ISSN 2250-3153

Nutrient Recovery Systems for Human Urine - Ways to Realize Closed Loop Sanitation and Future Sustainable Agricultural Systems

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Abstract- This paper provides an overview on the concept of closed loop sanitation systems. A brief outline has been given on existing sanitation facilities in India, ways to implement ecological sanitation and retrofitting of nutrient recovery systems into existing sanitation facilities. In recent times, though India has witnessed phenomenal development in water resources, access to adequate sanitation facilities remain one of its major development issues. Urine Diversion Systems as a sustainable sanitation alternative can help India move closer in achieving such goals. Today, a new paradigm is being formed in wastewater management that focuses on what resources can be recovered from wastes rather than what constituents must be removed from it. Such a paradigm can help us develop a 'closed loop fertility system' that can re-circulate nutrients from human beings back to agricultural fields. At present a wide research gap exists in this sector as research has been more focused on engineering better sanitation facilities. Sanitation systems could be re-designed in order to incorporate processes that simultaneously recover and recycle nutrients being flushed away. Any proposed project to implement these ideas can only be regarded successful if the agricultural trials of urine recycling provide useful data on agricultural benefits and potential savings in chemical fertilizers.

Index Terms- Human Urine, Nutrient Recovery Systems, Ecological Sanitation, Urine Diversion, Food Security

I. SANITATION – THE INDIAN SCENARIO

With its landmass of 3.29 million square kilometers and a population of over a billion, India is an assortment of pluralistic diversity in terms of culture, religion and language. Endowed with enormous natural resources, the Indian economy has grown steadily, and economic liberalization has unleashed the vast potential of the private sector, which today accounts for nearly 75 % of GDP [1]. India has witnessed phenomenal development of water resources and self sufficiency in food grains, rapid expansion in the urban, energy and industrial sectors, and drinking water infrastructure for about 85 % of India's urban and rural population. The report Asia Water Watch 2015 projected that India can achieve its Millennium Development Goals (MDG) Sanitation Targets in both urban and rural areas if it continues expanding access at its 1990-2002 rates. By 2015, the percentage of people in urban areas served by improved sanitation is expected to reach 80 %, up from 43 % in 1990. In rural areas, the projection is 48 %, an incredible improvement over the coverage rate of just 1 % in 1990. In real numbers, that means more Indians will have improved their sanitation situation from 1990 to 2015 than the total number of people currently residing in the United States [2].

Though it seems that India is on track in achieving its sanitation targets, the reality of such a scenario depends on several factors. MDG only shows an achievable level if the country commits to use all its power to complete it. Despite recent progress, access to improved sanitation remains far lower in India compared to its neighboring countries, Bangladesh and Pakistan - both of which have a lower gross domestic product per capita than India. Both the countries have had a significant improvement in sanitation facilities over the past decade [3]. Analysis of sanitation coverage data from various sources show that despite the acceleration of coverage under the Eighth Plan, only between 18-19 % of all rural households have a toilet which indicates that the rest still defecate in the open. For these poverty ridden people who slog day and night for a two time meal, it is natural not to have facilities for defecation in or near their homes. While the urban households are not that deprived, sanitation problems in crowded environments are characteristically more serious. In these areas, there is a need for safe ecological sanitation. Out of the many developed cities in India, only around 70 have partial sewerage treatment facilities and systems. As of 2003, only 30 % of the wastewater was treated before disposal because state governments and municipalities did not have enough funds to either treat the waste water or build efficient sewage treatment systems. As a result, untreated water finds its way into water systems such as rivers, lakes, groundwater and coastal waters, causing severe water pollution [4].

Several other factors have often been the reasons for inadequate sanitation. Sanitation facilities may be available but could be *inconvenient, unpleasant* or *unhygienic.* This may be the result of inappropriate design and construction, or inadequate management and maintenance of such facilities. On the other hand, even where toilets are available, some are not used or are underused, with family members preferring open defecation. People may underuse their toilet because of misunderstandings in its functioning and maintenance. For instance, in case of twin-pit pour flush toilets, some people fear that the pits will fill rapidly if the toilet is used too often. They remain unaware of the fact that the contents of a full pit can be safely removed manually once they have been given time to degrade [5].

The impact of inadequate sanitation has been much worse on human health. Unsafe disposal of human excreta facilitates the transmission of oral-fecal diseases, including diarrhea and a range of intestinal worm infections such as hookworm and roundworm [6]. It has been estimated that diarrheal morbidity can be reduced by an average of 6-20 % with improvements in water supply and by 32 % with improvements in sanitation. [7]. Today, India is losing billions of dollars each year because of poor sanitation facilities. According to an assessment, Losses incurred on account of inadequate sanitation were as high as the state incomes of Andhra Pradesh or Tamil Nadu and were more than Gujarat's state income in 2006-07. The economic toll is mainly due to access time costs for households, illness costs for families, messed up cities causing fall in tourism, expenditure on medicines, healthcare and funerals. The total economic impact of inadequate sanitation in India amounts to Rs. 2.44 trillion a year which was equivalent of 6.4 percent of India's GDP in 2006. This means a per person annual impact of Rs. 2180 [8].

The provision of water and sanitation facilities are important public health measures that contribute significantly to the reduction in the disease burden of populations. The provision of such facilities is also critical to socio-economic development and has important equity implications as increasing numbers of international protocols and national policies emphasize the 'rights-based' approach to development [9].

II. IMPLEMENTING ECOLOGICAL SANITATION

A. A Success Story

It is important for the improvements in water and sanitation to be integrated and appropriately planned. Thousands of success stories have emerged from all over the country, focusing on either off-site or onsite sanitation. One such interesting story is of Dhikpur, a secondary school which designed a new scoring system for health classes that grades a student's performance based on his or her active participation in improving community sanitation. The school uses toilet construction assignments as a part of its effort to achieve total sanitation in the neighboring catchment area. A student who installs a toilet at home not only receives 10 marks in health class, but is given a 'tika' in appreciation and recognition. The student is invited to the front of the prayer ground, honored by all the students, and recognized by having a 'tika' placed on his or her forehead. The opportunity to earn respect increased student involvement and as a result, after a year, the town was declared an open-defecation-free-town by the state government [10].

B. Choice of Sanitation Technology

Many people in developing countries rely upon untreated groundwater supplies for their drinking water supplies. They are obtained from drilled boreholes or tube wells and springs. Such sources are usually of good quality and are much better than some traditional sources of supply. However, groundwater can become contaminated and there is special concern that the introduction of on-site sanitation systems may in certain circumstances contribute to contamination of drinking water supplies.

The choice of sanitation technology depends on many economic, technical and social issues. Whilst off site sewerage is often viewed as the most desirable form of sanitation, it has several drawbacks. There is evidence from European experiences that leaking sewers may significantly contribute to microbiological and nitrate contamination of groundwater and thus may present a significant risk in regions where groundwater is exploited for domestic supply. Furthermore, sewage treatment plants are often poorly operated and managed leading to the discharge of inadequately treated wastes into the environment. Some forms of treatments such as the waste stabilization ponds may be prone to leaching of both microbiological and chemical contaminants.

On-site systems (Septic Tanks, pit latrines, VIP latrines etc.) often represent a significant hazard through groundwater contamination as fecal matter accumulates in one place and leaching of contaminants into the subsurface environment can occur.[9] Septic tanks typically hold the solid component of wastes in a sealed tank where the matter decomposes an-aerobically. Liquid effluent is usually discharged into a soakaway pit. In well-designed septic tanks, the solid matter does not represent a significant threat, but the soakaway pits may cause contamination. Thus when considering the use of sewerage, attention must be paid to the possibility for groundwater contamination, ensuring that systems are operated and designed with groundwater protection needs in mind. In addition to being economically viable, socially acceptable, and technically appropriate, an advanced excreta treatment system should also protect the environment and natural resources.

C. Historical Background on Diversion Systems

The "Divide and Rule" policy, has gained momentum since the British first introduced it in India. Today, the alternatives to the conventional wastewater system include systems that separate or divert urine and feces in order to utilize the nutrients more efficiently. In Swedish cities, urine was often collected separately and poured into the drain to avoid smells and to prevent the latrine from filling too quickly [11]. Already in 1867 it was known that "the proportion of value of the fertilizing ingredients held in solution in urine to that contained in feces is as six to one" [12, 13] while Müller, a German scientist at that time, saw it as a necessity to separate the urine from the feces in order to produce a fertilizer that was of manageable proportions [14, 15].

In many other parts of the world, it is a tradition to keep the urine and feces apart. The old Japanese practice of nightsoil recovery from urban areas separated urine and feces, since urine was regarded as a valuable fertilizer [16]. In Yemen the urine is drained away and evaporated on the outer face of multistorey buildings to obtain the feces as a dry fraction without smell for later use as fuel, a system that has been in use for hundreds of years [17].

III. FOOD SECURITY IN INDIA

"Our modern society separates food production and consumption, which limits our ability to return nutrients to the land. Instead we use them and then flush them away" [18]. In addition to loss of nutrients, the exponential growth in population has created doubts regarding self-sufficiency in food production in near future paving a threat to sustainability. Food Security is not only dependent on ability of agriculture to produce sufficient food at national level; food insecurity also results from failure of communities to guarantee access to sufficient food at the household level [19]. India is characterized by high levels of poverty, especially in rural areas which accounts for approximately half of the country's population. These people depend only on agriculture to sustain their living. In order to feed a country of population much more than billion, farmers used chemical fertilizers to fulfill the ever increasing demands of food supply. Unbalanced application of chemical fertilizers have caused significant decline in soil health, including soil organic matter and crop productivity over the last few decades [20]. Increasing environmental awareness in the general population has caused many farmers in developed countries to switch over to organic farming which has been gaining popularity as a plant nutritional soil supplement [21]. Organic agricultural products are gaining popularity all over the world as they provide consumers with a basket of safer and better trusted foods. They contain fewer nitrates, nitrites, pesticide residues and trace elements compared to conventional crops. However, due to decrease in raw organic matter such as animal wastes, crop residues and green manure to prepare compost, scientists are looking forward for different organic sources which are abundant in nature and available at a very low cost. Human Urine, fulfils all the above requirements, and has been gaining importance for organic cultivation [22, 23].

A. Human Urine as a Plant Supplement

Each individual produces 1- 1.5 L of urine per day in 4-5 times [24] and an adult excretes on an average 500 L of urine in a year [25]. According to Wolgast (1993), one liter of urine contains 11 g Nitrogen (N), 0.8 g Phosphorous (P) and 2 g Potassium (K), developing an NPK ratio of about 11:1:2. Thus, if 500 L of urine is produced by each person in a year, it amounts to an equivalent of 5.6 kg of Nitrogen, 0.4 kg of Phosphorous, and 1 kg of Potassium. However, the composition of human urine varies from person to person and from region to region depending on his or her feeding habits, the amount of drinking water consumed, physical activities, body size, and environmental factors [26, 27].

Urine normally lacks hazardous chemical compounds or heavy metals [24]. Also, the strong odor of human urine is due to the body's breakdown of asparagusic acid or high amount of NH^{4+} present [28, 29]. The urine of a healthy person is sterile, and although bacteria may be picked up in urinary tracts they do not pose a significant health risk from a healthy person [30].

B. Agricultural Benefits of Urine

There are several reasons why urine works so well as a fertilizer. Urine contains few, if any pathogens but majority of the plant fertilizing nutrients [31]. This high nutrient content-low pathogen combination implies it can be used to increase the yield of crops. The nitrogen found in abundance in urine is good for plant growth because it helps to build protoplasm, protein and other components of plant growth. It certainly promotes leafy growth. Phosphorus is important in the root formation, ripening of fruits and germination of seeds, although the percentage of phosphorus compared to nitrogen in urine is low. Potassium is also essential for promoting good fruit (and flower) development. Plants differ in their requirements, but overall plants fed with some urine grow better than plants which never come into contact with urine. Urine is particularly valuable for grasses like maize and leafy green vegetables, and onions, which respond to the high nitrogen content of urine [32-40]. Studies conducted in Sweden [41] show that an adult's urine contains enough nutrients to fertilize 50-100% of the crops needed to feed one adult.

C. Linking Sanitation and Agricultural Productivity

A new paradigm is forming in the water and wastewater management sector to focus on the resources that can be recovered from wastewater rather than the constituents that must be removed [42]. Current human waste collection systems do much to minimize human contact with the pathogens in excrement, but little to ensure that those nutrients will be returned to natural systems in a way that benefits food production soils. Ecological Sanitation can help towards achieving a "closed loop fertility system" that can re-circulate nutrients from human beings in urban areas back to agricultural fields. A closed loop system can achieve dual goals of reduced health risks to humans by diverting urine from water systems where it acts as a pollutant and at the same time recovering useful nutrients and returning them back quickly to food systems. By closing the loop, energy that would be required for waste treatment can be saved and resources can be utilized to increase crop yields which would also offset the need to buy chemical fertilizers. Thus, urine diversion can provide additional positive impacts for meeting the MDGs.

IV. URINE DIVERSION SYSTEMS

Urine-Diversion Dehydration Toilets (UDD-Toilets; in India commonly referred to as "composting toilets") make use of a combination of composting and desiccation (dehydration) processes for the hygienically safe on-site treatment of human excreta [43]. A UD toilet has two outlets with two collection systems: one for urine and one for feces (and possibly a third one for anal wash water), in order to keep these two (or three) excreta or wastewater fractions separate. UD toilets may, or may not, mix water and feces, or some water and urine, but they never mix urine and feces.

There are two distinct types of UDTs. Double-Vault Toilets are designed to operate in batches. Fecal matter is collected and stored in twin compartment. Daily deposits are stored in one compartment. A small amount of ash, sawdust, sand etc. is sprinkled over the feces after each use, to absorb moisture and help in speeding up the dehydration process. The lead compartment is sealed after it is full for one year while the lag compartment is put to use. One year is provided for desiccation and hygienization. Urine and other wash water is diverted to plastic tank for further application as nitrogen rich fertilizer to agricultural fields. The finished compost is applied to the land in order to increase organic content, improve water holding capacity and availability of nutrients. The other type is Single-Vault UDD Toilet, where there is only one storage tank for collection of feces. Thus, secondary storage is necessary.[44] UDTs are mainly suitable for regions with high average temperatures, long dry and short rainy seasons or arid climatic conditions with high evaporation rates. Nevertheless, with the right designs, they can also work in a more humid climate and it is also possible to utilize a UDT in regions with cold climate conditions. Moreover, a UDT is slightly more difficult to keep clean than other toilets because of both the lack of water and need to separate the solid feces and liquid urine. For cleaning, a damp cloth may be used to wipe down the seat and the inner bowls. Special care should be taken to prevent cleaning water from entering the vaults. Some toilets are easily removable and can be cleaned more thoroughly. No particular design will work for everyone, and, therefore, some users may have difficulty separating both streams perfectly which may result in extra cleaning and maintenance.

A. Feasibility of Urine Diversion

It is often assumed that new sanitation systems would have to be designed and built on order to accomplish urine separation. Even today in developing countries misconception prevails that retrofitting existing systems would be expensive and ineffective [31]. Fortunately, this is not the case as by using a little creativity and behavior modifications urine diversion can be made easy, cost-effective and efficient addition to existing sanitation systems. Places using seat toilets can be modified easily to collect urine. In the worst case scenario, urinals can be set up that collect some portion of the urine in order to prevent at least some of the nutrients being lost away. Once people understand and embrace such a technology they would be more willing to upgrade to modified urine separating seats.

B. The Downside

In spite of the highlighted advantages of urine as a liquid fertilizer, using urine in its inherent form has several disadvantages. Higher rates of application of urine could increase soil salinity and electrical conductivity. Untimely and uneven application could cause considerable crop failure [45]. Urine is a fast acting fertilizer and the downside of using it is that, plants cannot use the nutrients it provides all at once. Thus, unless the soil that surrounds the plant can hold the nutrients, they will seep down the root line, and be lost to the plants. Dilution is usually required and this factor varies for different plants. Pharmaceutical residues may be excreted via urine which might eventually end up in agricultural fields (46, 47). Insufficiently treated urine could also cause a transmission of pathogens. Urine application being a labor intensive process may not be viable option in developed farmlands. It is a relatively heavy medium fluid (low value/weight), difficult to transport and store. Another concern is the volatility of nitrogen in urine. The high pH of urine in the collection vessel (normally 9-9.3), coupled with its high ammonium concentration, means there is a risk of losing nitrogen in the form of ammonia [25]. Cultural and ethical prejudices of using urine, has also been major setback to its popularity [41].

V. NUTRIENT RECOVERY SYSTEMS

Urine in its inherent form does not add much value in terms of agricultural productivity. However the components which make up this waste stream have the potential to do so. One of the most important compounds that can be recovered and recycled is Urea ($CO (NH_2)_2$). More than 90% of urea produced worldwide is used as a nitrogen-release fertilizer. Urea has the highest nitrogen content of all solid nitrogenous fertilizers in common use (standard crop-nutrient rating of 46-0-0). A wide variety of conventional and non-conventional technologies and processes have been developed for the manufacture and quantification of urea, like the diacetyl monoxime colorimetric method, Berthelot reaction, Bosch-Meiser urea process etc.. All of these methods necessitate high throughput instrumentation and hence high capital costs. More importantly, synthetic urea contains impurities like biuret and isocyanic acid which are toxic to the plants that are to be fertilized.

A more viable and sustainable alternative to the manufacture of synthetic urea could be to transform valuable nutrients in the urine into solid materials by employing existing separation operations. The advantages of such a process would be that the volume of material that needs to handled would be substantially reduced compared to liquid urine while also eliminating the loss of nitrogen to the atmosphere. Moreover, a high level of hygiene could be maintained and spreading of the recovered nutrients as fertilizer on arable land could be made much more flexible.

Conventional separation techniques such as reverse osmosis, chemical precipitation, electro-chemical process and ion exchange can be used for such urea recovery systems. However, strict operating conditions, high cost, long periods and bad impact from shock loads make them undesirable to be used in practical industrial applications [48]. Compared to these methods, adsorption has drawn more attention by researchers due to its feasibility, high safety and low cost [49]. Biomaterials (Sugarcane Bagasse, Coconut Shells, Vineyard Pruning, etc.), activated carbon, zeolite, chitosan, polymers, etc. all have the potential to be used as low cost adsorbents for recovery of urea from anthropogenic waste streams.

At present a wide research gap exists in this sector as research has been more focused on engineering better sanitation facilities in keeping with the Millennium Development Goals of the UN. However, a more integrated and holistic approach can help solve several of the problems faced today. Sanitation systems could be re-designed in order to incorporate a process that simultaneously recovers and recycles nutrients being flushed away. Such an approach would help us avoid redundancy and help formulate a more comprehensive research plan. If the long term perspective of increasing the circulation of nutrients from urban to rural areas is to increase more research effort needs to be focused on designing and implementing such systems.

VI. PRINCIPLES FOR LARGE SCALE IMPLEMENTATION

There is growing awareness among decision-makers, policy-makers and professionals within water and sanitation sector that wide demographic, geographic, socio-cultural, and financial conditions make attempts to direct sanitation technology transfer subject to large risks of failures. These risks can be considerably reduced if some principles for sanitation management are followed. One is to raise political will, and secure financial resources for such projects. Another is to involve all stakeholders throughout planning and implementation to the greatest possible extent, ensuring sanitation projects are not simply supply of dry-toilets to the targeted areas. Comprehensive installation of such systems along with a suitable mechanism for resource recovery from waste streams is needed. End users must be trained to use, operate and maintain the installed systems via workshops and practical demonstrations. Any such proposed project can only be regarded successful if the agricultural trials of urine recycling provide useful data on agricultural benefits and potential savings in chemical fertilizers. Simply put, we need to think about what we mean by sanitation, and think again about how we are going to do it right.

ACKNOWLEDGMENT

I would like to thank Prof. Dr. Mahesh Ganesapillai, VIT University for being the best research guide a student can expect to have. I am extremely thankful to him for introducing the concept of Ecological Sanitation and Resource Recovery to me.

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