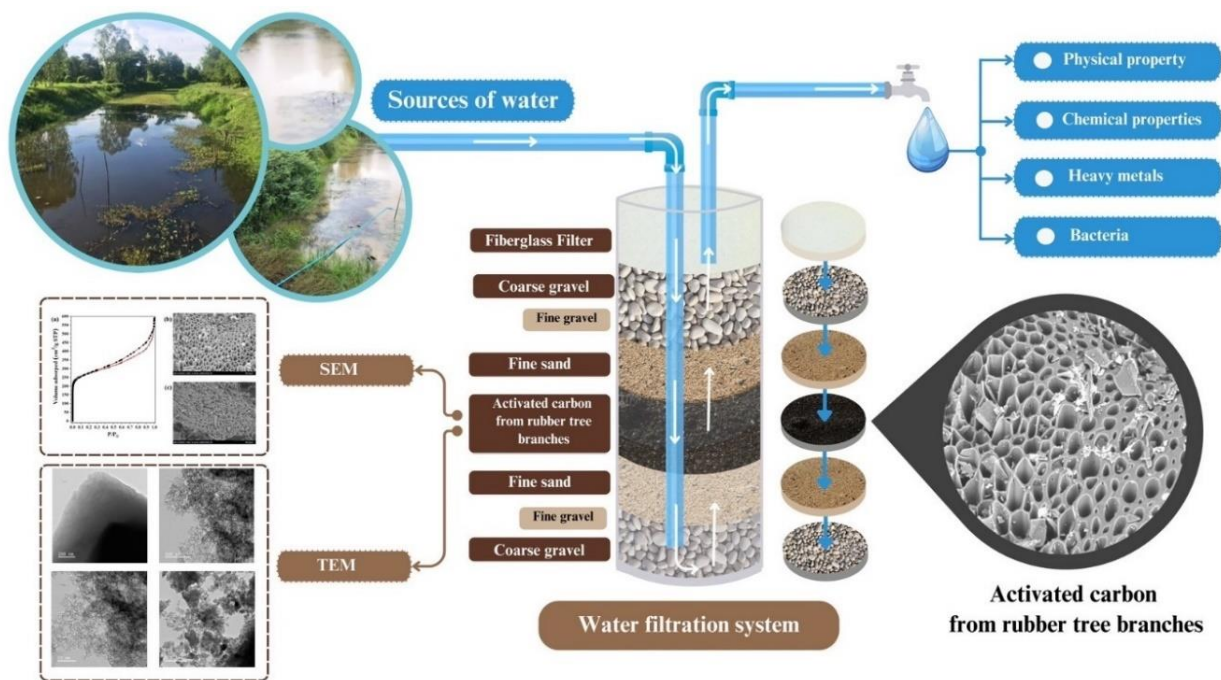


Figure 2 The flow diagram of the innovative simple water filter for producing utility water using activated carbon from rubber tree branches.

2. Materials and methods

2.1 Materials

This research has involved the collection of rubber tree branches, an agricultural waste material, from Ban Kut Saeng, a community in Wattana Subdistrict, Song Dao District, Sakon Nakhon Province, Thailand. The dried rubber tree branches were cut into small pieces of approximately 3–5 cm. The chemicals used in this experimental study are NaOH, HCl, $\text{Na}_2\text{S}_2\text{O}_3$, I_2 pellets, KIO_3 , and Na_2CO_3 , all of analytical reagent (AR) grade and supplied by Qrec. In addition, KI of laboratory (LAB) grade was obtained from Ajax, and methylene blue of laboratory (LAB) grade was supplied by KemAus™. The water samples used in this study were collected from Nong Kut Saeng in Ban Kut Saeng, Wattana Subdistrict, Song Dao District, Sakon Nakhon Province, Thailand.

2.2 Preparation of activated carbon

Rubber tree branches were first cut into small pieces, placed in containers, and weighed before carbonization in an innovative biomass incinerator at 600–800 °C for 2 h. After cooling, the carbonized material was weighed, and finely ground a portion and passed through a 60-mesh sieve (approximately 0.25 mm) for further use. The overall process for converting rubber tree branch agricultural waste into carbonized and activated carbon is shown in Figure 3. The preparation and activation procedures were adapted from previously reported methods, with minor modifications to suit the characteristics of rubber tree branch biomass and the intended community-scale application, based on earlier studies by Leelatam et al. [18] and Roschat et al. [29].

To activate the charcoal, 100 g of ground charcoal powder was thoroughly mixed with 300 g of solid NaOH at a mass ratio of 1:3. The mixture was then heated in the biomass incinerator at 600–800 °C for 2 h. After activation, the carbon was cooled to room temperature, boiled in distilled water at 80 °C for 30 min, and then purified by vacuum filtration. The activated carbon was repeatedly rinsed with distilled water until the wash water reached neutral pH (pH 7). Finally, the material was dried at 110 °C for 12 h, ground into a fine powder, and stored in airtight containers for subsequent physicochemical characterization and adsorption efficiency analysis. This preparation route follows a two-step dry-powder chemical activation process which are consistent with previously established methods for synthesizing biomass-derived activated carbon [18, 29, 32].



Figure 3 The process diagram illustrates the preparation of carbonized carbon and activated carbon from agricultural waste materials derived from rubber tree branches.

2.3 Physicochemical properties and adsorption efficiency analysis of the obtained activated carbon samples

The activated carbon samples derived from the agricultural waste of rubber tree branch were characterized using a range of analytical techniques. X-ray diffraction (XRD) analysis was performed using a PANalytical X'Pert Pro MPD instrument from the Netherlands. Surface area and porosity measurements were evaluated through Brunauer–Emmett–Teller (BET) analysis using a BEL BELSORP-mini II instrument from Japan. Transmission electron microscopy coupled with energy-dispersive spectroscopy (TEM-EDS) analysis was carried out using a TECNAI G2 20 instrument manufactured by FEI, the Netherlands. TEM analysis was performed to investigate the internal nanostructure, pore connectivity, and disordered carbon domains at the nanoscale, which cannot be fully resolved by SEM alone. Scanning electron microscopy (SEM) analysis was conducted using a QUANTA 450 instrument manufactured by FEI, the Netherlands, to examine the surface morphology, pore openings, and pore distribution in the activated carbon samples. Fourier transform infrared (FT-IR) spectroscopy analysis was performed using a SHIMADZU FT-IR-8900 instrument from Japan. Together, these methods provided a comprehensive evaluation of the physicochemical properties and detailed structural and morphological characteristics of the activated carbon.

In addition, adsorption efficiency was assessed by measuring the iodine number in accordance with TIS 900-2004, as specified by the Ministry of Industry of Thailand, and by evaluating methylene blue adsorption using methods adapted from Leelatam et al. [18], Jantaboot et al. [21], Roschat et al. [29], Ngernyen and Kamwilaisak [32], Roschat et al. [33]. All adsorption efficiency data were averaged from three measurements, by a deviation within 3%.

2.4 Design and application of an innovative simple water filter using activated carbon from rubber tree branches

This study employed a two-component water filtration system. The filtration column was custom-designed and constructed by the author rather than using a commercially available or standard carbon filtration unit, with the aim of ensuring low cost, structural simplicity, and suitability for community-level application. The first component consisting of a coarse filtration unit was designed to remove the large suspended solids, while the second component was an innovative filtration column containing activated carbon derived from rubber tree branches to remove fine impurities, adsorb color and odor, and improve the overall water quality. The filter was constructed from polyvinyl chloride (PVC) pipes, 4 inches in diameter and 1.5 meters in height, selected for their low cost, durability, and wide availability in rural areas. Two smaller PVC pipes, each 0.5 inch in diameter, were installed as the inlet and outlet to control water flow through the system. The filtration column comprised of multiple functional layers, including coarse gravel, fine gravel, fine sand, activated carbon derived from rubber tree branches, and a fiberglass filter layer, each serving a specific role in the filtration process. Coarse and fine gravel layers provided the structural support and aids to remove large suspended particles, while the fine sand layer has reduced the turbidity and removed finer particulates. The activated carbon served as the primary adsorbent for dissolved organic matter, color, odor, and microorganisms. The fiberglass filter layer functioned as a polishing and stabilizing medium to prevent media migration and improve the long-term filtration stability.

Structurally, the filtration system consisted of sequential layers of coarse gravel, fine gravel, fine sand, activated carbon from rubber tree branches, followed by another layer of fine sand, fine gravel, coarse gravel, and a fiberglass filter, as illustrated in Figure 2. Water was introduced through the inlet pipe at the bottom of the column, flowed upward through the filtration layers, and exited through the outlet pipe. The highly porous structure of the activated carbon has enabled an effective contaminant adsorption, resulting with an enhancement in the water quality. Figure 4(a) shows the installation and operation of the filtration system, while Figure 4(b) illustrates the physical characteristics of the water samples under different conditions: [A] raw water collected from a depth of 1 meter, [B] raw surface water, [C] water after the first filtration stage, and [D] water after the second filtration stage using the activated carbon filter. During the design and construction of the filtration column, several challenges were encountered. One major challenge was balancing filtration efficiency with water flow rate. Filter media with excessively fine particle sizes have improved the turbidity removal but significantly reduced flow, whereas coarser media increased flow at the expense of filtration performance. Therefore, optimization of particle-size distribution and layer thickness was necessary to achieve the effective filtration while maintaining a practical flow rate.

Another challenge was preventing media displacement and channeling within the column. The initial trials showed uneven water flow and preferential pathways, which has reduced the adsorption efficiency. This issue was addressed by carefully arranging the filtration layers and incorporating a fiberglass support layer to stabilize the filter media and promotes the uniform water distribution. In addition, the filtration system has to be simple, durable, and easily reproducible using locally available materials, as it was intended for community-based implementation. The use of PVC pipes and inert mineral filtration media has ensured the structural durability, chemical compatibility, and long-term usability under rural operating conditions without requiring specialized tools or technical expertise.

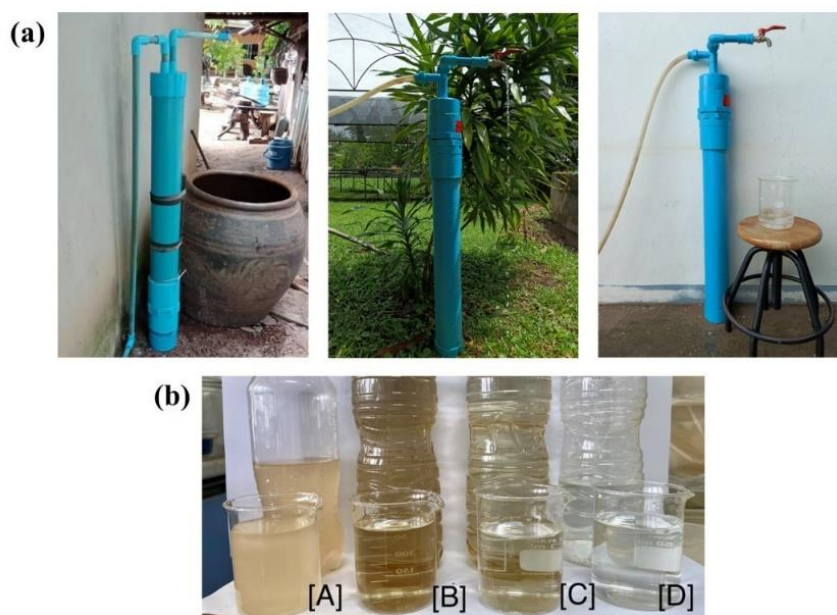


Figure 4 (a) Installation and use of the innovative water filter with activated carbon from rubber tree branches, and (b) water characteristics under different conditions: [A] raw water at 1-meter depth, [B] raw water at the surface, [C] water after first-stage filtration, and [D] water after second-stage filtration with the innovative filter.

2.5 Analysis of raw water samples and filtered water

The analysis of raw and filtered water samples was conducted based on the standard methods for the examination of water and wastewater established by APHA, AWWA, and WEF, and compared the results with the 2020 guidelines of the Department of Health, Ministry of Public Health of Thailand. The assessment covered four categories: physical properties, chemical properties, heavy metals, and bacteriological contamination. The physical parameters were measured which includes turbidity, color, and total dissolved solids (TDS). The evaluated chemical parameters are pH, total hardness, chloride, fluoride, nitrate, nitrite, and sulfate. The analyzed heavy metals were Mn, Cu, Zn, Pb, Cr, Cd, As, and Hg. Bacteriological contamination was assessed by measuring total coliform bacteria (TCB) and *E. coli*. The water samples included [B], raw surface water; [C], water filtered in the first stage; and [D], water filtered in the second stage using the activated carbon filter derived from rubber tree branches, as shown in Figure 4(b). In addition, absorbance at 530 nm was measured to evaluate turbidity and the presence of pigments using UV-Vis spectroscopy to assess suspended particles and certain organic compounds. UV-Vis spectroscopy was used to monitor water quality based on the Lambert–Beer law, which relates absorbance to contaminant concentration [34–36].

3. Results and discussion

3.1 Analysis of physicochemical properties of activated carbon synthesized from rubber tree branches

3.1.1 XRD and FT-IR analysis

The XRD pattern of activated carbon synthesized from rubber tree branches, shown in Figure 5(a), was analyzed over the 2θ range of 20° – 80° . The result has indicated an amorphous structure, with no distinct crystalline peaks. This is found to be consistent with the typical behavior of activated carbon, which generally lacks long-range crystalline order. During carbonization and chemical activation, the biomass components have decomposed, leaving a disordered carbon framework in which the carbon atoms are arranged irregularly. The synthesis conditions, including temperature and residence time have limited the formation of crystalline carbon domains. In addition, the amorphous nature of activated carbon often associated with a high surface area and a broad pore size distribution which are important for adsorption applications such as water filtration and contaminant removal. Similar amorphous XRD patterns have been reported for biomass-derived activated carbons, supporting the findings of this study for rubber tree branch-derived carbon [18, 29, 37–40].

The FT-IR spectrum of activated carbon synthesized from rubber tree branches, illustrated in Figure 5(b), shows several characteristic absorption bands. The peaks in the 2925 – 2840 cm^{-1} region are attributed to C–H stretching vibrations of methylene and methyl groups. The band at 1580 cm^{-1} corresponds to C=C stretching vibrations of alkenes, while the peaks at 1230 cm^{-1} and 800 – 756 cm^{-1} are associated with C–H bending vibrations of hydrocarbon compounds. These bands indicate that hydrocarbon-related functional groups remain on the carbon surface after activation. Such functional groups can contribute to adsorption performance by increasing the surface reactivity and promoting interactions with organic contaminants. Comparable FT-IR features have been reported for biomass-derived activated carbons. Phothong et al. [41] demonstrated that activated carbon derived from bamboo contains various surface functional groups and that its pore structure and surface chemistry are strongly influenced by the carbonization and activation conditions. Wang et al. [42] emphasized the important roles of surface characteristics and porous structures in the adsorption performance of biomass-derived activated carbons. Ullah et al. [43] reviewed the synthesis, surface properties, adsorption mechanisms, and wastewater-treatment applications of biomass-derived activated carbons. Additionally, Wang et al. [44] characterized biomass-derived activated carbon using FT-IR, BET, and SEM analyses and demonstrated its potential for contaminant removal from aqueous systems. These studies highlight the importance of FT-IR analysis in identifying surface functional groups and understanding the adsorption-related characteristics of biomass-derived activated carbons.

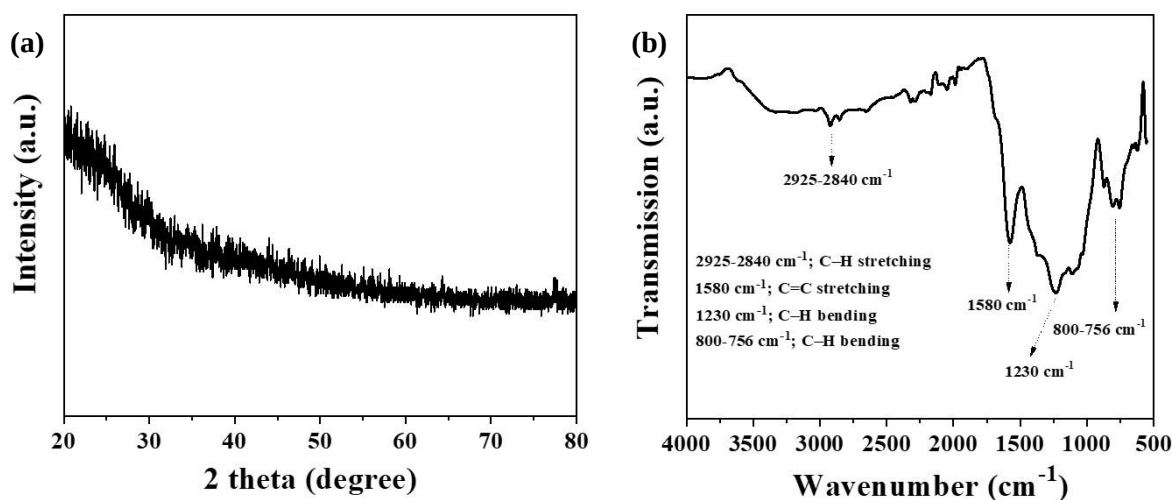


Figure 5 (a) XRD analysis and (b) the FT-IR analysis of the activated carbon synthesized from rubber tree branches.

3.1.2 Analysis of iodine and methylene blue adsorption efficiency

This study evaluated the iodine adsorption efficiency of activated carbon synthesized from rubber tree branches in accordance with the Thai Industrial Standard (TIS 900-2004) established by the Ministry of Industry of Thailand. The activated carbon exhibited an iodine number of 687.24 mg I₂/g, as shown in Table 1, exceeding the standard requirement of 600 mg I₂/g and confirming its strong adsorption capability. In addition, the methylene blue adsorption efficiency reached 100% when 1 gram of activated carbon was used to treat a 100 ppm methylene blue solution. These results are consistent with previous findings reported by Leelatam et al. [18], Roschat et al. [29], Pathania et al. [45], Ramalingam et al. [46], and Santoso et al. [47].

The activated carbon derived from rubber tree branches surpassed the national standard criteria, exhibiting superior adsorption performance for both iodine and methylene blue compared with other biomass-derived activated carbons. For example, Roschat et al. [29] reported that activated carbon from Krabok (*Irvingia malayana*) seed shells have achieved an iodine number of 611.10 mg I₂/g and a methylene blue adsorption efficiency of 99.35%. Rafatullah et al. [48] found that bamboo-derived activated carbon had an iodine number of 550 mg I₂/g with good methylene blue adsorption capacity. Similarly, Deng et al. [49] reported an iodine number of 620 mg I₂/g for activated carbon produced from cotton stalks activated with KOH, while Foo and Hameed reported their results with a value of 675 mg I₂/g from KOH-activated date palm seeds. These comparisons clearly demonstrate the superior adsorption capacity of activated carbon synthesized from rubber tree branches, emphasizing its high potential for efficient water treatment and contaminant removal applications.

Table 1 BET surface area, pore volume, average pore diameter, and adsorption efficiency of iodine and methylene blue for activated carbon synthesized from rubber tree branches.

Parameters	The activated carbon synthesized from rubber tree branches
BET surface area (m ² /g)	833.06
Total pore volume (cm ³ /g)	0.8397
Average pore diameter (nm)	4.0318
Iodine adsorption efficiency (mg I ₂ /g of the sample)	687.24
Methylene blue adsorption efficiency (%)	100

3.1.3 The BET surface area characterization from adsorption-desorption isotherms

The porous structural parameters of the activated carbon were evaluated using nitrogen adsorption-desorption isotherms measured at 77 K, in accordance with the Brunauer-Emmett-Teller (BET) method. The results, presented in Figure 6(a) and Table 1, summarizes values of the BET surface area, total pore volume, and average pore diameter. The adsorption-desorption isotherm of the activated carbon derived from rubber tree branches have exhibited a pattern consistent with the IUPAC classification, corresponding to type II and type IV behavior. This indicates the presence of both microporous and mesoporous structures.

Adsorption has occurred initially through monolayer formation, followed by multilayer adsorption as the relative pressure (P/P_0) increased. The isotherm also suggested that the pores are considerably larger than the adsorbed gas molecules, leading to bilayer molecular arrangement. At higher relative pressures, the slope of the curve was found to be increased due to capillary condensation within the pores, resulting in a pronounced hysteresis loop behavior consistent with observations reported in previous studies [13, 18, 29, 46].

The BET analysis yielded a surface area of 833.06 m²/g, a total pore volume of 0.8397 cm³/g, and an average pore diameter of 4.0318 nm. These values confirm that the synthesized activated carbon possesses a well-developed porous structure with high surface area and pore volume. The activated carbons typically exhibited the surface areas in the range of 600–2,400 m²/g, depending on the activation conditions and precursor materials [13, 18, 29, 50, 51, 52]. The average pore diameter measured here falls within the range of micropores (diameter < 2 nm) and mesopores (2–50 nm), classifying the material as a mixed micro-mesoporous adsorbent suitable for the efficient contaminant removal applications.

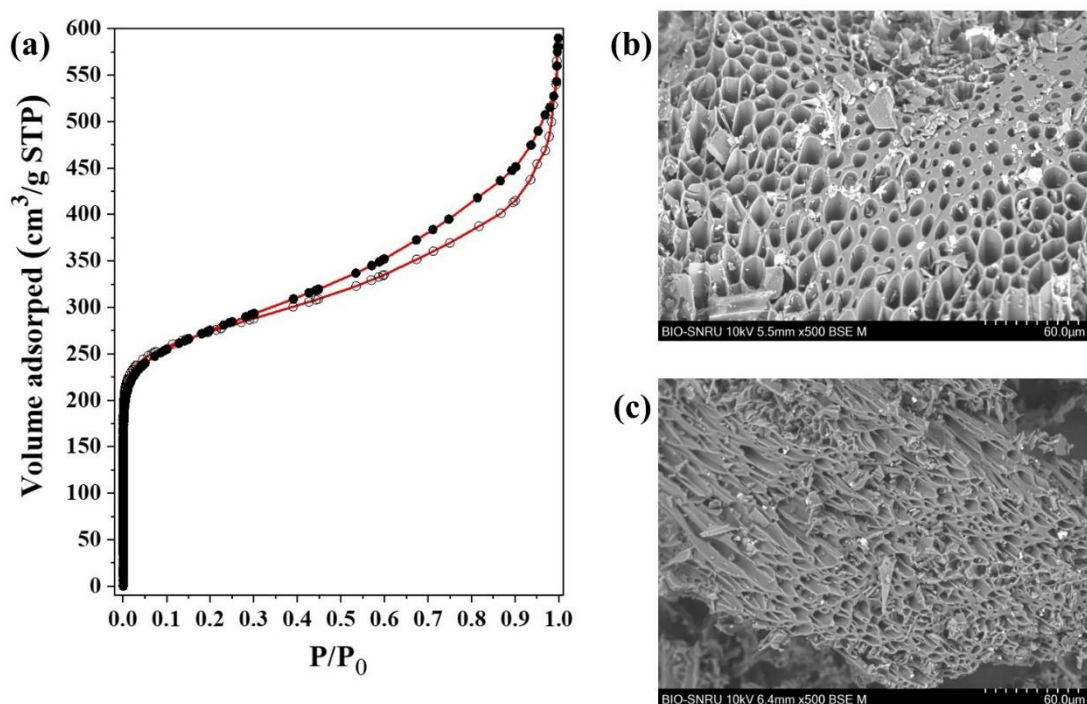


Figure 6 (a) The N_2 adsorption isotherms at 77 K, (b) and (c) SEM images of the activated carbon sample derived from rubber tree branches.

3.1.4 Surface morphology and internal nanostructure analysis by SEM and TEM

SEM images of the activated carbon derived from rubber tree branches are presented in Figures 6(b) and 6(c). The experimental observations have indicated that the samples possess relatively uniform pore sizes and well-developed pore structures, directly correlating with the adsorption performance of the synthesized activated carbon. The formation of these porous structures is primarily governed by gasification reactions occurring during NaOH activation, which plays a key role in generating the high surface area and adsorption capacity of the material. Similar mechanisms of pore development have been reported in previous studies by Mistar et al. [13], Xu et al. [14], Leelatam et al. [18], Roschat et al. [29], and Abdullah et al. [53]. While SEM analysis effectively reveals the surface morphology and pore openings, it does not provide information about internal pore connectivity or nanoscale structural characteristics. Therefore, to gain deeper insight into the internal architecture, the morphological and structural features of the activated carbon were further examined using TEM, as shown in Figure 7.

The TEM images clearly illustrate a well-organized network of internal pores and interconnected channels within the activated carbon matrix, allowing efficient electron beam transmission. These internal pore networks are critical for facilitating adsorption pathways for dissolved contaminants and microorganisms, thereby enhancing the overall adsorption efficiency. The TEM micrographs also reveal irregular, disordered carbon layers with randomly interconnected graphite-like domains formed during NaOH activation. Such turbostratic and heterogeneous structures are typical of chemically activated carbons and are associated with the coexistence of micro- and mesoporous features.

Furthermore, TEM results have provided direct nanoscale evidence of pore formation and internal structural heterogeneity, corroborating the BET surface area results and the high iodine and methylene blue adsorption efficiencies observed experimentally. The presence of electron-transparent regions in the TEM images have confirmed the pore generation through gasification during chemical activation, reinforcing the mechanistic interpretation derived from surface-level SEM analyses. Collectively, these results substantiate the gasification-based pore formation mechanism, which are consistent with findings from previous studies [18, 29, 46, 53-57].

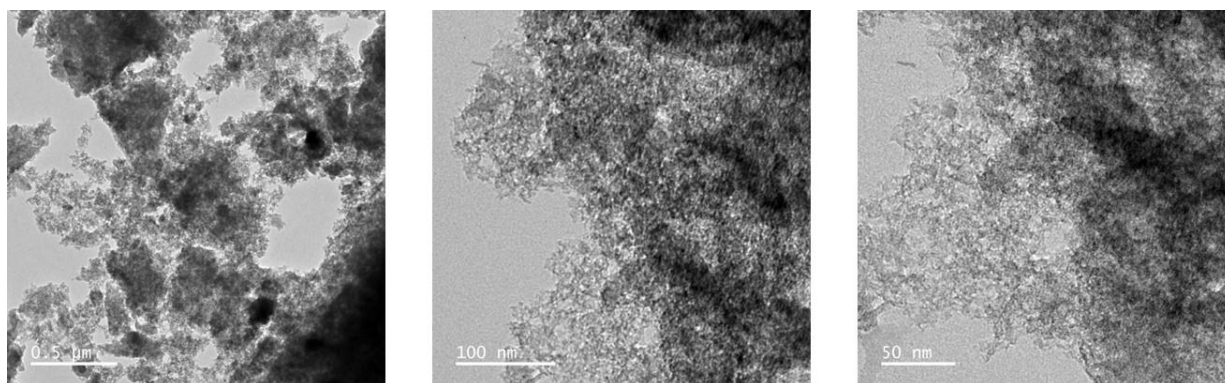


Figure 7 TEM images of the activated carbon sample derived from rubber tree branches.

3.1.5 Elemental composition analysis via energy dispersive X-Ray spectroscopy (EDS)

Elemental mapping obtained from the TEM image via EDS analysis is presented in Figure 8. The EDS results revealed that the activated carbon derived from rubber tree branches consists predominantly of carbon (C) and oxygen (O), with trace amounts of calcium (Ca), sodium (Na), magnesium (Mg), and silicon (Si). These findings are consistent with several previous studies that identify carbon and oxygen as the major constituents of activated carbon. Such elements are commonly abundant in plant-based raw materials including stems, branches, bark, and fruit peels that have been frequently used in activated carbon production [13, 18, 40, 58]. The experimental data also indicated variations in the carbon and oxygen contents of activated carbon synthesized from different precursors, along with minor differences in trace elemental composition. During the carbonization process, part of the carbon is released as CO gas, contributing to the formation of larger pores. Consequently, the activated carbon exhibits a lower carbon content than typical carbonized samples. These observations agree with earlier reports that the elemental composition of activated carbon generally ranges between 60–80% carbon and 20–40% oxygen by weight. The quantities of secondary elements depend on the raw material used, though trace components are typically present at low levels, not exceeding 3–5% by weight [40, 45, 46, 53, 58].

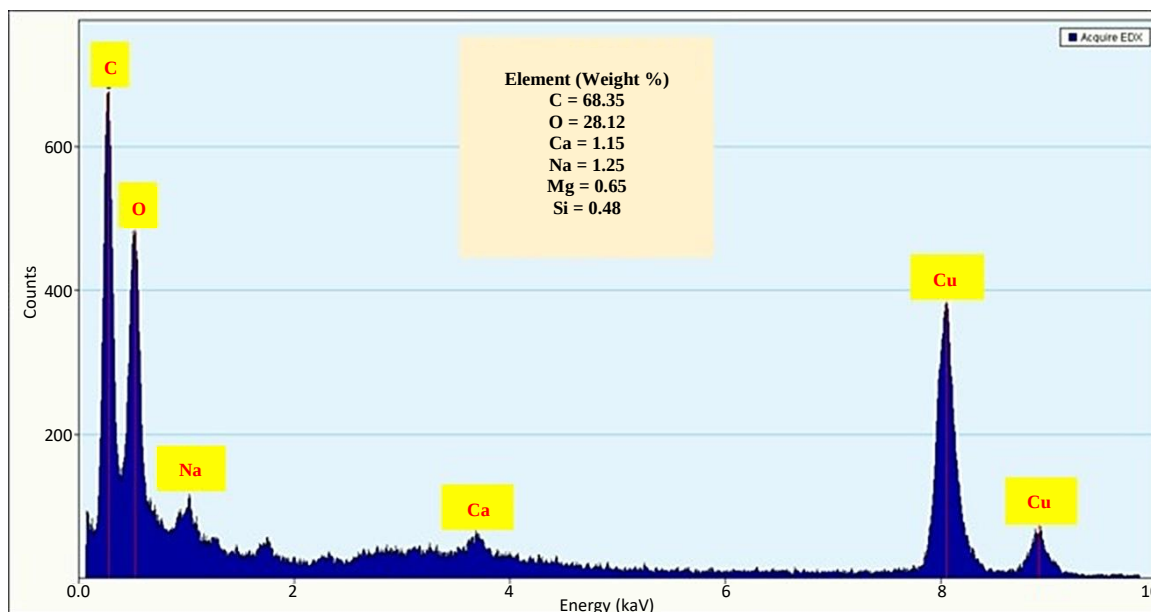


Figure 8 The EDS data for elemental analysis of the activated carbon sample derived from rubber tree branches.

3.2 Analysis and comparison of quality of raw water and filtered water samples

This study was aimed to assess and compare the quality of raw and filtered water using a simple yet innovative water filtration system containing activated carbon produced from rubber tree branches. The analysis has followed the Standard Methods for the Examination of Water and Wastewater established by the APHA, AWWA, and WEF, in accordance with the 2020 guidelines of the Department of Health, Ministry of Public Health of Thailand [30, 31]. Analysis is divided into three categories: physical analysis, which includes water turbidity, apparent color, and total dissolved solids; chemical analysis, involving acidity/alkalinity (pH), total hardness and ions such as Cl^- , F^- , NO_3^- , NO_2^- , SO_4^{2-} , and heavy metal groups (Fe, Mn, Cu, Zn, Pb, Cr, Cd, As, Hg); and analysis of pathogenic bacteria, which includes *total Coliform Bacteria* (TCB) and *E. coli*. The raw water sample [B], collected from a surface source, exhibited physical properties exceeding the standard limits for turbidity, apparent color, and TDS, consistent with visual observations. The total coliform count reached 120 CFU/100 mL significantly higher than the standard limit of 1.1 CFU/100 mL indicating possible contamination by pathogenic microorganisms, even though coliforms themselves are not necessarily harmful [59–61]. In contrast, the chemical parameters of this sample complied with the standard criteria, as all measured ion and heavy metal concentrations were within the permissible limits. Overall, the raw surface water quality was considered adequate as a preliminary source for community tap water production.

As shown in Table 2, sample [C], which obtained after the first-stage coarse filtration designed to remove larger particulates have exhibited superior physical and chemical properties compared to sample [B]. The filtered water was visually clearer but retained a slight yellow tint (Figure 4b). In the second stage, sample [D], filtered using the activated carbon-based unit, met all tap water quality criteria. The concentrations of ions and heavy metals were undetectable (ND), and both total coliform and *E. coli* counts observed to be below detectable limits (<1.1 CFU/100 mL). The visual inspection (Figure 4b) has confirmed that sample [D] appeared as clear as standard tap water. These findings align with the adsorption performance of the rubber tree-derived activated carbon, whose high porosity have effectively removed the various impurities, including pathogenic bacteria, from the source water.

All water samples were also analyzed using UV-Vis spectroscopy at 530 nm, a wavelength commonly employed to evaluate turbidity and pigment presence. The absorbance (Abs) values for samples [A], [B], [C], and [D] were observed as 1.350, 0.612, 0.103, and 0.063, respectively. These results further have supported the high adsorption efficiency of the activated carbon in contaminant removal. Specifically, the negligible absorbance of sample [D] indicates that the second-stage filtration has effectively eliminated the residual impurities. Overall, the findings demonstrate that the innovative water filter incorporating activated carbon from rubber tree branches provides a practical, low-cost, and sustainable solution to the water quality challenges faced by the Ban Kut Saeng Community. The resulting tap water meets all standard criteria, offering a simple, economical, and scalable approach to improve the household water quality in rural or resource-limited areas of developing countries.

Table 2 Water quality analysis results of Ban Kut Saeng Community, Sakon Nakhon Province, Thailand.

Parameters tested	Unit	Test Results ^(a)			Reference test method ^(b)	Standard Value ^(c)
		Sample [B]	Sample [C]	Sample [D]		
Water turbidity	NTU	107	54	9	Nephelometric Method	5
Apparent color	Pt-Co	35.3	10.9	2.1	Visual Comparison Method	15
Total dissolved solids	ppm	762	305	151	Dried at 103 - 105 °C 2540 B.	500
Acidity/alkalinity (pH)	(pH at 25 °C)	6.7	6.7	6.8	Electrometric Method	6.5-8.5
Total hardness	ppm (as CaCO ₃)	34	72	30	EDTA Titration Method	300
Cl ⁻	ppm	4.6	31.0	9.8	Argentometric Method	250.0
F ⁻	ppm	0.98	ND	ND	SPADNS Method	0.70
NO ₃ ⁻	ppm	0.56	0.31	ND	Brucine Method	50.00
NO ₂ ⁻	ppm	0.02	ND	ND	Spectrophotometry Method	3
SO ₄ ²⁻	ppm	ND	ND	ND	Turbidimetric Method	250
Fe	ppm	0.152	0.046	ND	In-house method Flame AAS based on Standard Method	0.300
Mn	ppm	0.11	ND	ND	In-house method Flame AAS based on Standard Method	0.30
Cu	ppm	0.27	ND	ND	In-house method Flame AAS based on Standard Method	1.00
Zn	ppm	0.310	0.011	ND	In-house method Flame AAS based on Standard Method	3.000
Pb	ppm	0.001	ND	ND	In-house method Graphite Technique based on Standard Method	0.010
Cr	ppm	0.002	ND	ND	In-house method Graphite Technique based on Standard Method	0.050
Cd	ppm	ND	ND	ND	In-house method Graphite Technique based on Standard Method	0.003
As	ppm	ND	ND	ND	In-house method Gaseous Hydride Technique based on Standard Method	0.01
Hg	ppm	ND	ND	ND	In-house method Cold-vapor generation Technique based on Standard Method	0.001
Total <i>Coliform bacteria</i> (TCB)	CFU/100 mL	120.0	32.0	< 1.1	Multiple Tube Fermentation Technique	< 1.1
<i>Escherichia coli</i> (<i>E. coli</i>)	CFU/100 mL	< 1.1	< 1.1	< 1.1	Multiple Tube Fermentation Technique	< 1.1

Noted; (a) The water samples analyzed included: [B] raw water sample collected from the water surface, [C] water sample filtered in the first stage, and [D] water sample filtered in the second stage using the innovative, simple water filter with activated carbon derived from rubber tree branches, as shown in Figure 4(b).

(b) Standard Methods for the Examination of Water and Wastewater [30].

(c) The standard values specified in the 2020 announcement by the Department of Health, Ministry of Public Health of Thailand [31].

4. Conclusions

This research study provides a practical and sustainable solution to tap water quality problems in the Ban Kut Saeng Community, Sakon Nakhon Province, Thailand, by applying scientific principles to develop an innovative and user-friendly household water filter. The filter employs an activated carbon derived from locally sourced rubber tree branches, produced via a dry activation process using NaOH in a simple biomass incinerator. Characterization of the physical and chemical properties of the activated carbon has confirmed an amorphous structure, while FT-IR spectroscopy identified the presence of functional groups predominantly composed of hydrocarbons. The activated carbon exhibited an iodine adsorption capacity of 687.24 mg I₂/g, meeting the Thai Industrial Standard (TIS 900-2004), and achieved complete (100%) methylene blue removal using 1 g of carbon with a 100 ppm dye solution. BET analysis revealed a surface area of 833.06 m²/g, total pore volume of 0.8397 cm³/g, and an average pore diameter of 4.03 nm, indicating a mixed microporous–mesoporous structure. SEM and TEM imaging results confirmed the pore morphology and connectivity, offering valuable insights into the adsorption mechanisms that enhances the filtration performance. Water quality assessment, conducted in accordance with APHA, AWWA, and WEF standards and Thailand's 2020 water quality guidelines, demonstrated that while the raw water exhibited high turbidity and bacterial contamination, the filtrate particularly after the second filtration stage met all tap water quality standards. No harmful ions or bacterial contamination were detected. Overall, the study explores the system's high efficiency in contaminant removal and water purification, underscoring its viability as a low-cost, community-driven, and environmentally sustainable approach to improve the household water quality in rural and developing areas.

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6. Declarations

During the preparation of this manuscript, ChatGPT was used to assist with English grammar correction. The authors subsequently revised the content and take full responsibility for the accuracy and integrity of the final version.

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