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REVIEW PAPER

Promising approach for composting disposable diapers enhanced by *Cyanobacteria*

D.I. Kusumawati*, S. Mangkoedihardjo

Department of Environmental Engineering, Faculty of Civil, Planning and Geo-Engineering, Institut Teknologi Sepuluh Nopember, Surabaya, Indonesia

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ABSTRACT

Disposable diapers have become a complicated matter due to the risk generation to the environment and human health. This study presents a description of disposable diapers characteristics and the success-proven methods used to handle this waste. In many developing countries where an inadequate waste management system occurs, the handling method selection must consider effectivity, the affordable cost, and the end product quality. Despite the diaper composting has successfully conducted in several previous studies, some issues remain for researchers to address. Thus, it requires an improvement so that the system runs effectively and sustainably. This study aimed to determine the possibility of using Cyanobacteria for enhancing the diapers composting. This study gains insights from previous studies using a literature review method, with the year of publication between 2007 to 2020. The focus of the investigation relates to disposable diapers composting and its optimation by cyanobacteria addition. And so as the future prospecting for application and implication to the environment and human life. Cyanobacteria ability to carry out nitrogen fixation, carbon sequestration, ubiquitous in natural habitat, highly adaptive in a wide range environmental condition, can live in the composting system, perform bioremediation, and its application as quality fertilizer, and potentially degrade plastic polymers, spread the expectation to cyanobacteria which associated with its advantages over other microorganisms to enhance the disposable diapers composting.This study highlights the potential utilization of cyanobacteria as an opportunity for copping disposable diapers pollution. The application of compost resulted expected to provide promising-advantages to the environmental sustainability and agriculture. This paper proposes an overarching review of the feasibility in this regard.

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*Corresponding Author:
Email: *diana.indah.k@gmail.com*
Phone: +6231 5948886
Fax: +6231 5928387

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INTRODUCTION

Handling solid waste is an urgent problem in almost all developing countries where infrastructure and management systems cannot deal with the waste produced. Open dumping, open burning, disposal to water bodies and drainage channel, are commonly done by the community. It leads to negative impacts on the environment, human health and infrastructure. One of municipal solid waste that brings problem is disposable diapers which can be in baby diapers, sanitary napkins, personal care wipes, and adult incontinence products. Ever since the introduction of disposable diapers in 1961, it has become an integral part of the economy that gradually expands the baby diaper industry. Further-developments occurred in the mid-1980s. Since then, the growth of the baby diaper market continue increasing (Edana, 2008). The global market for diapers exhibits a rising trend. Europe dominates the market for disposable diapers worldwide followed by the Asia Pacific, North America, and Brazil. The high birth rate in developing countries, such as Latin America, the Middle East, and the Asia Pacific predicted to positively affect the regional diaper sales due to factors such as the rising cost of national health care, the increased of affordability and awareness of the infant health issues, the rapid economic development and urbanization, also influence the diaper industry (Khoo *et al.*, 2019). In the European Union alone, disposable baby diapers occupying 36% of the market of absorbent hygiene products (Mendoza *et al.*, 2019). Disposable baby diapers are used for about 3600 to 4250 units per child, mainly in the first 18 months up to 30 months (Edana, 2008). Another study estimated that the total number of disposable diapers used during the first three years is 4600-4800 (Dey *et al.,* 2016), and can even 6,300 diapers before potty training (Khoo *et al.*, 2019). It shows a very-large market need and the diaper industry will continue to grow in the future. Although disposable diapers represent a significant problem for the environment in terms of resource consumption, the increase in waste generation, environmental pollution, huger energy use, and hazard risk for human health compared to cloth diapers, the disposable diapers is unavoidable. Many people still use disposable diapers for convenience, better hygiene, and skin protection reason. Several studies conducted related to the final handling of diaper waste, including landfill, incineration, and processing in recycling centres. All of the options require land-use changes, energy, human resources, technology, and costs that difficult to meet for many countries. It becomes a great challenge to provide appropriate, low-cost, fast, and easily applicable waste management to deal with disposable diapers pollution. With compostable cellulose content, recoverable nutrient in human waste, evidence that superabsorbent polymers increase water retention in the soil, and the plastic polymers in diapers residue are potent to decompose by microorganisms, make composting a promising method for diaper waste recovery. Some research have proven the success of composting disposable diapers where the results are satisfactory, yet, some issues remain to address. A time-consuming process (Simamora and Pandebesie, 2019), plastic polymers and cellulose that do not fully degrade (Espinosa-Valdemar *et al.*, 2014), pathogens that still exist in compost (Zulfikar *et al.*, 2019), and lack of data of compost application on plants are challenges for diapers composting and compost produced utilization. According to Rudnik (2019a), some polymers can be degraded and even composted by a suitable condition and microorganisms. The compost produced can be used in many applications. Since composting is so meaningful to reduce the waste generation, to cut off the harmful exposure to human health and the environment. Also, to produce a valuable product as waste bioconversion result, this method is worthy of continuous improvement. This study objective is to present a description of the disposable diapers characteristics of the material and waste, the hazard risk to the environment and human, the recent technologies used for their disposal or recovery, and the cyanobacteria potential as optimal biological alternative for treatment. The main focus of the review is composting treatment using cyanobacteria. Due to their ability to carry out nitrogen fixation and carbon sequestration, to survive in a wide-range habitat including stressed environmental conditions, to perform bioremediation, and reported to be used as high-quality fertilizer. This review is part of a master thesis, carried out at the Sepuluh Nopember Insititute of Technology (ITS), in Surabaya, Indonesia during 2020 – 2021.

Disposable diaper waste

The life cycle of disposable diapers divided into four such as: 1) acquisition of raw materials, 2) manufacturing processes, 3) distribution and consumption of products, and 4) disposal of the products (Edana, 2008). It requires a significant amount of natural resources and energy, also cause some environmental impacts and risk to human healths. Several studies carried out to measure the composition of disposable diaper waste. A study showed that the weight average of diaper waste is 212 grams (Colón *et al*., 2013), while another study concluded the faeces content is around 192 grams per diaper (Budyk and Fullana, 2019). Disposable diaper waste composition consist of 88% human excreta (urine and faeces), and 12% diapers material itself, that is Cellulose, Super Absorbent Polymer (SAP), Polypropylene (PP), Low-Density Polyethylene (LDPE), and others. Fig. 1. illustrates the percentage of disposable diaper waste composition in general.

Hazard risk of disposable diaper waste

Human waste is considered quite dangerous for health because it contains pathogenic microorganisms that can increase the disease transmission. If it directly discharged into open environments and water bodies, the high nutrient content in human waste can cause detrimental effects such as eutrophication, then global warming and climate change, as well as water pollution and lack of clean water (Senecal *et al.,* 2018). The ammonia oxidation process that requires large amounts of oxygen can decrease the dissolved oxygen concentrations in the waters, and it is harmful to aquatic organisms (Rochmah and Mangkoedihardjo, 2020). Dispose off diapers in the rivers led to waterborne diseases, one of the leading causes of mortality in developing countries, where diarrhoea globally accounts for

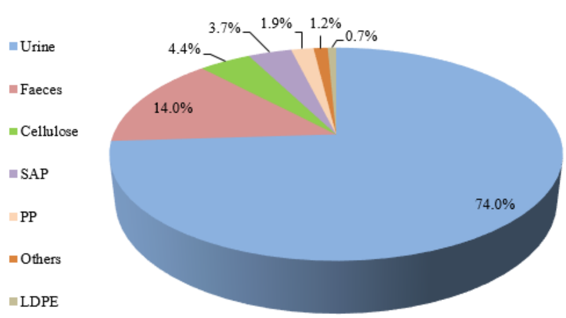

Fig. 1: Disposable diaper waste composition (Modified from Budyk and Fullana, 2019)

more than 1.5 million deaths each year (Garg *et al.,* 2018). SAP is the second-largest component in disposable diapers material made of inert polymer material, namely polymerized acrylic acid, in granular form derived from petroleum which can absorb and hold liquids. SAP allows the surface in contact with the skin to remain dry. A study concluded that there is no systemic human safety problem for acrylic acid residues present in SAP (Dey *et al.,* 2016). However, for the environment, the sodium polyacrylate content by the extensive use of disposable diapers has caused a growing environmental impact (Wang *et al.*, 2019). Disposable diapers also contain plastic polymers such as LDPE formed by the monomer ethylene, and PP by the propylene monomer. Both types of ethylene and propylene monomers can trigger flammable gases, and to human health, ethylene can cause drowsiness or dizziness (Lithner *et al.,* 2011). Plastic debris, even microplastic in particular, could give complex impact, such as worsens aesthetic values of environment, deteriorates water resource quality, threats aquatic biota biodiversity, and human health (Lestari and Trihadiningrum, 2019). The gases emitted by the combustion of plastic wastes cause extreme risk for respiratory disorders and air pollution. The deposition of plastic debris in the soil leads to soil decay, soil corrosion and landslides, threats domestic animals by consuming plastic, decreased water permeability, while in the sea, microplastic consumed by marine organisms pose a threat to human beings. Therefore, these pollutant impact has to address carefully to identify the associated hazards (Vaikarar *et al.,* 2019). Considering the occurrence of microplastics in diaper waste, the exposure and how it occurs is still not widely known. It can be such consideration to do further investigation.

Conventional disposal methods for disposable diaper waste

Due to its high volume, disposable diaper waste has become concern across the globe in recent years. In Malaysia, disposable diaper waste is 12.1% of total municipal waste (Khoo *et al.,* 2019), in Mexico is about 6.5% (Espinosa-Valdemar *et al.*, 2014). In Surabaya, one of the largest city in Indonesia, around 10.79% of the plastic waste pollutes the river, some of it is disposable diapers (Lestari and Trihadiningrum, 2019) where the diapers itself account for 6,97% of total municipal waste (Dhokhikah *et al.*, 2015). With the large volume of diaper waste, a proper handling method required at the disposal stage. The final disposal method commonly used for disposable diaper summarized in Table 1 is in landfills, incineration, and recycling facilities.

There are problems in handling diapers disposal due to the gap between developed and developing countries, viz. science and technology, the low awareness of the harmful effects of disposable diapers in developing countries, and the cost available to finance the waste management. That explains why the current diaper recycling facilities are only available in developed countries. Recycling facilities require the highest-cost compare to landfills and incinerators. It is for financing the technology, facilities investment, recycling operational, and worker health and safety.

Table 1: Summary of Conventional Disposal Methods for Disposable Diaper

Methods	Landfilling	Incineration	Recycling facilities	References
• Advantages	• The trash is immediately out of sight after being covered with a landfill cover (1) • The landfill can operate for a long-term (≥ 50 years, ≤ 100 years) (1)	• Completely burnt out wastes in a short time (1) • Potentially destroy any material containing organic carbon including pathogens (2) • Heat of combustion can be recovered and used to generate steam or hot water (2)	• Diaper waste can be separated and recycled for other purposes (1) • Reduce carbon emissions up to 71% (1)	(1) Khoo *et al*., 2019 (2) Shaaban, 2007 (3) Zhou *et al*., 2020 (4) Kim and Cho, 2017 (5) Kumar *et al.,* 2017 (6) Kerdsuwan *et al*., 2015 (7) Hoffmann *et al*., 2020 (8) Lavigne *et al*., 2014
• Limitations	• High cost in waste collection and transportation (3) • Disposable diapers would require up to 500 years to be fully degraded in landfill (1) • Pathogen contain in diaper waste can cause infectious diseases to the people nearby or landfill workers (1) • When the landfill capacity is full, it has to be shut-down, and post-decommission monitoring is needed (1) • Caused environmental problems such as land degradation, soil erosion, water and air pollution, unpleasant odours, and the greenhouse effect (4) • Require of large land space (5)	• High cost in waste transportation and collection (3) • Part of the ash produced is hazardous (1) • Constant maintenance of incinerator is needed to maintain incineration efficiency (1) • May release flue gas emissions, air pollution, and some hazardous greenhouse gases like furans and dioxins, which play a significant role in ozone layer depletion, and cause harmful problems in the human health and soil pollution (5) • The high moisture content and low heating value of the unseparated wet organic waste, causing high operating costs since the incinerator needs to run with additional fossil fuel (6)	• Additional cost for diaper collection is needed (1) • The complicated recycling processes aggravated by human excreta that attached to disposable diapers (4)	
• Example	• Brazilia (7), Malaysia (1), Indonesia (8)	• China, Japan, Sweden (1)	• Belgium, Singapore, United Kingdom (1)	
• Operating cost for one ton of waste (USD)	• $12.72 (1)	• $10.94-12.50 (1)	• $60 (1)	

Moreover, creating valuable recycled products is also a challenge because of the high level of uncertainty about the marketability and acceptance of these recycled products (Khoo *et al*., 2019; Kosemund *et al*., 2009; Mendoza *et al*., 2019). For the developing countries or low-income countries, with insufficient budget, non-sanitary and uncontrolled landfill used as the waste disposal method. At the local level, especially for areas that generate less than 5 tons per day, open dumping or open burning is the most common waste management done by the community (Kerdsuwan *et al.*, 2015). Inadequate waste collection systems of urban residents also causing waste is not transported to landfills but disposed of in the sea, rivers, and drainage (Handayani *et al.*, 2019) which end up with river sedimentation, blockages of drainage channels and watergates, result in flooding. In some extreme cases, can even lead to breaking the dam (Bott and Braun, 2019). Some researches reveal disposal methods of several countries. In Brazil, only around 40% of municipalities in the country is sent to sanitary landfill, since approximately 60% still lack proper waste management (Hoffmann *et al*., 2020). While in Vietnam, per 2014, the current practice of solid waste management in Ho Chi Minh City is landfilling about 86% of the total solid waste, and the rest 14% waste is recycled (Verma *et al.,* 2016). Out of the whole volume of waste produced in Bandung, Indonesia, in 2005, only 46% collected to landfill. Most of the uncollected waste dumped in the rivers (mainly the Citarum River), burned by the community or buried in the backyard (Lavigne *et al*., 2014). It expected that the number of untreated waste continue to decline along with the increase in waste handling. The Indonesian government targets to achieve 70% waste handling by 2025. It stated in the Indonesian National Policy and Strategy for Waste Management (Presiden Republik Indonesia, 2017). With some of the descriptions presented above, regarding the method of waste disposing, especially for diapers, it is clear that waste recycling is the best choice for environmental sustainability. However, not all countries can have these recycling facilities for the reasons previously mentioned. A waste management system can be sustainable if it meets the following essential factors (Edana, 2008).

Human health and safety; environmentally beneficial; economically affordable; and accepted by the community. If a treatment method proves to be effective in treating waste, but is financially burdensome or cannot apply by the community, then that method will stop running. Considerations for choosing a treatment method may differ based on the potential of each country. Therefore, it is necessary to carry out further studies to find sustainable processing methods, especially for countries that do not have sufficient waste management budgets. For better outlook in sustainable waste management system in the future, increasing the authority for handling waste to the Local Government will give positive-impact, since each region has its strengths, both in different resources and potential budgets. Likewise, community participation is an absolute way. Experience has shown, that in developing countries, the Central Government finds it difficult to implement a well-established waste management system without understanding and community involvement. Public participation is not a new thing in waste management. Lots of research on this subject has done, one of them is in Indonesia and India. Sorting, recycling and composting are main waste management activities done by local community using the 3R principles (Reuse, Reduce, and Recycle) (Dhokhikah *et al.*, 2015, Kerdsuwan *et al.*, 2015, Basu and Punjabi, 2020). Rather than seeing each other as an opposite, it would better the local government and the community co-operate in a harmonious relationship towards a better quality of life.

Recent technologies used for recycling disposable diaper waste

Disposable diaper waste can be treated biologically or by thermal methods. These are some processing technologies that summarized from prior research:

1. Biodegradation of by microorganisms (Moharir and Kumar, 2018),
2. Biodegradation by the cultivation of the fungus Pleurotus ostreatus (Espinosa-Valdemar *et al.,* 2011),
3. Biodegradation into compost (Mendoza *et al.,* 2019),
4. Anaerobic digestion (Torrijos *et al.*, 2014),
5. Microwave pyrolysis (Lam *et al.,* 2019),
6. Hydrothermal carbonization or wet pyrolysis (Budyk and Fullana, 2019), and
7. Steam sterilization (Maamari *et al*., 2016).

Degradation of plastic by microbes is one of the eco-friendly and innovative methods shortly. Biodegradation with the suitable microbial species is an effective-option for eco-friendly plastic waste degradation even though no protocol has developed yet to biodegrade polyethylene on a commercial scale (Kumar *et al.,* 2017, Moharir and Kumar, 2018). Among those treatment options, composting has gained attention for its benefits, such as waste hygiene, cost-effectiveness, and waste conversion into value-added products (Onwosi *et al.*, 2017). So according to the author, the improvement of this method by combining composting and microorganism addition, is worthy of continuous efforts.

Composting methods

According to Palaniveloo et al., (2020), there are some composting methods such as vermicomposting, windrow composting, aerated static pile composting, and in-vessel composting illustrated in Table 2.

From the two options for large scale composting: windrow and aerated static pile, windrow appears to be most appropriate for low-cost waste algae stabilization, while the in-vessel composting is suitable for studying algal composting at lab or pilot scale (Han *et al.,* 2014). As for diaper composting, the in-vessel and aerated static pile methods have been used in previous studies as it mentioned in Table 3.

Disposable diapers composting

Composting is a promising method to treat diaper waste for the following reasons. Composting recover nutrients from human waste (Tucho and Okoth, 2020). Cellulose is the biodegradable polymer made from renewable resources (Rudnik, 2019a), which an aerobic composting consider to be an eco-sustainable green approach for lignocellulosic biomass treatment and agricultural development (Harindintwali *et al.,* 2020; Wu *et al.,* 2020). According to previous research, SAP has the technical feasibility to improve water retention in soils and irrigation capabilities (Al-jabari *et al.*, 2019). In terms of plastic polymers LDPE and PP, require further research to obtain the optimum method for the possibility of its degradation through composting by inoculating suitable microorganism. As mentioned in Tables 1 and 2, regarding the high additional costs of transporting waste to landfills, incinerators, recycling centres, or city-scale composting, also because diaper waste contain various harmful pathogens, and the diaper can completely degraded after 500 years in the

Table 2: Characteristics of Composting Techniques

Characteristics	VermiComposting	Windrow Composting
Preferred waste input	Wastes mixed with manure	Wastes with less emission of odour such as plant-based
Land requirement	Low	High
Site selection	Anywhere equipment can be placed	Away from populated area
Cost of waste transportation	High	High
Composting period	Short	Long
Amendment	Addition of bulking agent, animal manure and microbial additives, consistent temperature	Addition of bulking agent, chemical additives and microbial additives, increase of aeration
Amendment effects on compost	Increase in production biomass by more than 20%	Reduce the total composting period by 30%
Compost quality	Good	Medium
Characteristics	**Aeratic Static Pile**	**In-Vessel**
Preferred waste input	Waste with more homogeneity, consistency and required bulking agent	Easily degraded wastes such as food waste
Land requirement	Medium	Low
Site selection	Away from populated area	Anywhere equipment can be placed
Cost of waste transportation	High	High
Composting period	Long	Short
Amendment	Addition chemical additives and microbial additives, increase of aeration	Increase the in-vessel temperature, pressure and turning rate
Amendment effects on compost	Reduce the total composting period by more than 30%	Reduce the total composting period by more than 30%
Compost quality	Medium	Good

landfill (Khoo *et al.,* 2019). Moreover, the COVID-19 pandemic era nowadays requires everyone to adapt to new life to avoid transmission of COVID-19. This new life is related to compliance with health protocol in every activity (Samudro and Mangkoedihardjo, 2020). It is critical to cut the disease transmission might be contained in domestic waste. As stated in Table 1, that pathogen in diaper waste can cause infectious diseases to the residents around the landfill area or landfill workers, so centralized waste facilities are not very efficient in handling diaper waste. The household-scale composting model provides a reliable alternative solution to address the growing waste problem. Household-scale composting saves labour costs, transport and waste sorting, compared to centralized composting systems (Zhou et al., 2020). About 87% of diaper mass reduction noted through this small-scale composting system (Espinosa-Valdemar *et al.,* 2014). Despite the difficulties in implementing household-scale composting, among others (Bernal *et al.,* 2017, Awasthi *et al.,* 2020): relatively high salt content in compost, animal disturbances, leachate and unpleasant odours due to the production of ammonia (NH_3), nitrous oxide (N_2O) and methane (CH_4), household scale composting can play a role in helping local governments achieve targets in increasing the rate of waste recovery and diverting waste from landfills (Faverial and Sierra, 2014). The innovation to handle diaper waste by composting is necessary to pursue. Table 3 shows the comparison of several studies conducted in disposable diapers composting.

Some issues remain to address include time duration, plastic polymers that do not decompose, pathogens in compost, and lack of data about compost application on plants. The initial C/N ratio of diaper waste which is high, namely 92.09, is a challenge in composting this waste (Simamora and Pandebesie, 2019). Likewise, the diaper waste is flushing (in terms of solid, liquid, semi-solid, both wet and dry condition). This problem overcome by combining composting materials or what is commonly called co-composting, which is known to have many benefits in composting. The wet material or too dry material, can be mixed with other suitable materials to obtain the initial conditions optimum

Table 3: Comparison of Disposable Diapers Composting Results

No.	1	2	3	4
Main composting feedstock	Diaper + Garden waste	Diaper + Garden waste + food waste	Diaper + Garden waste + food waste	Diaper + Vegetable waste
Regulator	-	-	-	Urea
Bulking Agent	-	Sawdust	Rice husks and bran	Rice husks
Microbial Agent	-	-	-	EM4
Optimum variation Diaper waste to organic waste	3:7	3:7	4:6	3:7
Composting method, Reactor	In-Vessel, HDPE plastic	Aerated static pile with pipes on the floor to provide aeration and to collect leachate	In-Vessel, Takakura baskets	In-Vessel, A plastic barrel with a hole at the reactor bottom to remove leachate
C/N Ratio	11	14	10-20	10-20
Pathogen in compost	Below the regulatory standard	Below the regulatory standard	above the regulatory standard at 4 of 5 reactors	not mentioned
Phytotoxicity test	On tomato plants, no phytotoxic effects detected	-	-	-
Processing time	12 weeks	106 days	90 days	60 days
References	(Espinosa-Valdemar *et al.,* 2014)	(Colón *et al.,* 2013)	(Zulfikar *et al.,* 2019)	(Simamora and Pandebesie, 2019)

for aerobic microorganisms activities in composting. Table 3 describes the materials that used in diaper co-composting research. Column number 2 is a study conducted in a city composting centre, where garbage is collected door to door. It allows the condition of the diaper waste to be inhomogeneous. However, composting for 106 days is running well. Further explanation regarding co-composting is in the next section.

The role of diverse microorganisms in the composting process

Composting is a biological conversion process where the organic material undergoes degradation by various groups of microorganisms under controlled environmental conditions in the presence of air into a stable humus-like substance that applied to the soil without affecting the environment (Bernal *et al.,* 2017; Onwosi *et al.*, 2017; Rudnik, 2019b). Co-composting is composting more than one organic waste together, for example, food waste with manure or with lignocellulosic biomass, whose benefits are not only to balance the C/N ratio, but also to increase aeration and reduce leachate (Lin *et al.,* 2019). Another example, a mixture of animal manure as a regulator, with materials from agricultural waste as a bulking agent (Said, 2020). Co-composting is a way to gain varies microorganisms in the composting system (Baharuddin *et al.,* 2009). Since the addition of compost additives determines the duration of composting, humification, and product quality, it is essential to select additive types and combinations carefully to ensure optimal effect. Various compost additives divided into bulking agents, regulators, and microbial agents. The bulking agent is a material to provide a support structure and air pores for the pile of materials. Regulators can speed up the composting rate and improve the final product quality. The addition of microbial agents expected to improve composting performance (Guo *et al.,* 2019). Although theoretically, composting does not require a special inoculum because aerobic microbes abundant in organic waste provide enough microorganisms (Bernal *et al.,* 2017), the inoculation with a suitable microbial source yielded more advantages composting performance (Harindintwali *et al.,* 2020). The diverse-combination can be applied because the mixed inoculants generate appealing results (Flores-felix *et al.,* 2019). Some of the microorganisms commonly used in the composting process are bacteria, actinomycetes, fungi (Wei *et al.,* 2007), and algae (Han *et al.,* 2014). Among the various microbial population associated with polymer degradation, only a few microbial strains capable of cellulase enzyme secretion and solid-waste degradation through cellulose hydrolysis are in light. Cellulomonas, Bacillus, Pseudomonas, Rhodococcus, Thermoactionmycetes, and Staphylococcus are the prevalent bacterial genera. Likewise, fungal species Aspergillus, Trichoderma, Sclerotium, Penicillium and white-rot fungi, are the dominant fungal genera that also produce extracellular enzymes accountable cellulose and lignin degradation during composting (Khoo *et al*., 2019, Rastogi *et al.,* 2020).

The benefits of microorganisms in the composting process are as follows:

1) Increase the mineralization of organic carbon, improve the degradation of lignocellulose, promote the humification process, accelerate the compost maturation process (Guo *et al.,* 2019; Wei *et al.,* 2007; Xu *et al.,* 2019).
2) Accelerate composting time, producing pathogen-free compost, possibly increasing the production of different enzymes resulting in a better waste degradation rate (Hashemi and Han, 2018; Rastogi *et al.,* 2020).
3) Play a role in plastic degradation (Jaiswal *et al.*, 2019; Moharir and Kumar, 2018), even microplastics (Yuan *et al.,* 2020).
4) Removal of harmful toxins or pollutants such as PCDD / F (Polychlorinated dibenzodioxin and dibenzofuran) (Huang *et al.,* 2019), dan microcystin (Han *et al.,* 2019; Han *et al.,* 2014).

The inoculation timing, whether at the initial stage, thermophilic, maturation stage, or multi-stages, affected the process to produce compost with the expected quality. Inoculation at 0, 120, and 180 days show that, lignin degradation paced maximum at the maturation phase for all the treatments (Bernal *et al.,* 2017; Rastogi *et al.,* 2020). Bacteria community play critical roles in the thermophilic and post-aeration phase while fungi take over in the maturing phase (Arab *et al.,* 2017). Nitrogen-turnover bacterial agent or nitrogen-altering bacterial inoculation at the beginning of composting, results in a high organic carbon degradation, nitrogen-loss reduction, and the compost quality improvement (Han *et al.,* 2019). Meanwhile, white-rot fungi inoculation during the thermophilic stage was effective than in the mesophilic (Lin *et al.,* 2019). During maturation, microorganisms that control plant diseases inoculated into the compost (Bernal *et al.,* 2017). An effective Microorganism (EM) inoculated compost attains better compost quality and maturity in less process time. These EM's can be isolated from various of conventional sources, such as soil, waste material or leachate and applied to the process at different stages (initial, mid or last) (Rastogi *et al.,* 2020). In terms of composting diaper waste, the commercial EM4 addition, as stated in Table 3, resulted in no effect on the composting process (Simamora and Pandebesie, 2019), the further experiments with different levels of EM4 can be conducted. It is a challenge to define a compost enhancement strategy by adjusting the relevant parameters and add the appropriate inoculants at the right point in time. Enhanced composting performance could mean better organic matter degradation, faster stability time (Arab *et al.,* 2017), and reduce nitrogen-loss (Han *et al.,* 2019). According to the reason, cyanobacteria consider as one of the most suitable microorganisms. Cyanobacteria have the exclusive capabilities called nitrogen fixation (Abatenh *et al*., 2018). Inoculation of filamentous cyanobacteria to compost, accelerate the decomposition rate and provide many nutrients for plant growth (El-Gamal, 2011). Also, the high Germination Index (GI) value (Han *et al.,* 2014). Some research has already declared success in polyethylene biodegradation by alga and cyanobacteria. Besides other microbes, the colonizing algae on the polymer surfaces found to be nontoxic and less hazardous (Sarmah and Rout, 2020), and it has concluded that among different groups of microalgae, the filamentous cyanobacteria are most effective in the biodegradation of polyethylene sheet (Kumar *et al.,* 2017).

Cyanobacteria

Cyanobacteria are a group of bacteria characterized by various structural features (El Gamal, 2010). Cyanobacteria grow autotrophically, heterotrophically, or mixotrophically (Subashchandrabose *et al.,* 2013). With the ability to adapt in diverse environmental fluctuations, making them easy to find everywhere (Yadav *et al.,* 2018). Cyanobacteria exist in almost every terrestrial and aquatic habitat, under high pressure such as UV radiation, drying, and a wide range of pH, temperature, salinity, and water potential conditions (Naik *et al.*, 2019; Pandey *et al.,* 2020). Although these microorganisms appear in most aquatic ecosystems, they can spread to the surrounding environment (Takahashi *et al.*, 2014), especially for cyanobacteria aerosols, which passively transported through the air, and released into the atmosphere from the surface of water and soil, then grow on buildings, trees or roofs (Wiśniewska *et al*., 2019). Cyanobacteria occur in soil by agricultural activities, through irrigation water and plants (Cao *et al.,* 2018). They classified as blue-green algae (Cyanophyta), have a combination of green chlorophyll and blue phycocyanin. The presence of carotenoid and phycoerythrin pigments causes cyanobacteria to be green, turquoise, brown, purple, red, and even black. Taxonomically, they included in the prokaryote group and are gram-negative bacteria (Noreña-Caro and Benton, 2018). Cyanobacteria divided into four orders, viz Nostocales, Stigonematales, Chroococcales, and Oscillatoriales. They further divided into families, subfamilies, genera, and species. Morphologically, blue-green algae identified in various forms, such as filamentous, unicellular, planktonic or benthic and colonies. They have a unique combination of plant-like photosynthesis and microbes ability (Gupta *et al.,* 2013). Cyanobacteria are capable of producing various forms of organic molecules called secondary metabolites which function as defence mechanisms under stressful conditions, facilitate reproduction, and provide the ability to survive in aquatic environments inhabited by various types of predatory macroorganisms. Overall, cyanobacteria produce three secondary metabolites, viz UV protectants, bioactive compounds, and cyanotoxins (Noreña-Caro and Benton, 2018). Several studies have conducted to increase the usefulness of cyanobacteria for human life. The unique characteristics of cyanobacteria, namely their ubiquitous habitat, short generation time, low growth requirements, and ease of genetic manipulation, make them prominent candidates in various biotechnological applications (Yadav *et al.,* 2018). These microorganisms have proven their diverse roles by offering many benefits to the environment and also their application for several valuable products, including bioenergy (such as bioethanol, biodiesel, and biohydrogen), bioremediation (ex wastewater treatment, nutrient recovery or disposal, pesticide remediation), and bioproducts made from secondary metabolites (such as pigments, vitamins, and biopolymers, and other products related to the food industry, feed additives, cosmetics, and pharmaceuticals) (Axmann *et al.,* 2014; Deviram *et al.,* 2020; Gupta *et al.,* 2013; Patel *et al.,* 2019). There are four classes cyanotoxins, including microcystin, cylindrospermopsin, anatoxin, and saxitoxin (He *et al.,* 2016). Among the diversity of peptides produced by cyanobacteria, only microcystin has studied intensively (Janssen, 2019) where microcystin-LR (MC-LR) is the most prominent because of its distribution and high toxicity (Martins *et al.,* 2017), followed by MC-YR, MC-LA, MC-YM and MC-RR (Herrera *et al.,* 2015). Some researchers declare microcystin as a poison that is harmful to plants (Cao *et al.,* 2018), animals (Al-hazmi *et al.,* 2019; Martins *et al.,* 2017), and possibly humans (Fontanillo and Köhn, 2018; Herrera *et al.,* 2018; Lone *et al.,* 2015; Preece *et al.,* 2017). Anabaena should considered as a source of high levels of microcystin-LR (Dreher *et al.,* 2019).

Potential utilization of cyanobacteria in the composting process

Nitrogen considered the prime nutrient for plant growth is the main component of air making up about 78% of the gases in the Earth's atmosphere, available in highly stable molecular form which plants and animals cannot directly use. Nitrogen fixation is converting atmospheric nitrogen into a chemical substance, namely ammonium through combination nitrogen gas with hydrogen to produce ammonia by microorganisms with the nitrogenase enzyme. Then decomposition stage called the ammonification or mineralization process occurs. It is when decomposing-microbes convert ammonia to ammonium. Furthermore, in the maturation phase, nitrification takes-place as the transformation of ammonium into nitrite then nitrate. Ammonium ion is a source of energy for microorganisms, while nitrite is poisonous, and must immediately convert into nitrate, so can be absorbed by plants (Abatenh *et al.,* 2018; El-Gamal, 2011). The nitrogen cycle occurs in the composting process illustrated in Fig. 2.

Thereby nitrogen loss is an essential aspect of the composting process from a nutrient conservation and environmental perspective. Poorly managed composting of organic waste contributes to the loss of nutrients by releasing large emissions into the atmosphere and the leachate removal (Bernal *et al.,* 2017). Total nitrogen during composting lost through ammonia and nitrous oxide emissions (Lin *et al.,* 2018; Maulini-Duran *et al.,* 2014). Cyanobacteria recover the ammonia in composting process (Koyama *et al.,* 2020). A study concluded that composting plays a significant role in blue-green algae enrichment (Pawar

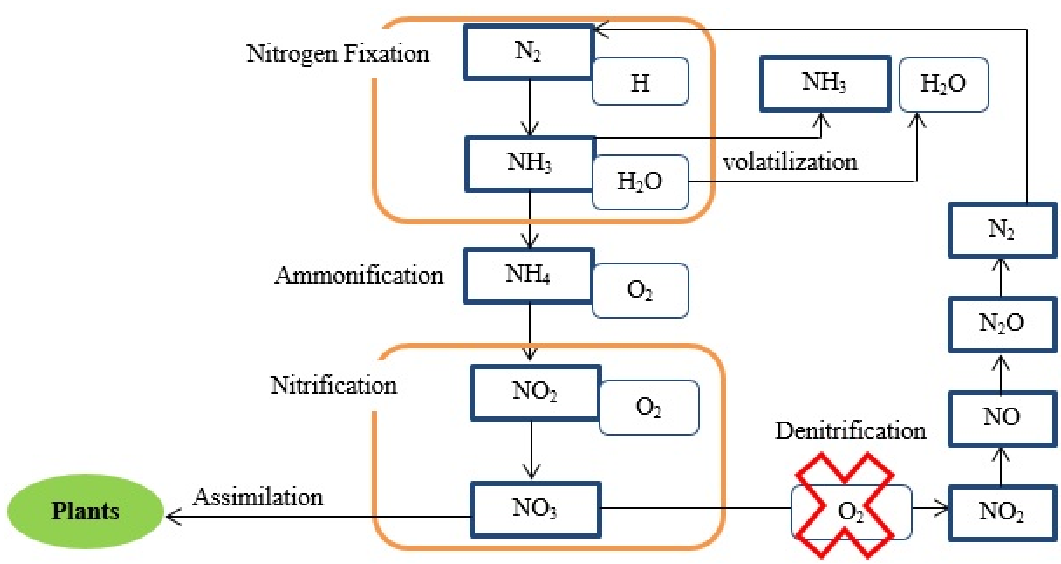

Fig. 2: The Nitrogen cycle occurs in the composting process

and Suryawanshi, 2016). Compost enrichment by blue-green algae significantly improve the nitrogen content (El-Gamal, 2011). Then, this is a mutually beneficial relationship between composting and cyanobacteria. Consideration in cyanobacteria use in composting strengthened by their resistance to high temperatures which needed to eliminate pathogenic bacteria found in organic waste. Cyanobacteria's resistance in high temperature proven by their abundance in the thermophilic phase with a temperature setting of 50-70 °C (Koyama *et al*., 2020). They reported present from early thermophilic until in mature compost (Tumuhairwe and Tenywa, 2018). Thus, the thermophilic condition can eliminate harmful pathogens without affecting cyanobacteria growth in composting system. Moisture is a dominant factor impacting growth for most cyanobacteria and microbial activity in the composting process. Water content had a significant effect on cyanobacteria growth in compost material. High moisture level resulted in nitrogen loss in compost, due to the anaerobic conditions from the waterlogged pore spaces obstructing composting processes, and also caused by denitrification process. Increasing moisture content also resulted in organic matter decreasing. The 50% moisture composition considered appropriate for cyanobacteria growth and the optimal degradation rate (Baftehchi *et al.,* 2007; El-Gamal, 2011). The carbon to nitrogen ratio (C/N ratio) of the organic material to be composted is an important factor. A higher initial C/N value may result in a long time to stabilize the compost material and shift the microbial community to include higher relative abundances of fungal biomass. A low initial C/N ratio degrades material quickly, means lots of available nutrients, but can result in nitrogen loss via ammonia emission, also the generation of unwanted odours. Generally, Blue-Green Algae has a relatively low C/N ratio, typically ranging from 4,9 to 6,06. An effective way to adjust the algal-based feedstock to have a suitable C/N value (around 30) is co-composting with a high C/N value material. Sawdust, wood chips, bark, straw, hull, bran, and animal manure commonly added as algal co-composting materials (Han *et al.,* 2014). Therefore, cyanobacteria addition to the composting of diaper waste with a high C/N ratio is proper. Cyanobacteria enrich nitrogen to the composting system that will raise the optimum C/N immediately. It also means accelerate the compost maturity. Microcystins are the obstacles for utilizing cyanobacteria since in under natural condition, cyanobacteria contain high contents of microcystins. Some microcystins residues inevitably left in cyanobacteria fertilizer. Microcystins accumulation cause the problems of food safety. However, the standard for the MC-LR in grains and vegetables has not reported yet. The composting process with microbial inoculation such as *Bacillus subtilis, Bacillus licheniformis* and *Bacillus stearothermophilus*, increased the microcystins degradation rate. A study founded the high level of MC-RR and MC-LR in the organic materials mixture without composting. However, in mature compost, it found very low, under the MC-LR limited value in drinking water which is ≤1µg/L (Han *et al.,* 2019). Another study revealed that 90% of both MC-RR and MC-LR degraded by day 48 in cyanobacteria composting. Efficient degradation of microcystins during composting may be due to the wide variety of microorganisms present in compost systems (Han *et al*., 2014).

Cyanobacteria applications for environment and sustainable agriculture

Cyanobacteria are potential oxygenic phototrophic organisms that can aid plant repair in many ways (Abatenh *et al*., 2018). The potential of new concepts of cyanobacteria-based biofilms as biological fertilizers has investigated in the last two decades. Cyanobacteria which are known as nutritional supplements (inoculants), provide high value in agriculture as biofertilizers (Renuka *et al.,* 2018), also bring some extraordinary ecological benefits (Gupta *et al.,* 2013), either individually or in combination with other biofertilizers (Hegazi *et al.,* 2015). Integration of various microorganisms with cyanobacteria produces the best results (Manjunath *et al.,* 2016). Although the use of cyanobacteria as biological fertilizers has known for a long time (Han *et al.,* 2019), recent attention has focused on the function of cyanobacteria secondary metabolites in the control of phytopathogens and their potential applications in crop protection (Yadav *et al*., 2018). Many studies have conducted to study the beneficial effects of cyanobacteria on rice, wheat, soybeans, tomatoes, oats, sugar cane, maize, radishes, muskmelons, cotton, lettuce, nuts and peppers, cantaloupe (Farrag *et al*., 2017; Naik *et al.,* 2019).

The promising functions of cyanobacteria to improve soil fertility and environmental quality noted as follows:

1) Improve soil aggregation, soil structure, soil permeability and water holding capacity of soil (Pawar and Suryawanshi, 2016), thus controlling runoff, decreasing soil loss and water conservation (Sadeghi *et al.*, 2020a; Sadeghi *et al.,* 2020b). The cyanobacteria used: Gloecapsa, Phormidium, Nostoc, and Oscillatoria.
2) Improving soil quality indicators, soil remediation, and soil stabilization (Sadeghi *et al.,* 2020b). The cyanobacteria used: Nostoc and Oscillatoria.
3) Increased soil biomass after cyanobacteria die and increased soil porosity due to fibrous structures (Renuka *et al*., 2018; Yadav *et al.,* 2018). The cyanobacteria used: Anabaena and Nostoc.
4) Increase soil fertility by releasing growth-promoting substances such as hormones, vitamins, and amino acids (Yadav *et al.,* 2018) and IAA (indole-3-acetic acid) (Chatterjee *et al*., 2019).
5) Increase in macros and micronutrients content in grains (Pandey *et al*., 2020), leaves (Rashad et al., 2019), straw (Eletr *et al.,* 2013), root (Menamo and Wolde, 2015), also in the rhizosphere of plants (Manjunath *et al.,* 2016; Prasanna *et al.,* 2016).
6) Utilized as a biocontrol agent against several pathogenic microbes, weeds, insects, fungal diseases. *Spirulina platensis* showed more allelopathic activity over other cyanobacterial strains (Dukare *et al*., 2011; Prasanna *et al*., 2015; Renuka *et al.,* 2018; Yadav *et al*., 2018).
7) Used as a bioremediation agent to remove toxic compounds such as toxic chemicals, heavy metals, and other pollutants in contaminated environments (Pandey *et al.,* 2020; Renuka *et al.,* 2018), including pesticides, lindane (Chatterjee *et al.,* 2019), salt (Li *et al.,* 2019), chemical fertilizers (Burjus *et al.,* 2020). Tolerant strains such as: Fischerella, Anabaena, Nostoc, Oscillatoria.
8) It used to detoxify industrial waste (Patel *et al.,* 2019), for example, a biological template for the synthesis of metal nanoparticles (Pandey *et al.,* 2020). The cyanobacteria used: Phormidium.
9) Reducing greenhouse gases from the environment, for example, methane mitigation (Malyan *et al.,* 2016), and carbon sequestration due to cyanobacteria showing a higher photosynthetic efficiency compared to land plants (Pandey *et al.,* 2020). *Synechocystis sp.* are one of the most beneficial for lowering methane emission from soils, presumably aiding methane oxidation via oxygenation during photosynthesis (Shankar and Strong, 2016).
10) The decomposition of polyethylene sheets by cyanobacteria in the form of filaments, where the enzymatic activity of microorganisms and breaking the polymer bonds are the main steps (Kumar *et al.,* 2017; Chia *et al.,* 2020). For example: Anabaena.
11) Reducing the chemical fertilizer utilization (Burjus *et al.,* 2020; Hegazi *et al.,* 2015).
12) Can be applied together with soil substitute planting media made of minerals such as perlite, vermiculite (Prasanna *et al*., 2020) and biochar (Kholssi *et al.,* 2017).

According to Rudnik (2019b), compost applicable for fertilizer, soil improver/conditioner, manufactured topsoil, growing medium, mulch, and even as a landfill cover. Compost can be used in various purposes depending on the quality. High-quality compost is used in agriculture, horticulture, landscaping and home gardening, while medium-quality compost used in applications such as erosion control and roadside landscaping. Low-quality compost can be used as a landfill cover or in land reclamation projects. Moreover, with the greening trend during the COVID-19 pandemic, where people spent more home activities, the compost requirement will increase. Environment greening by the community, will lead them to participate sustainably to maintain personal and environmental health. So the diaper composting at home-scale, then used for home gardening could be one solution to the purpose: eliminating toxicants, and selected biodiversity according to local preferences and conditions (Samudro and Mangkoedihardjo, 2020). With the advantages of cyanobacteria applications previously stated, these microorganisms addition to the composting system will expand the resulting diaper compost utilization for a wide range of environmental benefits.

CONCLUSION

Nowadays, where people move dynamically and well sanitation is necessary, disposable diaper is unavoidable. The current challenges lead to the development of solutions, that guarantee both ecosystems sustainability and human life quality. Concerning the problems associated with disposable diapers pollution, there have been many technological strategies developed, such as biodegradation and thermal methods, besides disposal to landfill. Composting strategies have evolved over the years. It is a route led by biodegradation methods done by microbial activities affected by the physical and chemical condition, such as oxygen, moisture, nutrition, and particle size, which progressed towards environmentally friendly and profitable biological solutions. The mixed inoculants of different microorganisms will be the right way to solve composting challenges. Co-composting with various organic materials is required to balance the carbon sources and nutrients, also provided adequate moisture to optimize diaper waste degradation. Due to the diversity of species, widely available in nature, can grow everywhere, with highly adaptive ability, also its unique combination, to do nitrogen fixation and carbon sequestration by photosynthesize like plants but in the other hand has microbial capabilities, making cyanobacteria potentially suitable candidates for various purposes. Furthermore, their possibility to decompose plastic polymers, reinforces the reasons for cyanobacteria utilization in diapers composting. Based on the literature review carried out, the authors believed that cyanobacteria are promising candidates for enhancing disposable diaper composting in providing advantages as follow: 1) Improvement in composting performance, include: reducing composting time, increase the decomposition rate of compost, eliminating pathogens and toxic compounds, breaking down plastic polymers contained in diaper waste, and minimizing nuisance animals. 2) Production of valuable product that used for several applications. 3) Environmental protection by reducing waste disposed off into the soil and water bodies, greenhouse gasses mitigation, land remediation and restoration, biodiversity and water conservation. Nevertheless, it is clear that a more detailed investigation required to prove the viability concept of this emerging option. Further research to address challenges should include integration, optimization, modification, and social-economics aspect assessment. Those might contain several things as follows: the selection of cyanobacteria species, the planning of appropriate methods, the determination mixing variation of the material composted, the calculation of investment and operational costs, and the market share research willing to accept the compost produced. Regarding the risk of harm to humans and the environment, the quality of compost in terms of stability and maturity should be assessed respectfully, by parameters such as physics-chemistry parameters, pathogen and phytotoxin content. Planting experiments on various types of plants is a fascinating matter to researched forward. Considering the microplastic accumulation in some plants, according to the authors, is something that needs to find out whether these cyanobacteria can indeed decompose plastic polymers completely or only tear them into microscopic forms. Furthermore, it is also necessary to ensure the absence of microcystin in the compost.

AUTHOR CONTRIBUTIONS

D.I. Kusumawati performed the conceptualization, literature review, writing-original draft, visualization, administration, obtaining funding. S. Mangkoedihardjo also performed the conceptualization, methodology, supervision. critical revision of the manuscript for important intellectual content.

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CONFLICT OF INTEREST

The authors declare no potential conflict of interest regarding the publication of this work. In addition, the ethical issues including plagiarism, informed consent, misconduct, data fabrication and, or falsification, double publication and, or submission, and redundancy have been completely witnessed by the authors.

ABBREVIATIONS

C	Carbon
CH_4	Methane
C / N ratio	Carbon to nitrogen ratio
EM	Effective microorganism
H	Hydrogen
H_2O	Water
IAA	Indole-3-acetic acid
LDPE	Low-density polyethylene
MC	Microcystin
N	Nitrogen
N_2	Nitrogen
NO	Nitrogen monoxide
N_2O	Nitrous oxide
NH_3	Ammonia
NH_4	Ammonium
O_2	Oxygen
PP	Polypropylene
PCDD / F	Polychlorinated dibenzodioxin and dibenzofuran
SAP	Super absorbent polymer

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AUTHOR (S) BIOSKETCHES

Kusumawati, D.I., M.Sc., Assistant Professor, Department of Environmental Engineering, Faculty of Civil, Planning and Geo-Engineering, Institut Teknologi Sepuluh Nopember, Surabaya, Indonesia. Email: *diana.indah.k@gmail.com*

Mangkoedihardjo, S., Ph.D., Professor, Department of Environmental Engineering, Faculty of Civil, Planning and Geo-Engineering, Institut Teknologi Sepuluh Nopember, Surabaya, Indonesia. Email: *prosarwoko@gmail.com*

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