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# Evaluating microwave-synthesized silver nanoparticles from silver nitrate with life cycle assessment techniques

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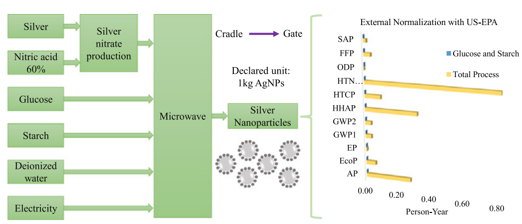
## HIGHLIGHTS

- This is an environmental impact assessment study for <10 nm silver nanoparticles.
- A tool from the United States Environmental Protection Agency is used.
- The processes include the synthesis, transportation and raw materials acquisition.
- A microwave-based nanoparticle synthesis method with reduced environmental impacts

## GRAPHICAL ABSTRACT

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## ABSTRACT

Silver Nanoparticles (AgNPs) are well known for applications in electronics and as antimicrobial agents because of their unique optical, electrical, cytotoxic and thermal properties. These nanoparticles can be synthesized via a wide variety of techniques; however, they require the use of hazardous solvents which have very high environmental impacts. Nanoscience researchers have attempted novel synthesis routes that reduce resource requirements and use benign chemicals, while maintaining control over their unique properties. The present study evaluates the potential environmental impacts of one such benign method using Life Cycle Assessment (LCA) techniques which are used to assess the environmental impacts of a product's life through all the stages from raw material extraction to disposal/ recycling. This research evaluates AgNPs which were synthesized using glucose as the reducing agent and food grade corn starch as the stabilizing agent in a microwave-assisted reaction system. GaBi 6.0 software was used to carry out the Life Cycle Impact Assessment on a declared unit of 1 kg of $3.0 \pm 1.2$ nm diameter AgNPs. The results indicate that the impacts are predominantly on acidification (AP), human health particulate air (HHAP) and human toxicity non-cancer (HTNCP) potentials. These impacts are mainly from the production of silver metal and electricity used. The starch and glucose used to produce AgNPs of $3.0 \pm 1.2$ nm is shown to have negligible environmental impacts and is therefore considered to be environmentally benign.



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## 1. Introduction

Nanoparticles (NPs) may be defined as any intentionally produced particles that have a characteristic dimension from 1 nm to 100 nm and have properties that are not shared by non-nanoscale particles with the same chemical composition (Auffan et al., 2009). Silver nanoparticles (AgNPs) are widely used in high electrical conductivity and antimicrobial activity applications because of their unique optical, electrical and thermal properties (Chandran et al., 2006).

Metallic nanoparticles, such as those of gold and silver, can be synthesized using a wide variety of techniques, including vapor deposition, ablation and sputtering, flame spray pyrolysis, electrochemical methods, chemical reduction (Pourzahedi and Eckelman, 2015), bio-reduction (Ahmad et al., 2003) and microwave-assisted methods as shown in Fig. 1 (Ali et al., 2015). Nanoscience researchers have been successful at developing novel synthesis routes that reduce resource requirements and use benign chemicals, while maintaining control of the size and morphology of NPs (Cheviron et al., 2014). These benign chemicals are used as reducing agents and can be obtained from natural resources such as plants, algae, bacterial and other microbial cultures as well as the refined products obtained from them (Dahoumane et al., 2017b, 2017a, 2016; Hebbalalu et al., 2013).

Microwave heating has been shown to be superior to conductive heating methods for aqueous, heat-activated, one-pot nanoparticle synthesis reactions as the energy transfer may be faster and more uniform (Ali et al., 2015; Dahal et al., 2012). Many noble metal nanoparticle syntheses have used microwaving for these reasons (Bilecka and Niederberger, 2010). An additional advantage of microwave-assisted heating over conventional heating methods may be reduced energy use (Dahal et al., 2012).

The present life cycle research is based on the data from a recent laboratory study conducted at Lamar University's Nanobiomaterials and Bioprocessing Laboratory, TX, USA wherein, AgNPs were synthesized with the combination of glucose as the reducing agent and food grade corn starch as the stabilizing agent in a microwave-assisted reaction system (Kumar et al., 2018), which is referred to as the glucose-starch (GS) method. Starch and glucose are relatively benign agents obtained from natural sources and are readily available at affordable prices. The GS method using microwaves as the heating source and silver nitrate ($AgNO_3$) as the silver salt has been shown to reduce the use of potentially hazardous chemicals, such as $NaBH_4$ (Tolaymat et al., 2010), as well as minimizing side reactions and increasing the yield of the primary product (Anastas and Warner, 2000; Hischier and Walser, 2012).

Literature on Life Cycle Assessment (LCA) studies for silver nanoparticles synthesis routes with starch have considered the synthesis of 1 kg of AgNPs using 90 kg of starch and 1 h of heating on a hotplate (Pourzahedi and Eckelman, 2015). The study by Kumar et al. (2018) was carried out for the GS method with the intent of maximizing the conversion of $AgNO_3$ to AgNPs as a function of glucose and starch concentration using an industrial grade microwave system to minimize environmental impact, resource and energy requirements. Resultantly, the GS method provides a reduction in reaction time to 4.5 min, 35% reduction in energy consumption and 99 ± 1% conversion to AgNPs, thereby providing information to further investigate its environmental footprints. The goal of the work in this manuscript is to evaluate the environmental and resource impacts of the GS method using life cycle techniques.

**Table 1**
Silver nitrate production.

| Silver nitrate production | | | | |
|---|---|---|---|---|
| Input/output | Material | Amount | Unit | Selected flow/process in GaBi 6.0 |
| Input | Nitric acid | 0.77 | kg | RER[a]: nitric acid, 50% in $H_2O$, at plant [inorganics] |
| | Silver | 1.00 | kg | Silver [non-renewable elements] |
| Output | Silver nitrate | 1.57 | kg | Silver nitrate |
| | Nitrogen monoxide | 0.09 | kg | Nitrogen monoxide [inorganic emissions to air] |
| | Water | 0.11 | kg | Water [inorganic emissions to air] |

[a] RER: region of the flow is Europe.

## 2. Methodology

This environmental evaluation is based on the international standards ISO 14040 (ISO 14040, 2006) and ISO 14044 (ISO 14044, 2006). It is not a full life cycle assessment (LCA) from cradle-to-grave, but rather the analysis for environmental impacts and resources are from cradle-to-gate for an AgNP synthesis process that includes extraction, transportation and manufacturing on a laboratory scale. ISO 14040 requires (1) defining a goal, the scope, and the system boundary, (2) the listed inventory sources, and (3) choosing the impact assessment methodologies and potentials to be evaluated, as detailed herein.

### 2.1. Goal and scope

The goal was to generate a quantitative environmental profile for the synthesis of glucose-reduced and starch-stabilized silver nanoparticles in Beaumont, TX, USA, using microwave-assisted heating. The results of this study will provide sufficient information about the environmental impacts of the aforementioned process to enable future analyses on the use of these biomolecules for "green," inorganic nanoparticles synthesis. The intended use of this study is for researchers, the industrial sectors, policy makers and the public at large to develop more benign routes for nanomaterials synthesis.

The function of the as produced AgNPs was also studied by Kumar et al. (2018), using them as an antibacterial agent. These AgNPs were used

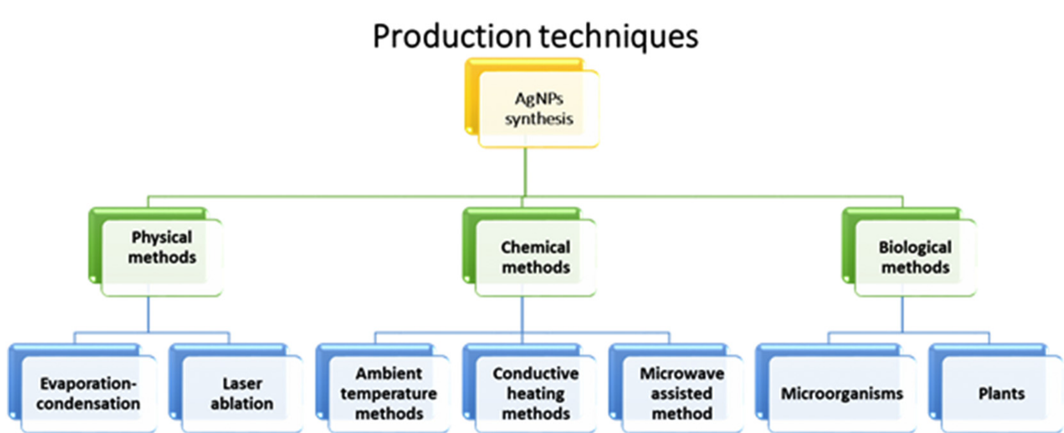


**Fig. 1.** Production techniques for silver nanoparticles (AgNPs).