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일회용 폐기저귀에서 양액 추출 방안

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Method for nutrient solution extraction from used diposed diapers

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Abstract

Used disposable diapers have been considered for a long time as a type of waste difficult to recycle and valorize due to their composite nature including plastic, cellulose pulp, a super absorbent polymer and either urine, feces or both. Therefore, the fate of disposed diapers often is either incineration or landfill burial which both have various adverse environmental impacts. However, used disposable diapers contain nutrients: cellulose is an organic matter while urine and feces contain non negligible amounts of nitrogen, phosphorus and potassium which are primary nutrients included in most chemical fertilizers used in agriculture. In a scope of waste recycling and valorization, this study focuses on developing a method to achieve nutrient solution extraction from used disposable diapers. The experiment essentially consists in shredding the diapers and letting them macerate in solutions of sodium hydroxide with various concentrations to allow breaking down of the cellulose and super absorbent polymer and release of urine and feces before sterilizing the solutions in an autoclave to remove potential coliform bacteria. At the end of the experiment, a set of parameters is measured for the final solution to identify concentrations of nutrients as well as presence or absence of harmful substances. Results are discussed and directions for future studies are suggested, which include mechanization of the diapers shredding process or added aeration to enhance nitrification and absorption of extracted nutrients from plants.

Key words : Disposable diapers, Night soil, Nutrient extraction, Fertilizer, Agriculture

I. Introduction

Disposable diapers are part of the Absorbent Hygiene Products (AHP) and are mainly used by toddlers, the elderly or people suffering from incontinence to retain urine and feces. The main components of a standard diaper are cellulose (pulp), a carbohydrate which is the primary constituent of the biomass, a Super Absorbent Polymer (a polyacrylate polymer hereafter referred to as SAP) and plastics used to hold the diaper together. One of the characteristics of the SAP is its faculty to absorb and retain liquid to a ratio corresponding to approximately several hundred of times its own weight and volume. Diaper composition varies from one manufacturer to another but usually cellulose makes up for approximately 15% of the diaper weight, SAP for approximately 30% and plastic for approximately 45% [9]. In South Korea, an amount of approx-

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imately 240,000 tons of diapers are discharged every year, of which 140,000 tons come from infant day-care centers [1], therefore our study focuses primarily on baby diapers. After usage, diapers are disposed together with non-recycled waste and the weight proportion of disposable diapers in total non-recycled waste is projected to increase from 2.1% in 2002 to 3.6% in 2020 [1]. Disposed diapers are therefore buried in landfill (with adverse impacts including land usage, methane rejections, smell, seepage of harmful substances to soil or groundwater) or incinerated (causing CO_2 and other greenhouse gases emissions). It is estimated that an equivalent of approximately 210,000 tons of greenhouse gases are emitted every year as a consequence of both landfill burial and incineration of disposable diapers (which represents approximately 880g of greenhouse gas emission for 1kg of disposed diapers) [8]. Developing alternative solutions to be able to valorize waste diapers appears crucial to reduce environmental pollution.

Used disposable diapers possess valuable constituents which could be harvested: the pulp is made of cellulose, a carbohydrate and the principal component of the biomass and could be used as organic matter. Moreover, used diapers contain urine and feces. A literature review in Rose et al. estimated that, as shown in Table 1, more than 16g of nitrogen, 2g of phosphorus and 0.8g of potassium are present in a daily urine output while more than 0.8g of phosphorus and 0.9g of potassium are present in a daily feces output [2]. Babies and toddlers until the age of 3, use an average of 7.5 diapers a day [1] and with an urine output which can be estimated on average to be approximately 500mL/day [11], it is expected that each disposed diaper can contain on average 67mL of urine. Trials for recycling of used diapers have been carried out in South Korea ([9], [10]) and around the world with the main aim of recycling plastic and cellulose pulp as raw materials to be reused in other sectors (recycled paper, recycled resins and fillers for the construction industry etc). Knowaste, a private company from Canada, developed a method for recycling used diapers with the following steps: 1) used diapers are put on a conveying belt and sterilized in a autoclave, 2) sterilized diapers are mixed with water and shredded in a mechanical cutter, 3) plastic is collected by centrifugation and gravity, washed and dried up, 4) cellulose pulp is separated from SAP by the addition of water soluble alkaline-earth metals, washed and dried up, 5) the liquid portion of remaining SAP (containing residual night soil) is sent to wastewater treatment plants and the solid portion composted [10]. This method also focuses on recycling of plastic and cellulose as raw material and considers night soil as waste. Moreover, the input of alkaline-earth metals for separation of SAP and cellulose makes it difficult to use the residual solid as compost due to restrictions on the presence of hazardous substances such as heavy metals.

Recycling trials focusing on the use of nutrients for agriculture have essentially considered the option of composting. Espinosa-Valdemar et al. composted

Table 1. Average nutrients content of urine and feces (wet weight, g/capita/day)

Nutrient	Urine	Feces
Total Nitrogen (TN)	16.34	N/A
Total Phosphorus (TP)	2.28	0.82
Total Potassium (TK)	0.85	0.92

Table 2. Urinary output of a toddler

Age	Urine Output (mL/24hrs)
Newborn	15 ~ 60
2 weeks	100 ~ 300
1 ~ 2 months	250 ~ 450
Less than 12 months	400 ~ 600

used diapers together with organic yard waste (leaves, grass, mulch etc.) and used the compost as a fertilizer for the culture of tomato, obtaining satisfying results for the quality of the compost and the phyto-toxicity of plants grown using it [3]. Similarly, Zulfikar et al. mixed used diapers with organic waste (bran, rice husk etc.) and obtained a compost which complied with all local standards [4]. However, composting is a method which has several drawbacks such as long residence time, bad smell or release of methane gas to the atmosphere [5]. Finally, Pinho et al. analyzed the compared effects of autoclave sterilization and alkaline hydrolysis (using solutions of sodium hydroxide with various concentrations) on various healthcare waste products including diapers and showed that alkaline hydrolysis has the potential to break down the cellulose pulp and leads to mass reduction and carbon loss after treatment [6]. It appears from our literature review that research work aiming to directly extract nutrients from waste diapers into a liquid phase and produce a nutrient solution is still lacking.

2. Materials and methods

A small amount of used disposable diapers was collected for this trial and preliminary measures were carried out to understand basic parameters, making a discrimination between used diapers containing urine and used diapers containing urine and feces. Unused diaper mass based on 3 unused diapers was determined to be 39.41g. The average mass of a diaper containing urine (based on 20 diapers) was determined to be 113.5g and the average mass of a diaper containing urine and feces (based on 20 diapers) was determined to be 205g. In order to understand the water content of each diaper, diapers were dried in a Vision VS-1202D3N drying oven for 12 hours to a temperature of 90℃. The average dry mass of a diaper containing urine was determined to be 43.3g and the average dry mass of a diaper containing urine and feces was determined to be 80g. In average, the moisture mass percentage of a diaper containing urine is estimated to be 64.88% and the residual solid mass percentage 3.16%. For a diaper containing urine and feces, the moisture mass percentage is estimated to be 64.44% and the residual solid mass percentage 18.04%. Diapers containing urine and both urine and feces show very similar mass percentages of moisture but waste diapers containing feces show more important residual solid mass after drying which is due to the presence of solid feces.

This study aims at collecting nutrients from both cellulose and the urine and feces contained in used disposable diapers. Urine and liquid feces are absorbed by the SAP which consistence turns into a gel after absorption therefore to release the urine and liquid feces contained in the SAP, we decided in the first experiment to shred the diapers and make them macerate in solutions of sodium hydroxide. To maximize the contact surface, several whole diapers were manually shredded to pieces of approximately 1㎠ surface and homogeneously mixed as shown in Fig. 1. The sodium hydroxide solution has the capacity to break down the SAP structure and help the release of urine and feces therefore shredded diapers were macerated into the sodium hydroxide solution for a duration of 24 hours and stored in a 20℃ temperature controlled room. To understand which sodium hydroxide concentration allows to obtain optimal breakdown of the SAP and cellulose pulp, three solutions with a respective concentration of 0.1mol/L, 1mol/L and 2mol/L were prepared by dissolving 98% pure sodium hydroxide (NaOH) beads into distilled water. The measured pH of each solution were respectively 12.86, 13.62 and 13.79. 10g of the shredded diapers containing urine and 10g of the shredded diapers containing feces were separately mixed with 50mL of each one of the sodium hydroxide solutions (liquid/solid ratio of 5:1)

Table 3. Mass statistics of dry and wet diapers before and after usage

Diaper type	Average wet mass (g)	Average dry mass (g)	Average moisture mass percentage (%)	Average residual solid mass percentage (%)
Diaper containing urine	123.3	43.3	64.88	3.16
Diaper containing urine and feces	225	80	64.44	18.04

Table 4. Prepared mixtures for the experiment

Code	Diaper type	Diaper mass (g)	Sodium hydroxide solution concentration (mol/L)	Solution pH
U0.1	Urine	10	0.1	12.86
U1	Urine		1	13.62
U2	Urine		2	13.79
F0.1	Urine and Feces		0.1	12.86
F1	Urine and Feces		1	13.62
F2	Urine and Feces		2	13.79

Fig. 1. Shredded diapers containing urine (left) and both urine and feces (right)

for a total of six mixtures as shown in Table 4.

After 24 hours maceration, in order to bring the pH back to a point close to equilibrium and stabilize the mixture before the sterilization in the autoclave, a solution of acid was added to each mixture. A strong acid was selected to neutralize the OH^- ions in the prepared solution and it was decided to use nitric acid. Nitric acid reacts with sodium hydroxide according to the reaction shown in Fig 1 and holds the advantage of enriching the final solution in nitrogen, one of the main nutrients present in chemical fertilizers. Using another strong acid such as hydrochloric acid HCl ultimately leads to the precipitation of NaCl (common salt) which presence is considered a hindrance to plant growth and has adverse effects on soil [13].

After stabilizing the pH, the mixture was sterilized in a Sejong SJ-2000 series autoclave for 30 minutes to a temperature of 120℃. This step of the process has two objectives, enhancing the break-

$$Na^+ + NO_3^- \rightarrow NaNO_3$$

$$OH^- + H^+ \rightarrow H_2O$$

Fig. 2. Reaction of sodium hydroxide with nitric acid

down of the cellulose pulp and SAP and sterilizing the final product. After the end of the sterilization in the autoclave, the mixtures were cooled down and filtered to separate the solid residuals from the liquid extract which was analyzed to estimate the concentration in nutrients and the absence of harmful substances using the Hach DR6000 spectrophotometer and the Hach DRB200 digital reactor block for sample digestion.

3. Results and discussion

After macerating the diapers in various solutions of sodium hydroxide for 24 hours, several observations can be made. In the solutions were diapers containing urine only were input, we observe a change of colour from yellow (due to the presence of urine) to almost transparent. This is likely due to the interaction with air during the maceration process which causes transformation of the ammonia (NH_3) in nitrate ions (NO_3^-) which absorption by plants is easier. In solutions were diapers containing urine and feces were input we can see a change in colour with the increase of sodium hydroxide concentration from yellow to dark brown. Moreover, all solutions look more turbid with the presence of white fiber-like elements due to the break down of the cellulose pulp under the effect of sodium hydroxide. Finally, in the solutions containing sodium hydroxide in a concentration of 0.1mol/L, the liquid phase is almost not present with the SAP having absorbed all the injected liquid and retain its gel consistency. However, in the solutions containing sodium hydroxide in a concentration of 1mol/L and 2mol/L, liquid is present in more important quantities and the gel consistency of the SAP cannot be observed (Fig. 3). This indicates that the sodium hydroxide concentration of 0.1mol/L is not sufficient to allow breakdown of the SAP structure whereas concentrations of 1mol/L and above allow efficient breakdown of the SAP structure and release of the urine and feces contained in it. At this stage, all solutions are characterized by a strong smell of urine and feces respectively.

After the mixtures were put into an autoclave for 30 minutes with a temperature of 120℃ and cooled down to room temperature, it can be observed that for all six mixtures, the consistence of the obtained solution is more liquid which demonstrates that the autoclave further enhances the decomposition process. After filtering, for solutions containing urine and feces, as shown in Fig. 4, all three solutions have a dark brown colour but the solution with a sodium hydroxide concentration of 0.1mol/L has a viscous texture with viscous lumps which are absent from the two other solutions in which the concentration of NaOH is respectively 1mol/L and 2mol/L. Therefore, even though the autoclave has a role in enhancing the extraction process, as mentioned previously, a concentration of sodium hydroxide of 0.1mol/L does not ensure sufficient breakdown of the SAP and cellulose which is more efficiently achieved with sodium hydroxide concentrations of 1mol/L and above. At this final stage, we can also observe that the strong smell of urine and feces respectively remains present for all extracted solutions.

As mentioned previously in this article, research work with the objective of directly extracting a nutrient solution from waste diapers is lacking, therefore when examining the extracted solutions, we essentially focused on three parameters: presence or absence of *E. Coli* bacteria which can be responsible for diarrhea and other health issues [13], measure of Total Nitrogen (TN) and Total Phosphorus (TP), which are the two main nutrients used in the plant growth process. Results are shown in Fig. 5 and Table 5. Nitrogen is present in all six samples as values of Total Nitrogen measured rank from 3mg/L to 177mg/L and Phosphorus is also present in all six samples as values of Total Phosphorus rank from 0.56mg/L to 19.65mg/L. For all six samples, as the concentration of sodium hydroxide increases, the

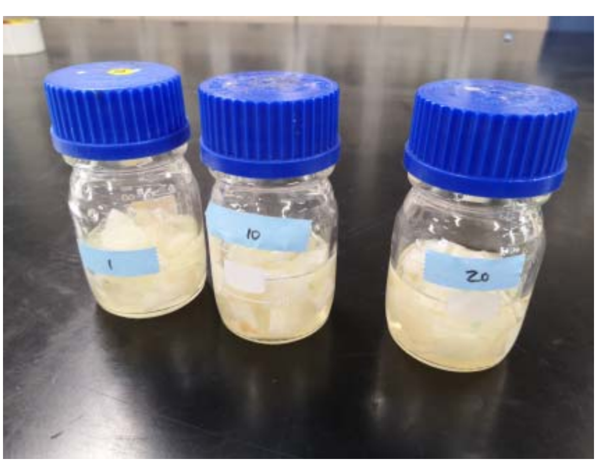

Fig. 3. From left to right, 0.1mol/L, 1mol/L and 2mol/L sodium hydroxide solutions with urine diapers after 24 hours maceration

Fig. 4. From left to right, 0.1mol/L, 1mol/L and 2 mol/L feces and urine diapers solution after autoclave and filtration

Table 5. Prepared mixtures for the experiment

Sample Code	*E. Coli* bacteria	TN concentration (mg/L)	TP concentration (mg/L)
U0.1	Absence	3	0.56
U1		69	10.1
U2		118	19.65
F0.1		26.8	2.2
F1		177	3.25
F2		105.5	6.8

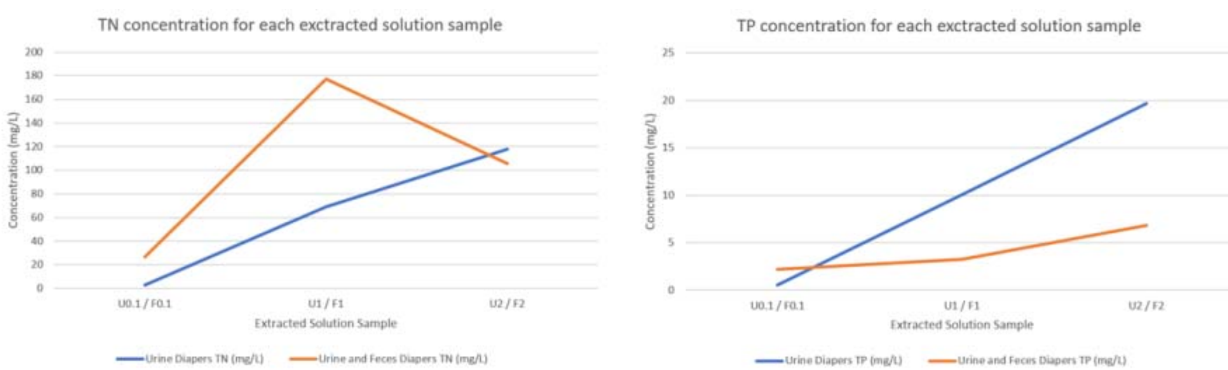

Fig. 5. TN and TP concentrations for each extracted solution sample

value of TN and TP concentrations also increases which tends to back up visual observations and demonstrate that the sodium hydroxide concentration of 0.1mol/L is not sufficient to allow satisfying breakdown of the SAP and cellulose but concentrations of 1mol/L and above are. For the solutions prepared from urine containing diapers only, the growth ratios for the TN and TP concentration are very similar: a growth ratio of 23 and 18 for TN and TP respectively between the 0.1mol/L and the 1mol/L solutions and a growth ratio of 39.3 and 35.1 for TN and TP respectively between the 0.1mol/L and the 2mol/L solutions. The only exception is observed for the 1mol/L solution prepared from diapers containing both urine and feces which shows the highest TN concentration (177mg/L), value which might come from measurement error and will need further investigation in future experiments. Other growth ratios for solutions made from diapers containing urine and feces are consistent: a growth ratio of 3.9 and 3.1 for TN and TP respectively between the 0.1mol/L and the 2mol/L solutions. Moreover, as shown in Fig. 6, test for presence of *E. Coli* were negative for all six extracted solutions

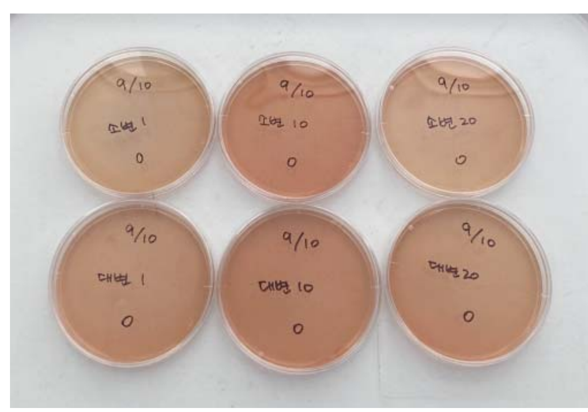

Fig. 6. Negative test results showing the absence of *E. Coli* in all six extracted solutions

which demonstrates that the autoclave process allows efficient sterilization of extracted solutions.

Further work which will need to be carried out shall consider several aspects. Firstly, a mechanization of the diapers shredding process shall be designed using mechanical cutting machines or a pulper to ensure standardized cutting size and homogeneous distribution of all components (cellulose

$$NH_4^+ + 1.5O_2 \rightarrow 2H^+ + 2H_2O + NO_2^-$$
$$NO_2^- + 0.5O_2 \rightarrow NO_3^-$$

$$6NO_3^- + 5CH_3OH \rightarrow 3N_2 + 5CO_2 + 7H_2O + 6OH^-$$

Fig. 7. Nitrification and denitrification reactions

pulp, SAP, plastic). Secondly, this work aims at extracting a nutrient solution which could be used in the agricultural sector to grow plants instead of chemical fertilizers. Therefore, nitrogen should be present in a form which is easily assimilable by plants. Under the effect of oxygen, the nitrification reaction transforms the ammonium NH_4^+ into nitrate NO_3^- which is more easily assimilated by plants [7] and the further reaction of denitrification transforms nitrate NO_3^- in nitrogen gas NH_2. In order to ensure nitrification, aeration should be applied to the extracted solution and optimal aeration conditions (aeration rate and duration) which allow nitrification but avoid denitrification shall be identified. This process is also expected to have positive effect on removal of the final solution smell. Thirdly, the extraction process should consider bringing back the pH to a value close to 7 as a final step and check for concentrations of nitrogen before and after the pH correction. This will allow to understand the influence of adding nitric acid into the solution from the viewpoint of TN concentration of the final solution.

Finally, obtained solutions should be compared against the korean regulations on commercial fertilizers. The Korean Fertilizer Law (Fertilizer Official Standards Settings and Regulations [12]) allows to identify two categories in which the nutrient solution produced from waste diapers could be encompassed. The first one is the Night Soil Byproduct Fertilizer (Category 1: Decomposed Manure, Type 5) which primarily refers to the process of composting nigh soil alone or together with other organic products and obtaining a solid compost. The second one is the Nutrient Solution for Irrigation Use (Category 4: Composite Fertilizer, Type 5) which is a liquid fertilizer containing a combination of water soluble nitrogen, phosphorus and potassium but does not refer to a regulation regarding the presence or absence of coliform bacteria as the origin of the fertilizer is not supposed to be from human feces or urine. Further investigation should be carried out linking with relevant authorities to understand potential for use and commercialization of a nutrient solution extracted from waste diapers containing urine and feces.

4. Conclusion

We developed a method for extracting a nutrient solution from waste diapers containing urine and feces by applying the successive steps of shredding, maceration in a sodium hydroxide solution, passage into an autoclave and filtering. We can make the following conclusions and recommendations:

1. All six extracted solutions (three from urine containing diapers and three from diapers containing both urine and feces) showed absence of *E. Coli* and presence of both nitrogen and phosphorus. This demonstrates that NaOH allows for the breakdown of the cellulose and SAP contained in diapers and the release of nutrients from urine and feces to the extracted solution. This also demonstrates that the passage into an autoclave ensures sterilization of the final product.
2. Solutions with a sodium hydroxide concentration of 0.1mol/L were not able to allow efficient breakdown of the SAP structure in both solutions made from diapers containing urine only and urine and feces. This results in final solutions in which part of the SAP retains is gel like aspect and releases less liquid. From the viewpoint of nutrient concentration of the extracted solutions, final concentrations of TN and TP are the lowest for a sodium hydroxide concentration of 0.1mol/L and increase to be maximal for the sodium hydroxide concentration of 2mol/L. Efficient breakdown of the SAP and release of nutrients to the final extracted solution occurs for sodium hydroxide concentrations of 1mol/L and above.

3. Results from this research allowed to identify directions for further work including mechanization of the diapers shredding process, use of aeration with optimal aeration rate and duration to allow nitrification and make nitrogen available in a form which can be easily absorbed by plants, bringing back the pH to a neutral value as a final step of the nutrient extraction process and conformity of final extracted solution with the korean legislation on fertilizers.

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