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# Closed-loop fertility cycle: Realizing sustainability in sanitation and agricultural production through the design and implementation of nutrient recovery systems for human urine

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A B S T R A C T

As a solution to the drawbacks of modern sanitation systems and to shift towards a recycling society, source separation of human wastes coupled with resource recovery could be seen as a potential solution. In this research, microwave activated coconut shells were utilized to recover urea from human urine. Batch adsorption studies were carried out to determine the effect of initial concentration, adsorption temperature, microwave output power and irradiation time on the urea uptake capacity of the tailored activated carbon. The shells pretreated with microwave irradiation of 360 W, for 15 min (MACCS-360W-15) shown to be promising adsorbents with BET surface area $> 1000$ $m^2$ $g^{-1}$. The sorption data were tested against different isotherm models and found to closely follow Langmuir isotherm with a maximum monolayer sorption capacity of 312 mg $g^{-1}$. Kinetic data over temperature range of 30–60 °C was found to closely follow pseudo-first-order at all adsorbate concentrations. Gibbs free energy ($\Delta G°$), enthalpy ($\Delta H°$) and entropy ($\Delta S°$) indicated the spontaneity and physical nature of the sorption; sorption experiments indicated a urea recovery of ~95% from urine. Finally, the application of urea adsorbed carbon as a soil conditioner in field trials resulted in significant improvement in the number of seed germination and plant biomass (132%) with a substantial increase in the soil nitrogen and cation exchange capacity. Results also indicated that nearly all the urea was desorbed within the soil during irrigation becoming readily available to the plants. This study demonstrates a closed-loop sanitation cycle that channels nutrients from human beings back to agricultural fields.

*Keywords:* Urine; Urea; Activated carbon; Sustainable sanitation; Resource recovery



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## 1. Introduction

The drawback of 'modern' sanitation systems is that it uses freshwater (up to 50,000 liters per person annually), a scare resource, as a transport medium and sink for waste disposal (Esrey et al., 1998). Sanitation systems are based on the premise that excreta are wastes that mandate disposal and operate on the assumption that the environment can safely assimilate them. Human appropriation of water for use in sewage systems has deemed a significant portion of freshwater unusable, unavailable or raised the cost of down-the-pipe wastewater treatment (Palaniappan et al., 2010; Gleick, 2014). This continued improper handling of wastewater streams has dramatically altered the fluxes of growth-limiting nutrients, resulting in accelerated eutrophication of freshwater ecosystems (Dupas et al., 2015; Humphrey et al., 2015). Moreover, moving towards to agree upon and adopt a post-2015 developmental agenda, it is still evident that a substantial fraction of our society still lacks access to adequate water and sanitation. Climate change adds another complexity to this discussion, as several projections point towards an increase in the number of people living under the conditions of absolute water scarcity (Haddeland et al., 2014; Martens, 2014).

Consequently, as Esrey et al. (1998) points out, the technological developments that were once designed to solve the sanitation problem have become part of the problem; in the discussions of most issues, it has become an obligatory imperative to incorporate sustainable development as a criterion irrespective of its vagueness or even triviality. However, it is in the discourse surrounding the conceptualization of modern sanitation systems, where the notion of sustainability finds most appropriateness. This is emphasized in the findings of the UN Task Force 7 which found inherent linkages between water and sanitation to other critical issues like food security, environmental protection and women empowerment (Kvarnström et al., 2006). To this effect, the concept of source separation has been put forward as an integrated solution. Though the notion of source-separating human wastes is not new (Larsen and Gujer, 1996), of late, there has been renewed interest in promoting innovative processes designed specifically to recover resources with economic value from wastewater streams (Ganrot et al., 2007; Wilsenach et al., 2007; Tilmans et al., 2014; Matassa et al., 2015; Ganesapillai et al., 2015). The objective of such processes is to address the limitations of conventional sewage systems that flush away valuable resources, especially nutrients that could potentially be used in agricultural production (Langergraber and Muellegger, 2005). As Smit and Nasr (1992) argue, it is imperative that new closed-loop sanitation systems should be envisioned that promote a circular flow of nutrient and blur definitions of 'wastes' and 'resources'. In order to usher in such a paradigmatic change and a new philosophy in handling wastewater, research effort must be directed towards devising processes that demonstrate the potential benefits of resource recovery.

The human body retains a very small percentage of nutrients that enter it; thus, at fairly constant rate, nutrients enter into and leave the body (Jönsson et al., 2004). Thus, the human excrement represents a valuable source of plant-building nutrients. One way to promote sustainability in sanitation and subsequently, in water usage and agricultural production could be to recover and channel such valuable nutrients to agro-ecosystems which in essence, is the goal of a 'closed-loop fertility cycle' (Langergraber and Muellegger, 2005). Human urine is one such wastewater stream that has found large-scale application in supplementing agricultural productivity as a liquid fertilizer (Stenström, 2004; Beler-Baykal et al., 2011). Source separation of urine has been made possible through the use of Urine Diversion Dry Toilets (UDDTs) that utilize the anatomy of human body that separately excretes urine and feces.

The use of UDDTs coupled with large-scale urine diversion mainstreaming has made the use of urine in agriculture a good venture with a number of projects successfully implementing this approach (Lienert, 2013; Fam and Mitchell, 2012; Wood et al., 2015). However, there are several documented shortcomings in the direct application of urine as a liquid fertilizer (Heinonen-Tanski et al., 2007) along with the cultural and ethical prejudices against its use (Drangert, 1998; Jönsson et al., 2004). To this effect, the conceptualization of a nutrient recovery system that allows removal and recovery of resources from urine for subsequent re-use on arable land could be seen as a potential win–win scenario.

Currently, the loss of nutrients on farms is compensated by the application of commercially produced, fossil fuel-intensive synthetic fertilizers (Vinnerås, 2002). To move towards the goal of efficiency in use of our limited resources, a change in the existing dynamics can be effected through the design and implementation of resource recovery processes that allow recycling of nutrients from humans to farmlands where they act as soil supplements. In our previous work, a process to this effect was demonstrated that recovers ∼70% of urea from human urine through bio-sorption onto coconut shells based activated carbon (Ganesapillai et al., 2014).

In the present investigation, an initiative to improve the efficiency of urea recovery has been undertaken through the incorporation of a wider range of process parameters. To improve the efficacy of the sorbent, the effect of activation parameters (microwave power and exposure time) were investigated during the preparation of microwave activated carbonized coconut shells. Following the textural characterization, the effect of various process parameters was examined to evaluate the urea uptake capacity. Finally, the effect of urea adsorbed carbon as a soil conditioner was analyzed on the plant test species (*Vigna mungo and Vigna radiata*).

## 2. Methods and materials

### 2.1. Adsorbate and adsorbent pre-treatment and preparation

Coconut shells obtained locally in Vellore, Tamil Nadu, India, were washed with distilled water, dried at 105 °C for 24 h and crushed to a size of 1–2 cm. The shells were then subjected to different microwave output power (180–600 W) at varying exposure times (5–20 min) in a domestic microwave (CE104VD-Samsung, Malaysia). Subsequently, they were carbonized at 500 °C for 2 h (heating rate of 24 °C $min^{-1}$) in an industrial high temperature furnace (T-14/HTF-1400—Technico, India). The carbonized shells were then ground using a mortar, sieved to 100 mesh (0.149 mm) and stored in air tight bottles. The activated carbon thus prepared was abbreviated as Microwave Activated Carbonized Coconut Shells (MACCS). All chemicals (analytical grade) used in the study were purchased from Nice Chemicals private limited, Cochin, India and used without further purification.

Human urine was obtained from randomly selected twenty healthy young male volunteers of early twenties and