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Team 24

TREATED RICE HUSK ASH AS A NOVEL BIOSORPTION COMPLEX FOR LOW-COST WATER DETOXIFICATION

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Abstract—*Biosorption technology seeks to harness the physiochemical ability of porous, treated biomass to concentrate dangerous levels of contaminants from even very dilute solutions. In particular, rice husk ash (RHA), an abundant byproduct of the rice milling process, has shown promise toward applications as diverse as the adsorption of dyes, petroleum, and heavy metal toxins from water. This paper will examine the adsorption properties of rice husk in context, reviewing experimental results obtained from metal and bacteria removal studies. Characterization of the biomatrix using Fourier transformation infrared spectroscopy will be related, as will the significance of the Langmuir and Freundlich equilibrium isotherms for modeling the kinetics of the surface binding site interaction. We will further demonstrate how rice husk's optimal surface area, chemical composition, and price point contribute to its good candidacy for water and wastewater treatment, and how variables such as pH and husk preparation can affect the maximum adsorption capacity. With this groundwork in place, we will discuss how an understanding of social and economic equity contributes to "sustainability" in this filtration context.*

The removal of E. coli will then serve as one identifiable application of this technology, and a case study involving ceramic rice husk filter implementation in rural Cambodia will serve as an example of this application in action. Upon further analysis of the extent to which social and economic viability was achieved on a small scale, we will introduce a macroscale counterpart in the proprietary Swach filtration system designed by Tata Chemicals in Gujarat, western India. Having also compared RHA technology to conventional decontamination techniques, a concluding commentary will consider the potential of rice husk filters to reach economies of scale in developing nations and the resulting implications for the global drinking water supply.

Key Words—Biosorption, Decontamination, Developing nations, E. coli, Effluent, Potable water, Rice husk ash (RHA)

CLEAN WATER AND CLIMATE CHANGE

According to a 2018 report by UN Water, the worldwide demand for clean, drinkable water has risen at a rate of about 1% each year over the last few decades, and that rate is predicted to grow significantly in the next few decades as well [1]. This, together with the intensification of global trends such as urbanization, deforestation, and climate change has called into question the ability of today's developing nations to meet the future water needs of their citizens, owing to the prevalent issues of overpopulation and relative non-regulation of the public water supply for such places. Research by Adger et al. on climate change adaptation indicates that societal vulnerability to changes wrought by the changing climate may exacerbate ongoing social and economic challenges for these nations [2]. Effective and equitable natural resource management at the watershed level, together with the technology necessary to safeguard water supply, is therefore critical to the adaptation process.

The *Guidelines For Drinking Water Quality*, released routinely by the World Health Organization (WHO), details the WHO's recommendations to maintain the safety of drinking water and inhibit its contamination. Within these guidelines, the WHO states: "Water is essential to sustain life. An adequate, safe, and accessible supply of water must be provided to all… and every effort should be made to make drinking water as safe as possible" [3]. The detection of toxic heavy metals such as arsenic, lead, and mercury [4]; and of biocontaminants such as the intestinal bacteria E. coli (*Escherichia coli*) in industrial effluent and certain sectors of the global drinking water supply stands in direct opposition to WHO standards, and has raised concerns over their potential adverse effects on human health and environmental integrity [5]. Rice husk ash (RHA) will be evaluated as a potentially important player for water purification in this changing climate landscape.

CHARACTERIZATION OF THE HUSK

A review of the literature by Subki and Hashim records that rice husks are the hard coverings of grains of rice, which protect the seed during its season of germination [6]. In the milling process, the mostly indigestible husks are removed from the grain to produce brown rice, which is then often further refined into white rice by stripping away nutrients and fiber [6]. According to a morphological study of the husk published in *Industrial and Engineering Chemistry Research*, the husk possesses a "corrugate structural outer epidermis that is highly ridged… and that its ridges are punctuated with prominent globular protrusions [7]." This polyamorphous, interlocking assemblage of RHA allows for diverse adsorption capabilities [7]. Shown below is an image from a scanning electron microscope (SEM), which highlights these traits.

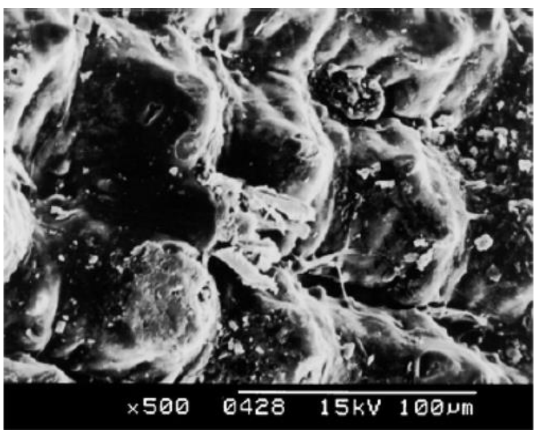

FIGURE 1 [7]
SEM micrographs of RHA epidermis

Figure 1 exhibits that the epidermis of the husk is visibly marked by such ridges and protrusions, which cause the other particulate matter in the frame to pale in comparison. Essentially, these folds, wrinkles, and pockets on the surface provide a unique physical binding site for contaminants.

Chemical Composition

The chemical component of the binding site is characterized primarily by the presence of silicon in the RHA (~20%), which is well-known for its diversity of formations [7]. The exact amount of silicon, however, depends on climatic variation and human factors in rice production [7]. The chemistry of the husk is then typically altered by various preparations before being applied in a system, though the raw husk itself supplies most of the adsorption capability [8]. The relative insignificance of two such treatments will be discussed in the "Effects of Carbon Doping and Silver Impregnation" section. In general, the aim of these preparations is to produce activated carbons and silica, which are highly sought after for their known adsorption properties, among other advantages. In general, activated carbon is more directly involved with the adsorption mechanism, whereas the activated silica reduces the turbidity, or suspended particle count, and elongates the life of the filtration system. When burned, RHA produces significant amounts of these amorphous silica, which render the husk an excellent thermal insulator [7]. The chemical formula for silica, $SiO_4.4H_2O$, shows that each oxygen atom is shared between two SiO_4 tetrahedrons [7]. This creates an ionic Si-O bond, which facilitates cation exchange [7].

One study of husk chemistry from the *International Journal of Nanotechnology and Applications* reveals that certain participating functional groups such as carboxyls and silanols compound this exchange. Their presence may be inferred from Fourier Transformation Infrared Spectroscopy (FTIR), a technique by which varying wavelengths of infrared light are shot at a sample of husk, and the resulting vibrations of the constituent molecules recorded. Each functional group has a characteristic wavelength at which it will vibrate, betraying its presence [9].

FTIR spectra of RHA, shown as Figure 2, reveals three key absorption peaks located at roughly the 3500, 1100, and 450 cm^{-1} marks [9]. These correspond to O-H, Si-OH, and Si-O-Si bands respectively [9]. Those bands which contain silicon are associated with an asymmetric stretching mode of vibration, a property characteristic of activated silica [9]. Again, it is the flexibility—physical and chemical—of this activated silica which allows RHA to be utilized for such diverse applications.

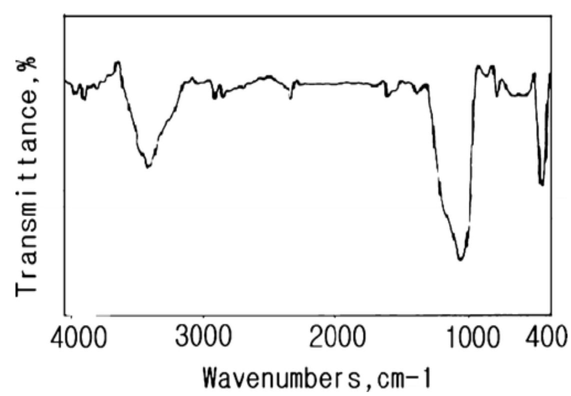

FIGURE 2 [9]
FTIR peaks observed for untreated RHA sample

ION EXCHANGE MECHANISM

RHA works to filter water through adsorption. Anne Helmenstine of ThoughtCo Chemistry defines *ad*sorption simply as "the adhesion of a chemical species onto the surface of particles" [10]. This is in contrast to *ab*sorption, in which the species is enveloped by the surface. For an RHA application, the gas or liquid contaminant particles bind to the surface of the husk, termed the adsorbent. Even more specific to RHA is the concept of biosorption, which Dr. Volesky of McGill University describes as a property of dead, physically or chemically-treated biomass to bind, concentrate, and remove harmful particles from water [11]. Use of this term speaks more to the agricultural origins of the adsorbent than anything else. Fundamentally, the biomass acts as a chemical surface which accumulates ions found in the water, and, after the particles are adsorbed, the biomass can easily be removed from the water, allowing for cheap and effective filtration [11]. Ion exchange adsorption, which falls under the umbrella of biosorption, is the most common mechanism relevant to RHA, and may be demonstrated taking the specific case of heavy metal contaminants.

Amin et al. found that the mechanism of adsorption of metal anions onto RHA generally occurs in two steps. First, carbon in contact with the water reduces oxygen to a hydroxyl group,

$$O_2 + 2H_2O + 2e^- \rightarrow H_2O_2 + 2OH^-$$

FIGURE 3 [12]
The reduction step

leaving electrically-neutral hydroxyl ions intact, shown by Figure 3. When a metal-bearing solution comes along with anions more strongly attracted to the carbon than the hydroxyl groups, the latter are exchanged, adsorbing the contaminant [12]. For example, with adsorption of arsenic (As(V)), we have

$$\text{carbon-}(OH)_2 + HAsO_4^{2-} \rightarrow \text{carbon-}HAsO_4 + 2OH$$

FIGURE 4 [12]
The adsorption step

This process differs slightly once one starts to look outside of metal contaminants. Depending on the chemical identity of the contaminant, different functional groups within the husk participate in the reaction. In many cases however, such as for removal of pesticides or synthetic fertilizers containing various organic anions, a nearly identical reaction occurs involving the activated carbon from the husk [12].

Comparison to Conventional Techniques

Several different techniques are commonly used to filter water, and biosorption matches up seemingly well against each one, as they all appear to have at least one significant drawback associated with them. A 2018 article by L. Regina explains that activated alumina filters, for example, though highly efficient, can leach aluminum into the water depending on the water's pH and mineral hardness. Standard ceramic filters are inexpensive and do not require electricity for operation, but they are generally slower, and cannot be used to clean large quantities of water (e.g. current from rivers, streams, or lakes). Reverse osmosis filters can lead to a large amount of water wasted, as only about 25 to 33% of the water that enters these filters is actually purified, with the rest being disposed of. Ultraviolet filters are very good at killing any parasites, bacteria, or viruses found in the water, but they are relatively expensive, require vast quantities of energy to operate, and are unable to filter out abiotic water contaminants. Water distillation filters are able to remove most contaminants while also killing bacteria found in water, yet they, too, are slow and also require a large power supply [13].

S. Gunatilake of Sabaragamuwa University in Sri Lanka performed a 2015 study on heavy metal filtration utilizing biosorption techniques, and discovered that biosorption filter systems compete well when matched with these and other common methods of water filtration due to several key factors: the exceedingly low cost of biomass needed for the filtration, the ability of biosorption filters to remove heavy metals in addition to biocontaminants found in water, and the filters' usability on large bodies of water as well as small quantities [14]. Biosorptive filters are also able to accumulate more than 25% of their dry weight in deposited materials, and after the saturated biomass is removed from the water, it can be washed in concentrated solution to remove accumulated ions for future reuse [11]. This in conjunction with the environmentally conscious aspects of biosorption devices, including RHA filters, make them favorable for low-cost and energy-efficient applications.

Considerations for Sustainability

One of RHA's greatest strengths lies in the fact that it is widely available and routinely underutilized. 2015 findings from the journal *Reviews in Environmental Science and Biotechnology* claim that around 600 million tons of rice are produced worldwide annually, and its cultivation covers approximately 1% of the Earth's surface [15]. For every 100 kg of rice produced, 22 kg of rice husk is generated alongside of it [15]. In fact, the amount of RHA byproduct available is in such great excess that it has quickly evolved into a disposal problem for developing nations such as India and Malaysia, which rely heavily on rice for nutrition [7]. Consequently, farmers often burn the RHA in mostly uncontrolled heaps, which releases carbon dioxide into the atmosphere and may therefore contribute to climate change [7]. The *India Tribune* even reported in 2018 that when the untreated husk is not burned, it can pile high on riversides, and its contaminant-laden surface leech anions into the proximal water source, as shown in Figure 5 [16]. In other words, if consistent efforts are not applied to convert RHA to more useful forms, it has the potential to do more harm than good.

FIGURE 5 [16]
Excess RHA can pollute local waterways

This rice husk has several potential modifications which potentially make it even more useful for adsorption. As an illustration, this commodity waste product can be made into activated carbon [7]. Activated carbons have been the subject of intense research in chemistry recently, though their biggest barrier to industry applications is their cost: around $600 per ton or more. RHA, by contrast, results in activated carbons at only a quarter of that price, running between $100-200 per ton, according to Foo and Hameed [17]. These activated carbons purchased separately also experience difficulties associated with regeneration, which RHA does not [16]. If anything, desorption efficiency involving RHA generally tends to increase with time allowed, and certain acid treatments can greatly quicken the regenerative process [12]. From a cost standpoint, the recovery of the adsorbed material and regeneration of the adsorbent constitute critical aspects of wastewater management.

Adsorption using RHA also answers a pressing environmental question in places like Malaysia, where 21 million tons of RHA are produced annually. Foo and Hameed, in *Advances in Colloid and Interface Science*, argue that "within recent decades, the emission of rice husk ash into the ecosystem has attracted huge criticisms and complaints, mainly associated with its persistent carcinogenic and bioaccumulative effects, resulting in silicosis syndrome, fatigue, shortness of breath, loss of appetite, and even death" [17]. As a result, there is a threefold environmental sustainability advantage to the utilization of RHA: rice husk waste can be reduced, value-added adsorbents produced, and wastewater pollution mitigated at a reasonable cost. These cost incentives, if nothing else, may be enough to convince more rice mills to jump on board with the idea of commodifying their waste.

Perhaps a more operational definition for sustainability is in order to firmly establish RHA as such for this context. A 2014 report by Summers and Smith on "The Role of Social and Intergenerational Equity in Making Changes in Human Well-Being Sustainable" argues just that: that sustainable means viable for the next generation, and viable means that human well-being is fully encompassed [18]. More explicitly: "A sustainable world is one in which human needs are met equitably and without sacrificing the ability of future generations to meet their needs" [18]. It is the interaction between four factors of need—basic, economic, environmental, and subjective happiness—which complicates this understanding of well-being and subsequent sustainability [18]. Importantly, Summers and Smith also denote social equity as the "orphaned element of sustainable development [18]. A definition of sustainability linked to social equity is necessary to account for happiness, which is inherently more difficult to quantify. Social equity implies fair and equal access to the health, economic, and environmental rewards reaped from utilizing RHA technology. The biggest roadblock to social equity in this case is the affordability of the filter. As we will show in the section on "Implementation of RHA in Ceramic Water Purifiers," this issue is a real one, but may be sidestepped by careful consideration of the target market, and appropriate adaptation of the filter to that market.

With the case of RHA, we have basic needs being met directly. Humans cannot function without clean water, and in many parts of the developing world such as India and Cambodia, contamination is a serious threat to human health. The economic benefits of RHA filtration are also rather clear-cut: RHA is cheaper, and RHA works more efficiently than its counterparts. It is available abundantly in those places where it has the greatest potential, and no barriers of additional treatment or storage requirements drive the price or difficulty of application upward. Environmentally, use of RHA has been called a "judicious recycling of colloidal agricultural waste" by which excess pollution is prevented and present contamination is removed [17]. Social equity will be evaluated further following the presentation of cases from Cambodia, India, and Bangladesh. To prepare for this discussion, we now turn to an analysis of the highly specific relationship between adsorbent and contaminant.

ADSORPTION KINETICS: MODELING ARSENIC REMOVAL

In the journal *Desalination*, Chuah recognizes arsenic as a common toxic metalloid contaminant in many countries where rice is an agricultural staple, examples including China and Bangladesh [19]. About one-third of this contamination results from natural geological processes, while the remainder is due to human industrial wastewater pollution [19]. A large number of remediation techniques for arsenic have been developed, such as electrocoagulation, synthetic sorbents, water softening with lime, and many others [19]. RHA in a fixed bed column (gravity-driven) setup has been investigated as a low to no-cost alternative for the adsorption of arsenic.

In this fixed column apparatus, the contaminated water is first poured in through a top valve [11]. The water then trickles onto a layered arrangement of RHA, such that physical exposure is maximal, rippled, and repeated [11]. The effectiveness of RHA to remove various contaminants such as arsenic is largely specific to the chemistry of that contaminant, so the results from arsenic decontamination are not generalizable to every known application of RHA. However, as a major public health actor in rice-rich areas, arsenic comprises an important point of specificity.

pH is one of the most vital parameters for metallic adsorption, and arsenic is especially sensitive to changes in pH, existing as reactive oxyanions at neutral pH [19]. "The removal efficiency of As(V) increases slightly with increasing pH, is nearly constant above pH 8, and decreases tremendously at pH>12" [19]. This is because at the very basic end, hydroxyl groups are more abundant on the surface of the husk, decreasing adsorption efficiency [19]. This demonstrates that the effectiveness of RHA is subject to the chemistry of the contaminant. As a result, RHA filtration systems can be targeted toward those applications for which they are most effective, and selectively not applied for instances in which other means may prove more effective.

Isotherm Modeling

In order to get a sense for the extent to which such modifications can alter adsorption, it is necessary to discuss isotherm models. Foo and Hameed of Universiti Sains Malaysia describe an adsorption isotherm as "an invaluable curve describing the phenomenon governing the retention or mobility of a substance from the aqueous porous media" in the solid phase at constant temperature and pH [20]. Two of the most common such isotherms are the Langmuir and Freundlich. The Langmuir isotherm describes adsorption equilibrium, the state at which adsorbate concentration is in a dynamic balance with the medium [20]. It was originally designed to work with gas-solid adsorption onto activated carbon [20]. Perhaps an even more appropriate model for the adsorption of aqueous As(V) would be the Freundlich isotherm, which is widely applied in heterogeneous (multi-contaminant) systems, or systems in which highly interactive species encounter activated carbon [20].

Establishing the most appropriate adsorption equilibrium correlation for a system is, according to Foo and Hameed, "indispensable" for reliable prediction of adsorbent behavior, allowing for optimization of the mechanism, accurate expression of the capacities of the filter, and effective design of decontamination systems [20]. Clearly, a system whose proximity to the equilibrium state varies exponentially, or even inversely to a power, will require more fine tuning than one which might be described with linear, direct variation. It should be noted also that more favorable adsorption is often dependent on factors such as initial adsorbate concentration, molecular proximity, and free energy spontaneity of the relevant reaction [20]. These considerations are reflected in the different isotherm equations. For example, the Langmuir isotherm model,

$$R_L = 1/\ 1+K_LC_O$$

FIGURE 6 [20]
The Langmuir isotherm

describes a value R_L which varies inversely with the initial concentration, C_O. In this context, lower R_L, or higher C_O, means adsorption is more favorable. Now apply this to the adsorption of As(V). By knowing that this chemical interaction adheres generally to the Langmuir isotherm, preparations involving distillation of the sample to be treated may prove effective. After all, RHA may be low in cost, but if its chemistry is in conflict with that of the contaminant(s), the system as a whole will not be efficient [20].

This equation also demonstrates that adsorption capacity is dependent on more than just pH. Indeed, initial concentrations, particle size, flow rate, and others can all influence this bottom line. Expanding upon each of these briefly, it should be noted that adsorption does depend heavily on surface area availability for solute-surface interaction [7]. It is expected, then, that smaller particle size would mean more available surface area per unit mass of rice husk, and this has been shown to be true [19]. Silicon can be pointed toward as increasing porosity, and therefore surface area, for the RHA. As for flow/agitation rate, higher agitation is associated with reducing the film layer surrounding the particles, thus increasing the uptake rate [19]. Finally, additional column bed height tends to increase this exposure time and amount adsorbed, slowing the process marginally [11].

Effects of Carbon Doping and Silver Impregnation

Chemical alterations can be just as, if not more effective than physical ones for maximizing the adsorption capacity of an RHA system. For example, instead of distilling the contaminated medium, it could be possible to infuse the RHA with external activated carbons or silver nanoparticles (AgNPs). This was the case in a series of lab tests performed by Carmalin Sophia, where RHA arranged in a fixed bed column setup was found to be the single most impactful decontaminant of E. Coli [8]. All the carbons studied showed >99% removal, but the price and effort of sourcing each differed significantly [8]. The cost of synthetically-produced activated carbons has already been discussed at length. Ag-impregnated samples are likewise cost-intensive, in addition to being less known than activated carbons and scarcer as well. In accordance with the extensive development of nanotechnology, AgNPs have been investigated for their high specific surface area and bactericidal ability [20]. However, D. He writes in an article published in *Environmental Science and Technology* that "separation of nanosized particles from the solution phase renders their application as a water treatment technology impractical" without the addition of other expensive materials such as aluminum fibers and zeolites [20]. Expensive materials often come alongside expensive, time-intensive, or otherwise inefficient processes to render them useful, compounding the issue.

In the Sophia study, only marginal improvements in bactericidal properties were documented by the silver and carbon additions [8]. This is good news for the bottom line of RHA systems. The potential of AgNPs for this niche application is not yet well-understood, and so currently they pose an unnecessary expense in the majority of scenarios [20]. If expensive treatments do not significantly improve already effective filtration, and if inexpensive treatments do, then RHA is situated as an abundant, untapped resource. Many additional pits and outcroppings on the RHA surface were even generated in this experiment by the channeling of sulfuric acid, another readily-available raw material, through the husk [8]. This is thought to be the result of chemical attack at crystallite boundaries, a process wherein caustic fluid dissolves surface functional groups to polish rough surfaces and create holes [8]. Tentative research appears to indicate that controlled release of trace amounts of NPs into the medium may serve to supplement activated carbon and silica in the husk [20]. However, further research is needed to establish this premise. Until more data is available on this and other costly modifications to the husk, they should be avoided for economic considerations.

IMPLEMENTATION OF RHA IN CERAMIC WATER PURIFIERS

One small-scale use of this application of rice husk to remove E. coli will now be examined by looking at the implementation of handmade single-family filtration systems in rural Cambodia, where diarrheal disease is commonly attributed to bacterial contamination, and an estimated 10% of productive time is spent on the collection of still-dirty water. This poses a "significant barrier to development, both human and economic" [22]. A common technique to combat this by producing RHA filters at the lowest possible cost is to use the husk as a supplementary cementing material in what are called ceramic water purifiers (CWPs) [22]. In fact, according to Hossain in the *Journal of Asian Ceramic Societies*, RHA is so mechanically strong that it can be used in the creation of almost any ceramic product, from insulators, to roofing tiles, to ceramic-based dyes [23]. When it is simply incorporated into a filter, however, the husk is neither heat-treated nor has its silica extracted [23]. Rather, when the ceramic filter is fired in a kiln, the water contained in the particles of the husk evaporates and expands, leaving a large number of extremely small pores which allow the contaminated water to permeate through the filter [23].

In a study performed by Mark Brown of the department of Environmental Sciences and Engineering at the University of North Carolina at Chapel Hill, use of these CWPs was found to reduce the presence of E. Coli up to 99.9999% [22]. The difference in this method of utilizing rice husks is that they are not the main adsorptive part of the filter. During creation, the maker of the filter, according to Brown, adds "finely ground rice husks into the clay, which combust in the firing process to leave behind pore spaces" [22]. These pore spaces are what allow water to flow through the ceramic effectively filtering out almost all pathogens and other hazardous particles. As is common with many filters which utilize rice husk ash technology, silver is used to try and increase filtration effectiveness. In this instance, "Filters are treated with an $AgNO_3$ solution to reduce microbial recontamination of the filter and biofilm formation" [22].

Unfortunately, this filter style and treatment proved less effective than others at removing various biological contaminants such as the bacteriophage ms2 when compared to other similar commercially available filters [22]. In Brown's study, another issue with this specific related directly to sustainability through longevity: after a fairly short period of usage in Cambodian households, many of the filters were left out of use [22]. In fact, when the 328 households that reported discontinued use of the filter were asked why they no longer used the product, "it was found that 214 were out of use because they were broken" [22]. The fragility of the ceramic filter proved to be a critical issue with the product. Although the ceramic filters are easy to swap in and out of the filtration unit, only twenty six percent of people were aware of where they could purchase replacement filters [22]. In addition to not knowing where to buy the filters, prices of the filters ranged from $2.50 up to $4, which only 29% of filter owners were willing or able to pay [22]. This study showed the versatility of RHA for the purposes of filtration, but this implementation clearly had some issues. Filter users were certainly left better off than their non-user counterparts, yet from the data gathered through this trial, it appears as though research into rice husk filtration technologies of other styles may be more beneficial in the long run. Rice husk as a ceramic supplement might instead be utilized for its high mechanical strength, rather than its porosity.

Swach Filter Takes India by Storm

One possible alternative to CWPs which still makes use of RHA technology has been developed by Tata Chemicals in Gujarat, India [24]. India is another country experiencing similar clean water dilemmas comparable to that of Cambodia. Recent estimates by Hang et al. indicate that fewer than 4% of urban families and 1% of rural families in India using water purifiers, despite the fact that an estimated 7% of Indians lack access to clean drinking water [25]. In response to this issue, Tata Chemicals, using research dating back to the 1980s, released its first filter model, the Sujaal, in 2005. Though the Sujaal was sourced from abundant, inexpensive materials, driving down its price to a mere $16, customers soon responded concerning its failure to remove most microorganisms. Tata then redeveloped its product using RHA in conjunction with Ag-NPs in order to pass international water standards, and in 2009 released the Tata Swach model at around $15 per unit [25]. The silver compound helps to "inhibit bacteria multiplication by reacting with sulfhydryl (-SH) groups in the bacterial cells" [24]. NGOs such as Community Aid & Sponsorship Programme, Pune, and the Indian Institute of Youth Welfare, have distributed the Swach all over the nation, and the technology has won numerous national awards [26].

FIGURE 7 [27]
The Tata Swach (current model)

The Swach, shown previously in Figure 7, aims to hit a completely different market than the CWPs discussed previously, as is evidenced by its slightly higher price and the increased complexity of the technology utilized [28]. In essence, the target audience has shifted from subsistence farmers to those working low-level jobs in urban or suburban settings. This shift is reflected in the design of the Swach. It now features an easy-clean upper chamber, made of durable plastic, and the product comes with a set of instructions for simple, weekly maintenance [27]. Replacement parts are readily available online and through catalogues [24]. Additionally, in terms of effectiveness, whereas CWPs generally do not combat viruses, the Swach prides itself on its resistance to bacterial and viral contaminants alike [24]. These points of difference between the Swach and CWPs may hint at why the former has garnered widespread acceptance in India, and the latter has made only small waves in the world of economical filtration. To clarify, it is crucial that a filter be designed with the user in mind. Replacements must be accessible, and the filter must meet the water need in a tangible way (e.g. elimination of foul color, odor, or taste). Perhaps most importantly, users must come to understand the importance of filtration on their own terms, so that they are sufficiently motivated to sustainably pursue clean water. This was no problem for the Swach because users were also customers. In the case of Cambodia, however, users often failed to see the direct connection between filtration and health, despite the 40% drop in occurrence of gastrointestinal disease observed for those with CWPs [22]. In either case, the price attached to the filter was likely associated with an increased sense of agency and ownership among users, lending credence to the idea of RHA filtration as an expandable market.

Potential Implications for Bangladesh

The potential of a product such as the Swach to become normalized in the low-cost water filter sector is dependent upon a number of factors largely specific to local geology, industry, and resources. Consider the case of India's neighboring Bangladesh, and its capital city, Dhaka. Dhaka has faced the challenge of remediating industrial effluent into potable water for years. In 1994, 40,000 cubic meters of wastewater was discharged from a total of 502 textile factories each day in this city, and since then, the industry's production has continued to climb, accounting for $21.5 billion in income more recently in 2012 [29]. These effluents are highly colored and saline, and contain non-biodegradable compounds including heavy metals and dyes, which routinely overstep weakly-enforced discharge limits [29].

This represents an instance of multi-media contamination. Part of the problem stems from underground geological contamination of arsenic. The textile industry then exacerbates the issue by dumping dyes and chemicals into local rivers. This all results in competitive adsorption between As(V) and other oxyanions. In other words, for a system with multiple contaminants, RHA will tend to exhibit a certain adsorption affinity for some contaminants over others in most cases [19]. J. Cui writes that for Bangladesh, the situation is exceedingly complex, as effluent routinely contains cadmium, chromium, calcium, copper, iron, lead, arsenic, nitrates, nitrites, ammonia, sulphides, oils, and greases [30]. These concentrations can vary from less than 0.1 mg/L to upwards of 670 mg/L, a lethal dose in some circumstances [30]. It is documented that increased concentrations of phosphate, sulfates, and mineral anions tend to reduce As(V) adsorption when RHA is implemented [30]. Conversely, nitrates, chlorides, and bromides were shown to have no effect, and calcium cation actually improved arsenic removal due to "favorable electrostatic effects" [30].

Given this information, it appears that RHA filters may not be the most suitable for applications in Dhaka. Indeed, iron filings, charcoal, and even the water hyacinth plant have all met some success in this type of environment, while other biosorbents like RHA do not seem to make the cut [30]. This is likely because those contaminants which tend to have no effect on each other are generally lower in concentration for textile effluent, and those which have a competitive effect can be seen in higher quantities. RHA, therefore, may not be capable even of selectively filtering a single contaminant such as As(V) in situations like these. That said, to establish this notion for sure would require much more research in the area of competitive biosorption. The low-cost efficiency of RHA filters provide much hope for the future of filtration, but the potential of these filters to truly address local water needs to be evaluated on a case-by-case basis. This can be broken down by country, region, and even community or village. In fact, the latter may be necessary when treading in territory where not much is known about the competitive adsorption characteristics of the local system.

DISCUSSION AND FUTURE RESEARCH

The global clean water crisis facing developing nations today is truly staggering in its vastness and layers of complexity. Studies suggest that water demand management or water supply management alone will not able to adapt to mounting water stress [31]. As the politics of local water management and national regulation vie for control over this precious, finite resource, it has become apparent that a low-cost, sustainable water filter is the key to a cleaner future. In several ways, RHA appears uniquely positioned to meet this point of need in those places where it is needed most. That it stems from the rice milling process is potentially influential from a cost and availability standpoint for a large number of developing nations such as Cambodia, India, and Bangladesh, which depend upon rice for survival. That the use of RHA prevents it from being routinely burned by the masses, releasing greenhouse gases into the atmosphere gives its recycling a sense of environmental urgency. That the husk is able to be regenerated following its use speaks to the sustainability of such a simple approach to water filtration. Each of these works to fulfill the requirements for a sustainable solution, defined earlier as the binding of intergenerational equity to human well-being. RHA should be recognized as a long-lasting, low-tech solution accessible to people of any age and, to a varying degree, socioeconomic statuses.

This is not to say that RHA remediation is without its problems, however. From the Cambodia study, we learn that even a highly successful technology may not succeed in rural areas unless it is accepted by local residents and fits into those specific circumstances. If a filter is to be accepted, it must be simple, low-cost, and based on local resources and skills. Without each of these, filters end up broken, unused, or recontaminated. A filter must then be sold at a reasonable price, with "reasonable" being defined by the communities being served. Barriers such as average income and the living wage are just as significant as lack of funding for research or training in these instances. The importance of social equity for sustainability mandates that expectations for filter longevity should be adequately met, and the steps for replacement or repair well-defined. Though RHA is not some panacea for the impending global water crisis, it appears that *certain* applications in *certain* sectors may make a real difference for the lives of millions of people.

Clearly, additional research will be required in many interconnected areas to make a firm decision on the viability of RHA for its currently attempted applications. The most glaring of these has to do with the use of RHA in the situation of multiple contaminants. Understanding how organic and inorganic anions interact competitively on the globular surface will be critical for water sources contaminated by, for example, textile effluent, as was seen in Bangladesh. By increasing the predictive and descriptive advantages of accurate isotherm modeling for a greater number of contaminants, the efficiency of RHA filters, and the reliability of their claims as a product would certainly be bolstered as well. Moreover, the same ingenuity which led to the integration of RHA into cement and plastic filters begs the question: what other innovative, judicious applications of RHA lie waiting for researchers to discover next? Maybe the thermal insulation properties of RHA could be coupled with a source of heat to stave off bacterial activity through unconventional means. Maybe its high mechanical strength will cross over from the realm of supplementary construction material to a durable and effective filter in its own right. The future of RHA may not be crystal clear, but its record of past successes positions it a strong combatant to the world's shrinking water resources.

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