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Silver-Nanoparticle-Decorated Fused Carbon Sphere Composite as a Catalyst for Hydrogen Generation

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Abstract: The dwindling supply of fossil fuels has resulted in a search for an efficient alternative energy source. Hydrogen gas offers an abundant, clean-burning supply of energy that can be readily produced over time via the water-splitting reaction of sodium borohydride (NaBH₄). This study explored the synthesis of a novel catalyst comprised of silver nanoparticles supported on fused carbon spheres (AgNP-FCS). This composite catalyst was then tested for its ability to optimize the hydrolysis reaction of NaBH₄. The fused carbon spheres (FCS) were synthesized via a sustainable source, namely a dextrose solution. The synthesized AgNP-FCS catalyst was characterized using transmission electron microscopy (TEM), energy-dispersive X-ray spectroscopy (EDS), Fourier-transform infrared spectroscopy (FTIR), and X-ray diffraction (XRD). The average diameter of silver nanoparticles on the catalyst was found to be 30 nm with 3.7% loading. This catalyst was tested under various reaction conditions, including temperatures, doses of NaBH₄, and solution pHs. The activation energy of the reaction as catalyzed by AgNP-FCS was determined to be 37.0 kJ mol⁻¹, which was competitive when compared to similar catalysts for this reaction. A study of the reusability of this catalyst suggests that the catalyst can be used multiple times consecutively with no loss in hydrogen generated. This material presents an opportunity for a sustainable catalyst to optimize the amount of hydrogen generated via the hydrolysis of NaBH₄.

Keywords: silver nanoparticles; fused carbon spheres; hydrogen production; hydrogen feedstock; catalyst



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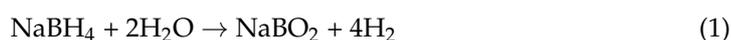
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1. Introduction

In recent years, there has been an increased focus on finding an alternative energy source that can replace fossil fuels, which are estimated to be responsible for up to 84.3% of the global energy supply [1]. These fossil fuels are the leading cause of greenhouse gas emissions and are finite in supply, with some models estimating coal, oil, and natural gas, will be depleted in 105, 37, and 35 years, respectively [2,3]. These issues associated with fossil fuel consumption can potentially be mitigated through the use of hydrogen gas as a fuel. Hydrogen, with an atomic mass of 1.008 amu, is the most abundant element in the universe and contains roughly three times the energy density of gasoline [4]. Unlike gasoline, however, hydrogen gas can be combusted with no harmful byproducts, only producing water. The major roadblock for the widespread implementation of this abundant, clean-burning fuel source is the danger associated with its storage. Typical methods of hydrogen storage involve compressing the explosive gas into tanks or cooling it to subzero temperatures in order to store it as a liquid [5]. An alternative method of storing hydrogen is through the use of a class of chemicals known as hydrogen feedstock materials (HFMs). Sodium borohydride (NaBH₄) is one such hydrogen feedstock material that has attracted a lot of attention for its high weight percentage of 10.8% hydrogen [6]. Additionally, sodium borohydride readily reacts in water, releasing its stored hydrogen (Equation (1)).



A drawback of this reaction is that it proceeds relatively slowly and therefore requires a catalyst to optimize the rate at which the hydrogen gas is produced [6]. Different metals can be used as catalysts, but transition metals are known to be an excellent choice for their ability to transfer electrons due to incomplete valence shells [7–10]. These metals can perform even better as catalysts at the nanoscale due to their increased surface area, and precious metal nanoparticles, including silver, gold, palladium, and platinum, have all been reported to effectively catalyze this reaction [8–11]. Silver nanoparticles (AgNPs) in particular have been extensively studied and found to have beneficial medical uses [12], antimicrobial properties [13], and catalytic ability in a multitude of different reactions [14–17]. One of the notable applications of AgNPs is their use as catalysts for the hydrolysis of sodium borohydride (NaBH_4). Silver nanoparticles have a variety of advantages when used as a catalyst, including a high catalytic activity, excellent structural stability, and selectivity. Several studies have already begun to explore the application of silver nanoparticles as catalysts for the hydrolysis of NaBH_4 . For instance, a study conducted by Sun et al. (2013) investigated the catalytic activity of AgNPs synthesized via a green chemistry approach using mulberry leaf extract [18]. The researchers found that the synthesized AgNPs exhibited excellent catalytic activity, achieving a high hydrogen generation rate during the hydrolysis of NaBH_4 [18]. The AgNPs in their study also demonstrated good stability over multiple cycles of reaction, highlighting their potential for long-term use as catalysts. A study by Huff et al. (2020) also focused on the synthesis of AgNPs and their subsequent application as catalysts for the hydrolysis of NaBH_4 [17]. The researchers in this team found that the AgNPs showed remarkable catalytic activity, achieving a high hydrogen generation rate at room temperature [17]. Additionally, in the study by Sun et al. (2013), the AgNPs exhibited good reusability and stability, making them a promising catalyst for practical applications [17]. Furthermore, a second study conducted by Huff et al. (2017) explored the role of supported AgNPs over carbon nanotubes (CNTs) and their influence on the catalytic activity during the hydrolysis of NaBH_4 [8]. The supported AgNPs over carbon nanotubes (CNTs) exhibited higher catalytic activity and stability compared to unsupported AgNPs [8]. Based on these studies, it appears that the use of AgNPs as catalysts for the hydrolysis of NaBH_4 offers several advantages. AgNPs have a high surface-to-volume ratio, providing a large number of active sites for the reaction to occur, thereby enhancing the catalytic activity [8,17,18]. Additionally, the unique electronic properties of AgNPs contribute to their catalytic performance [8,17,18]. The presence of AgNPs can significantly reduce the activation energy required for the hydrolysis reaction, enabling faster hydrogen generation [8,17,18]. In summary, the application of silver nanoparticles as catalysts for the hydrolysis of sodium borohydride has shown promising results in various studies. The synthesized AgNPs exhibit high catalytic activity, stability, and reusability, making them attractive candidates for hydrogen generation and storage applications. Further research in this area is likely to focus on optimizing the synthesis methods, exploring new stabilizing agents, and investigating the mechanistic aspects of the catalytic process.

While metal nanoparticles have great catalytic potential, their tendency to agglomerate into larger masses hinders their catalytic ability in the long run [19]. This agglomeration can be prevented by adding a support structure for the nanoparticles to adhere to [20–23]. The large surface area and stability of carbon-based material makes it a commonly used support material [19,23]. Fused carbon spheres (FCS) have begun to emerge as a promising support material for silver nanoparticles (AgNPs) in various catalytic applications. The unique structure and properties of fused carbon spheres offer several advantages, including high surface area, excellent stability, and efficient dispersion of AgNPs. This combination makes fused carbon spheres an attractive support material for enhancing the catalytic activity and stability of AgNPs. One study conducted by Peng Xu et al. (2021) investigated the use of fused carbon spheres as a support for AgNPs in the catalytic reduction of 4-nitrophenol [24]. The researchers successfully synthesized AgNPs supported on fused carbon spheres via a simple impregnation method [24]. Their results demonstrated that the FCS-supported AgNPs exhibited enhanced catalytic activity compared to unsupported AgNPs [24]. The fused

carbon sphere support provided a large surface area, and it was theorized that the support material allowed for an abundant number of active sites for AgNPs deposition, resulting in improved catalytic performance [24]. The use of fused carbon spheres as a support material for AgNPs offers several advantages. The high surface area and porous structure of FCS provide a large number of active sites for AgNP deposition, increasing the catalytic activity [24]. The stable and inert nature of FCS ensures the durability and longevity of the catalyst, enabling multiple reaction cycles without significant degradation [24]. The excellent dispersibility of AgNPs on FCS prevents their agglomeration and improves their accessibility for reactant molecules, enhancing the catalytic efficiency [24]. In summary, fused carbon spheres have shown great potential as a support material for silver nanoparticles in various catalytic applications. The unique structure and properties of FCS contribute to the improved dispersion, stability, and catalytic performance of AgNPs [24]. Further research in this field is expected to focus on optimizing the synthesis methods, exploring the influence of fused carbon spheres properties on catalytic activity, and investigating the mechanistic aspects of the catalytic reactions. In a different study by Martinez-Laguna et al. (2022), the author showed the benefit of utilizing a carbon template in supporting gold nanoparticles [25]. The supported gold nanoparticles not only showed exceptional catalyzing ability but also continued catalyzing the reaction after six consecutive uses [25]. In 2023, the study of Jiang et al. concluded that carbon spheres provided stable support for platinum, silver, and gold nanoparticles. The study indicated that gold nanoparticles supported on carbon spheres exhibited a stable catalytic activity [26]. The above studies highly suggested the potential of using gold nanoparticles supported over a carbon template in catalytic reactions.

It is clear from the previous literature that adding a carbon-based support structure to a nanoparticle catalyst is advantageous. This study aims to further the field of carbon-supported nanoparticle catalysts by combining fused carbon spheres (FCS) and AgNPs into a novel composite material (AgNPs-FCS) as a catalyst for the reaction of NaBH_4 in water. This novel catalyst was characterized and tested for catalytic ability at various doses of NaBH_4 , temperatures, and solution pHs. Lastly, the catalyst was tested for its stability by using the same catalyst for five consecutive trials.

2. Materials and Methods

2.1. Synthesis of Silver Nanoparticles (AgNPs)

The synthesis of AgNPs began with the preparation of a 1 mM silver precursor solution. Silver nitrate (AgNO_3) was dissolved into 100 mL of deionized water (DI, 18 M Ω) and the whole solution was heated until boiling. Once a rolling boil was achieved, a previously prepared 1% sodium citrate ($\text{Na}_3\text{C}_6\text{H}_5\text{O}_7$) solution was added dropwise with ample stirring to the precursor solution until a color change was observed. The solution was then cooled to room temperature (RT, 295 K) and was centrifuged to remove impurities.

2.2. Synthesis of Fused Carbon Spheres (FCS)

The fused carbon sphere (FCS) material synthesis was begun by dissolving dextrose into deionized water so that the final concentration of the solution would be 0.5 M. This solution was added to a stainless-steel reaction vessel so that there was a ratio of liquid to air of 2:3. The reaction vessel was tightly sealed and placed into an oven at 200 °C for approximately four hours. After the four-hour heating period had passed, the vessel was removed from the oven and allowed to cool to room temperature. Once cooled, the vessel was opened, and the resulting liquid was centrifuged to collect the solid product. The solid was then washed several times with DI water and dried in an oven at 60 °C overnight.

2.3. Synthesis of Silver Nanoparticles Supported over Fused Carbon Spheres (AgNP-FCS)

The AgNP-FCS composite material was prepared via the incipient wetness method described by Huff et al. [8], in which fused carbon sphere material was immersed in the AgNP solution and mixed to disperse the nanoparticles over the fused carbon spheres. The

mixture was placed into an oven at 60 °C to facilitate the evaporation of excess liquid. Once all liquid was gone, the resulting composite was collected and washed several times with DI water, then placed into an oven at 60 °C overnight to dry.

2.4. Characterization

AgNP-FCS was first characterized by transmission electron microscopy (TEM, JEM-2100F, JEOL Ltd., Akishima, Tokyo, Japan) to confirm the presence of nanoparticles within the composite, as well as to determine the dimensions of the material. Scanning electron microscopy (SEM, JEOL JSM-6060LV, Akishima, Tokyo) with energy dispersive spectroscopy (EDS, ThermoScientific UltraDry, Waltham, MA, USA) was used to determine the elemental composition of the composite. X-ray diffraction (XRD, Cu K α X-ray, nickel filter, Rigaku Miniflex II, Tokyo, Japan) was used to further confirm the identity of the elements within the sample. Finally, Fourier-transform infrared spectroscopy (FTIR, Shimadzu IR-Tracer 100, Kyoto, Japan) with an attenuated reflux attachment (ATR, Shimadzu QATR-S, Kyoto, Japan) was used to identify any functional groups within the samples.

2.5. Catalysis

Catalytic trials were run via a catalytic setup developed by Huff et al. [11]. Two vacuum flasks were connected with tubing and sealed with rubber stoppers. One flask was designated the reaction flask and the other the water flask. The stopper used to seal the water flask had thin plastic tubing that led from the flask itself into a cup on an electric mass balance (Pioneer, OHAUS, Parsippany, NJ, USA). The scale was connected to a computer where a data logging software (SPDC Data Collector v2.01, OHAUS) could record the mass of the scale every three seconds. When a trial was run, 100 mL of DI water was added to both flasks. To the reaction flask, 0.01 g of AgNP-FCS was added with magnetic stirring. Then, an appropriate dose of NaBH₄ for the trial was added and the reaction flask was sealed. As hydrogen was generated, it traveled through the tube connecting the reaction flask and the water flask, forcing the DI water up through the tubing in the stopper where it would drip into the cup on the scale. The volume of water displaced could be used to determine the volume of hydrogen produced.

3. Results and Discussion

Transmission electron microscopy imaging was used to characterize the novel AgNP-FCS catalyst (Figure 1). The images taken depict a mass of fused material with what appear to be nanoparticles scattered across its surface (Figure 1A,B). It was determined that the nanoparticles were somewhat round in shape and had an average diameter of 30 nm, with a size range from 4.5 nm to 75 nm.

Elemental analysis of the AgNP-FCS catalyst (Figure 2) confirmed the presence of silver within the composite. The most abundant element in the composite was shown to be carbon, likely due to the fused carbon sphere backbone being derived from dextrose. Oxygen in the sample can most likely be attributed to the sample being stored under standard atmospheric conditions, as well as oxygen being present in the chemical structure of the dextrose used to make the fused carbon spheres. This analysis revealed a silver content of roughly 3.7% in the sample; therefore, the nanoparticles seen in Figure 1 can be confirmed to be silver metal.

Next, both the AgNP-FCS catalyst and unsupported fused carbon sphere materials were characterized using powder X-ray diffraction analysis (Figure 3). A large broad peak was detected in both materials at around 22 degrees. This is a common peak amongst carbon-based materials [27,28] and is indicative of the fused carbon sphere material. In the composite material, there were four peaks observed that were not present in the unsupported fused carbon spheres. These peaks at 38.3 degrees, 44.3 degrees, 64.5 degrees, and 77.5 degrees are, respectively, indicative of the 111, 200, 220, and 311 faces of the FCC structure silver nanoparticles (JCPDS 65-2871) [29].

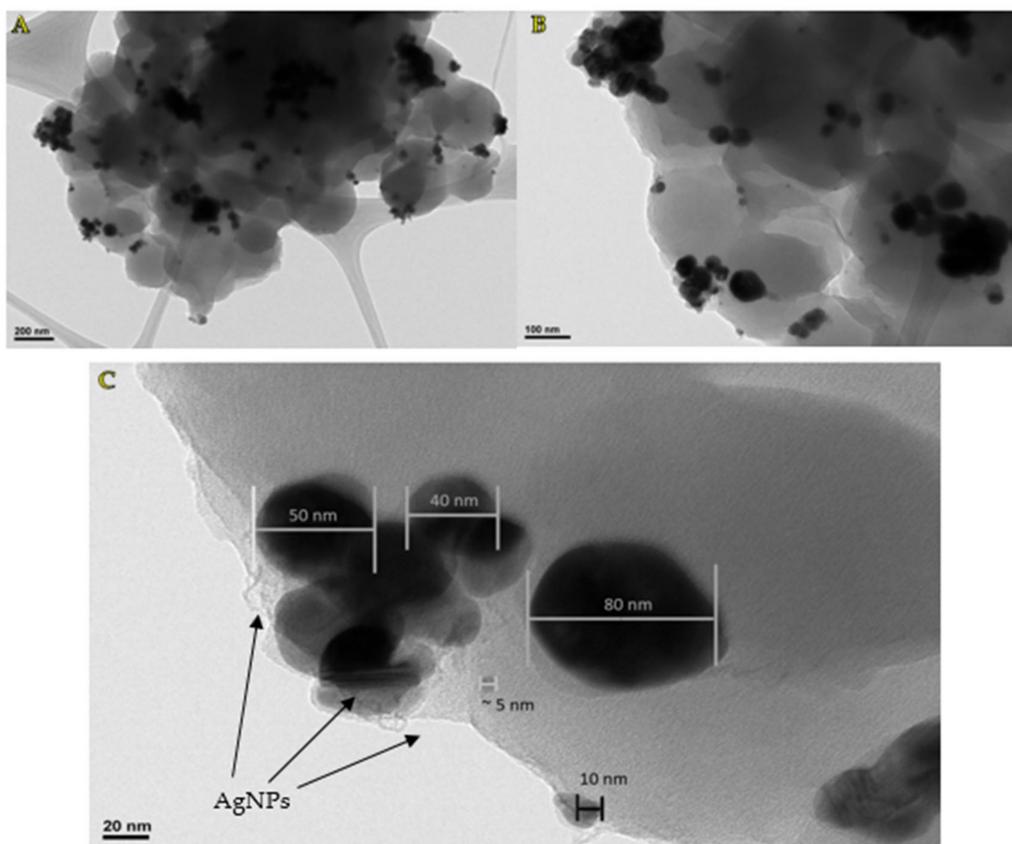


Figure 1. Transmission electron microscopy images of the AgNP-FCS composite material at scales of 200 nm (A), 100 nm (B), and 20 nm (C).

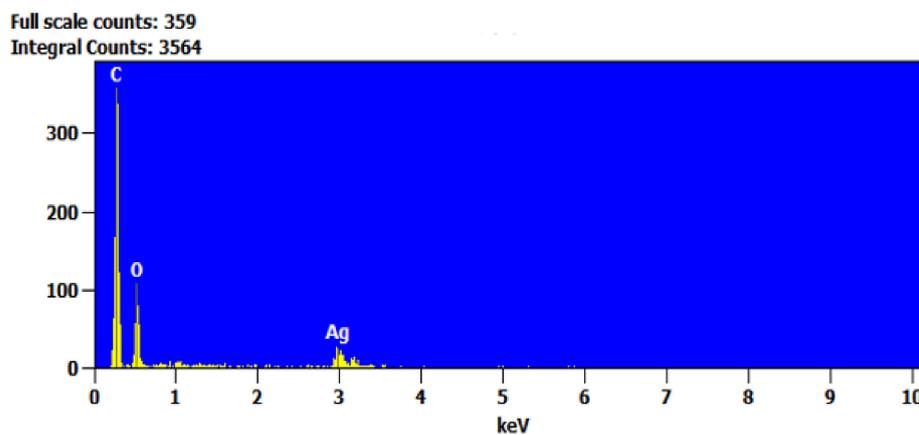


Figure 2. Energy-dispersive spectroscopy spectrum of the AgNP-FCS composite.

The final characterization technique used for the AgNP-FCS catalyst was FTIR (Figure 4). Both materials saw many of the same peaks with little change in the peak intensity. Most of the peaks can be attributed to the chemical structure of dextrose, which was used to make the fused carbon sphere backbone. A long broad peak ranging from 3600 cm^{-1} to 3000 cm^{-1} can be commonly associated with a hydroxyl ($-\text{OH}$) functional group. The short peak seen at 2900 cm^{-1} often represents a C-H stretching group, the peak at 1700 cm^{-1} can be attributed to a C=O bond, and the peak at 1067 cm^{-1} can be attributed to a C-O bond. The peak at 834 cm^{-1} ($800\text{--}900\text{ cm}^{-1}$ region) can be attributed to epoxides (C-O-C). The functional groups of fused carbon spheres were found to be the same as other reported graphene structures [30,31]. The peaks were observed in the same range for both materials;

there was a noticeable change in the intensity of the peaks with small shifts in wavenumber due to the loading of AgNPs to FCS. For example, the peak at 1067 cm^{-1} in FCS was shifted to 1076 cm^{-1} and the intensity slightly increased. This indicates successful addition of the silver nanoparticles without significant structural change(s) of the fused carbon sphere backbone.

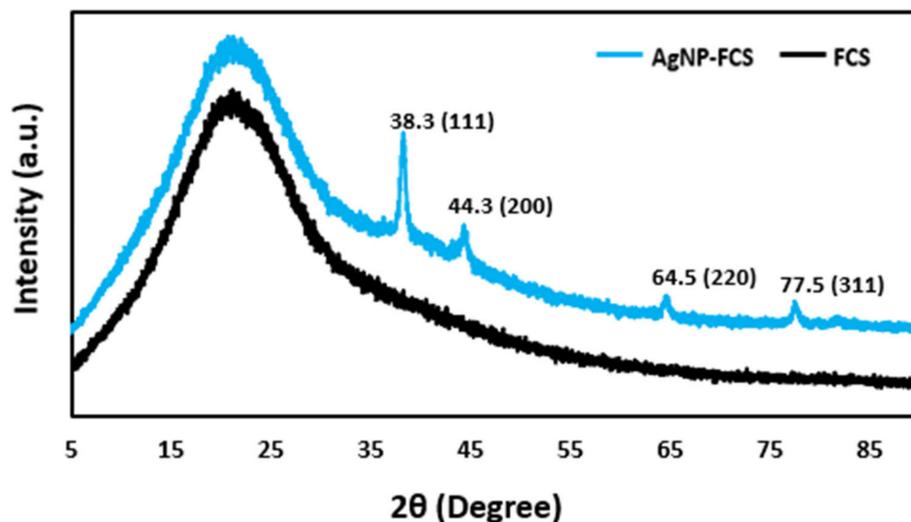


Figure 3. XRD analysis of the AgNP-FCS composite and unsupported fused carbon spheres.

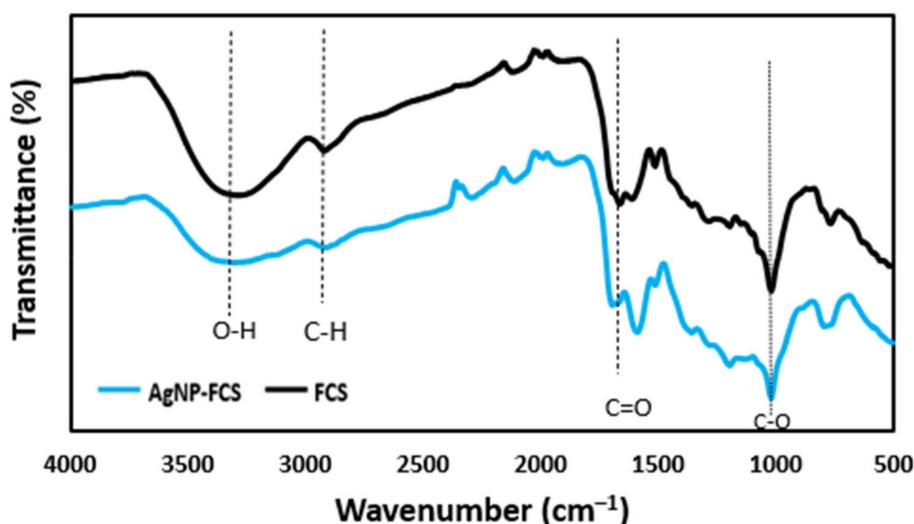


Figure 4. FTIR analysis of AgNP-FCS and unsupported FCS materials.

The first catalytic test performed was under the following standard conditions of room temperature (RT, 295 K), neutral solution pH (7), and an NaBH_4 dose of $925\text{ }\mu\text{mol}$. At these conditions, the volume of hydrogen gas produced by the reaction was observed to be 18.0 mL at a rate of $0.0151\text{ mL min}^{-1}\text{ mg}_{\text{cat}}^{-1}$. These conditions were the standard for comparison across all of the rest of the catalytic trials. Next, the effect of dose on the reaction was tested at NaBH_4 doses of $625\text{ }\mu\text{mol}$, $925\text{ }\mu\text{mol}$, and $1225\text{ }\mu\text{mol}$ (Figure 5). When the dose was lowered from $925\text{ }\mu\text{mol}$ to $625\text{ }\mu\text{mol}$, the volume of hydrogen gas produced was also lowered to 14.3 mL at a rate of $0.0119\text{ mL min}^{-1}\text{ mg}_{\text{cat}}^{-1}$. The dose of NaBH_4 was then raised to $1225\text{ }\mu\text{mol}$, which increased the generation rate to $0.0215\text{ mL min}^{-1}\text{ mg}_{\text{cat}}^{-1}$ and increased the volume of hydrogen gas produced to 25.8 mL . It is clear from these data that there is a direct relationship between the dose of NaBH_4 used and the amount of hydrogen gas produced. This was to be expected based on Equation (1) and the equilibrium law, which states that an increase in the amount of a reactant will cause the reaction to shift to increase the amount of the product; in this case, hydrogen.

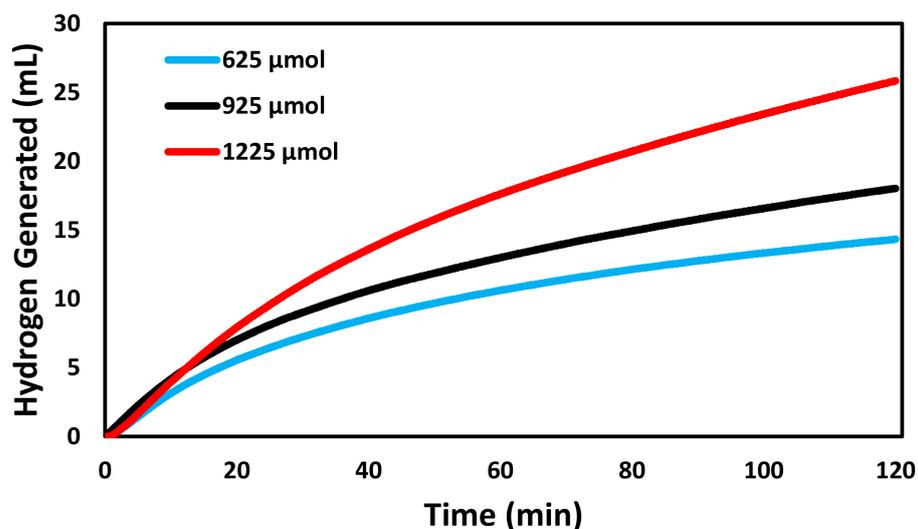


Figure 5. Effect of NaBH_4 dosage on the catalytic ability of AgNP-FCS.

Next, catalytic trials were performed under various pH conditions and compared to the standard trial (pH 7, Figure 6). When the pH of the reaction solution was lowered to 6, there was an observed increase in the volume of hydrogen gas produced from 18.0 mL at pH 7 to 48.6 mL. The rate of the reaction was also increased from $0.0151 \text{ mL min}^{-1} \text{ mg}_{\text{cat}}^{-1}$ at pH 7 to $0.0405 \text{ mL min}^{-1} \text{ mg}_{\text{cat}}^{-1}$ at pH 6. This increase in hydrogen gas produced under acidic conditions was first observed by the team of Schlesinger et al. (1953), who theorized that the increase in hydrogen gas produced was due to the increased presence of free hydrogen ions [6]. When the pH of the reaction solution was raised to a basic pH of 8, there was an observed decrease in the volume of hydrogen gas generated to 7.4 mL, with a reaction rate of $0.0061 \text{ mL min}^{-1} \text{ mg}_{\text{cat}}^{-1}$. This hindrance in gas production has been reported previously by the team of Kaufman et al. (1985), who also saw higher pHs result in a decrease in reactions [32].

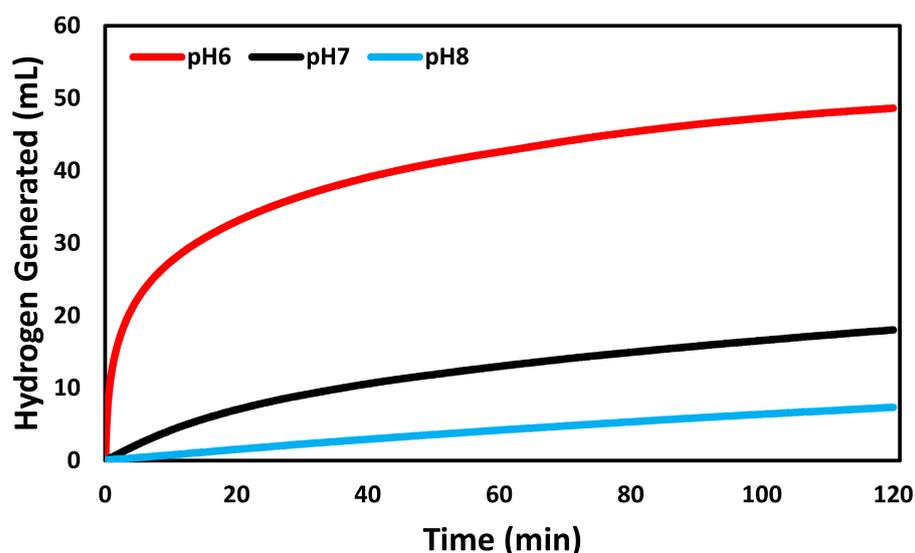


Figure 6. Effect of solution pH on the catalytic ability of AgNP-FCS.

The catalytic ability of AgNP-FCS was then tested at three different reaction temperatures (283 K, 288 K, and 303 K) and compared to the standard temperature (295 K, Figure 7). First, the temperature was raised to 303 K, which resulted in an increased volume of hydrogen gas produced compared to the standard reaction temperature of 295 K, with the volume of hydrogen gas generated observed to be 26.4 mL at a rate of $0.0220 \text{ mL min}^{-1} \text{ mg}_{\text{cat}}^{-1}$.

Next, the temperature was decreased to 288 K, which resulted in a decreased volume of hydrogen gas being produced: 11.2 mL at a rate of $0.0094 \text{ mL min}^{-1} \text{ mg}_{\text{cat}}^{-1}$. Finally, the temperature of the reaction was further reduced to 283 K, which further decreased the reaction rate to $0.0082 \text{ mL min}^{-1} \text{ mg}_{\text{cat}}^{-1}$ and the volume of hydrogen gas produced to 9.8 mL. Based on these data, it is clear that there is a direct relationship between the temperature of the reaction solution and the volume of hydrogen gas produced from this reaction. According to Le Chatelier's principle and what was observed in Figure 7, this reaction, as catalyzed by AgNP-FCS, is endothermic. These data were then used along with the Arrhenius Equation (2) to create an Arrhenius plot (Figure 8).

$$k = Ae^{-\frac{E_a}{RT}} \quad (2)$$

where in the previous equation, the variable k represents the rate constant of this reaction. The variable A is representative of this reaction's pre-exponential factor, while the variable E_a can be attributed to the activation energy of this reaction. The variable R is used to represent the universal gas constant and finally the variable T represents the temperature of the reaction.

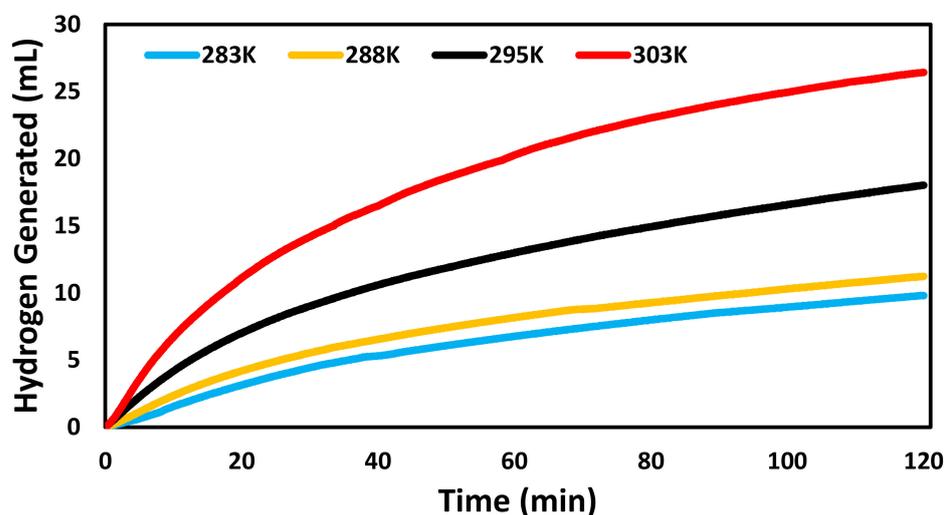


Figure 7. Effect of reaction temperature on the catalytic ability of AgNP-FCS.

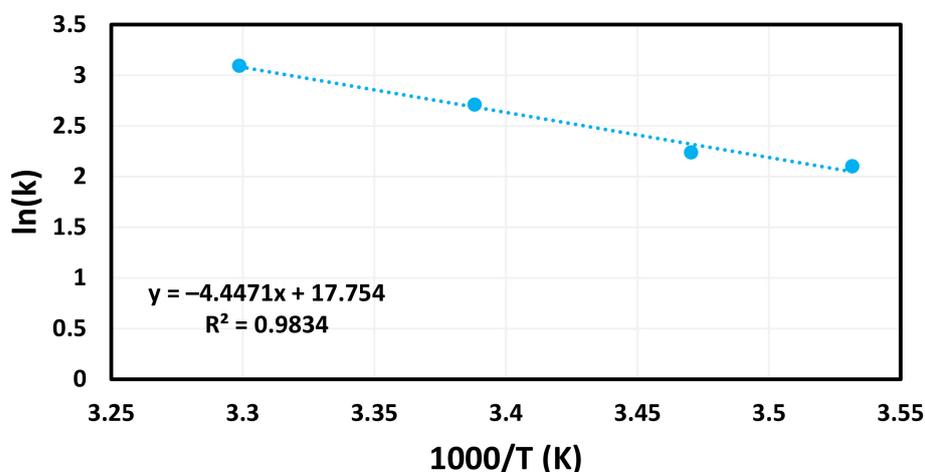


Figure 8. Arrhenius plot created via the rate constant at each tested temperature vs. 1000 divided by that temperature.

From Figure 8, the slope of the line allowed for the activation energy of the reaction to be determined to be 37.0 kJ/mol. This activation energy was then compared to other

activation energies reported for similar catalysts for the hydrolysis reaction of NaBH_4 (Table 1). When compared to other catalysts for the hydrolysis of NaBH_4 , AgNP-FCS was observed to have a lower activation energy than all but one. Compared to other precious metal nanoparticle catalysts, AgNP-FCS outperformed the other composites. Only the catalyst designated Au/MWCNTs had a lower activation energy than AgNP-FCS; however, the multiwalled carbon nanotube (MWCNTs) support material that was used requires harsher chemicals during synthesis than the safe and sustainable dextrose used to synthesize AgNP-FCS [9]. The simplicity of the fused carbon sphere support and the low activation energy needed to catalyze this reaction makes this novel composite material a competitive catalyst for this reaction.

Table 1. Reported catalysts and their activation energies for the catalyzed hydrolysis of NaBH_4 .

Catalyst	E_a (kJ mol ⁻¹)	Temperature (K)	Reference
Ni	71	273–308	[32]
Raney-Nickel	63	273–308	[32]
Co	75	273–308	[32]
Co nanoclusters	50	288–318	[33]
Ru/MMT	54.7	283–303	[34]
LSC/AgCo	49.3	293–323	[35]
Pt/MWCNTs	46.2	283–303	[36]
Ag/MWCNTs	44.5	273–303	[8]
Pd/MWCNTs	62.7	273–303	[10]
Au/MWCNTs	21.1	273–303	[37]
PtNPs	39.2	283–303	[11]
BCD-AuNP	54.7	283–303	[9]
PdNPs	58.9	273–303	[38]
AgNP-FCS	37.0	283–303	This Work

The final catalytic study performed by this team was to determine the reusability of the material after five consecutive trials (Figure 9). Each trial was run for two hours at the standard conditions of room temperature (295 K), a solution pH of 7, and a NaBH_4 dosage of 925 μmol . It was observed that the first two trials produced a relatively consistent amount of hydrogen gas, with an observed increase in volume produced with each subsequent trial. Across the five trials, there was an average volume of 28.7 mL produced per trial. These results indicate that the catalyst is not only stable up to at least five trials but may become more catalytically active with multiple uses. The phenomenon has previously been reported in the study of Deraedt et al. (2014) [39]. The study showed that the nanoparticles increased their catalytic efficiency due to the accumulation of BH_4^- and H forming bonds on the surface of nanoparticles. These bonds were then hydrolyzed and enhanced the electrostatic stability of the nanoparticles' surface, which made them more catalytically active [39]. In the study of Nguyen et al. (2018), the researchers also detected H radical adducts, which indicated that nanoparticles adsorbed BH_4^- ions [40].

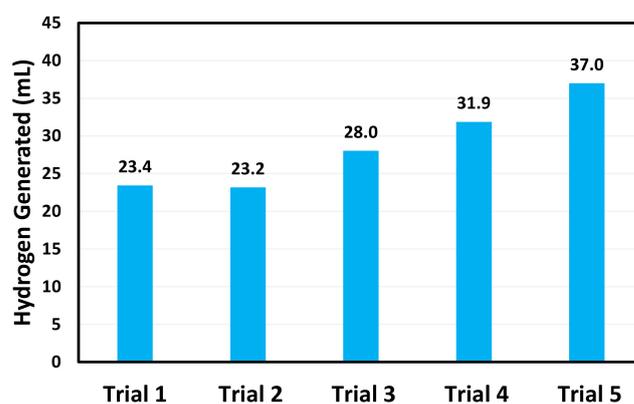
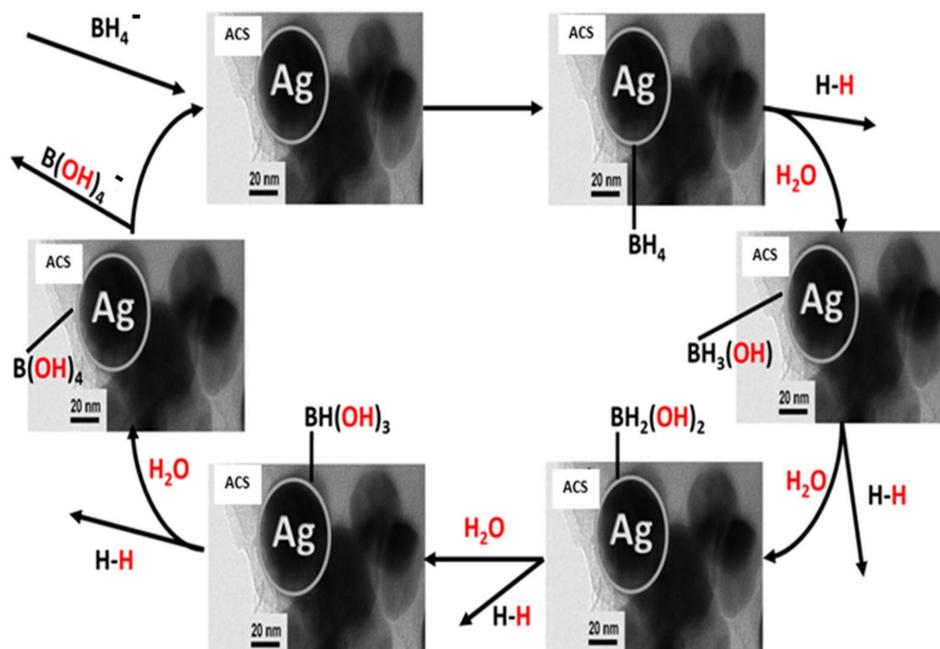


Figure 9. Catalytic reusability of AgNP-FCS.

Scheme 1 depicts a possible mechanism for how AgNP-FCS catalyzes the hydrolysis of NaBH_4 . In this scheme, it is proposed that a single borohydride ion (BH_4^-) ion bonds to a silver nanoparticle on the surface of the FCS support material. Water then attacks the boron from the BH_4^- and strips a single hydrogen atom off. This hydrogen then bonds to hydrogen from the water molecule and leaves it as a diatomic hydrogen gas molecule (H_2). This process leaves a hydroxyl group (OH) in the place of the hydrogen atom and can be repeated for each hydrogen on the BH_4^- . Once no hydrogen atoms are left, the tetrahydroxyborate molecule [$\text{B}(\text{OH})_4^-$] separates from the AgNP and the process begins again.



Scheme 1. A possible mechanism for how AgNP-FCS catalyzes the hydrolysis of NaBH_4 . Red text indicates the species originated from water, while black text indicates the species originated from a borohydride ion.

4. Conclusions

In conclusion, we report a novel composite catalyst comprised of silver nanoparticles supported on a sustainable dextrose-derived FCS support (AgNP-FCS). This material's synthesis was confirmed through different characterization techniques. AgNP-FCS was tested for catalytic ability under various reaction conditions, including dosage of NaBH_4 , temperatures, and solution pHs. It was observed that optimal reaction conditions included high temperatures, acidic conditions, and larger doses of NaBH_4 , with the most hydrogen being produced at a rate of to $0.0405 \text{ mL min}^{-1} \text{ mg}_{\text{cat}}^{-1}$ at pH 6. Temperature data allowed the activation energy of the reaction to be determined to be 37.0 kJ mol^{-1} , which is lower than many reported Eas of similar catalysts for this reaction. Reusability data indicate that the catalyst can be used multiple times in succession with no loss in catalytic ability, and may even become more catalytically active with multiple uses. The competitive activation energy and ability to be used multiple times, along with the simple sugar-derived fused carbon sphere backbone, makes this novel material an exciting option for the generation of hydrogen gas for fuel usage. This work can be expanded upon by exploring additional conditions for the trials we have already studied, such as increasing or cooling the temperature even further, different doses of NaBH_4 , or a full pH spectrum. Additionally, different metals could be explored, such as gold, platinum, and palladium, or even nonprecious metals like nickel and copper. Finally, there are a plethora of other carbon-based materials, such as graphene or fullerenes, that could be explored as support structures to make new composite catalysts. This study successfully sheds more light on a potential way to use hydrogen gas as a future fuel source.

Author Contributions: E.B.: data curation, formal analysis, writing—original draft. Q.Q.: data curation, formal analysis, writing—original draft. T.M.A.-F.: conceptualization, validation, formal analysis, investigation, resources, supervision, writing—review and editing. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

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