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Summary

The accumulation of plastic waste has become a global issue, contributing to global warming and environmental damage worldwide. Rutgers University currently generates around 1.5 million pounds of polystyrene waste per semester, most of which is either dumped in landfills, or processed through waste incineration or recycling plants. Apart from recycling, which only accounts for 9% of all polystyrene waste, these methods of waste processing result in significant greenhouse gas and environmental pollution. We are proposing the creation of a polystyrene plastic waste processing plant on Rutgers University, which would use mealworms to degrade polystyrene into 50% CO_2 and 50% nutrient-filled biomass. Although this process produces CO_2, the facility will be designed to capture this CO_2 to prevent it from entering the atmosphere. Mealworms can live off a diet of polystyrene and other types of plastics, processing about 34-50 mg of polystyrene/day by 100 mealworms. Although this is not a large number, an established mealworm farm costs as little as $0.10 per 1000 mealworms, making it possible to have an inexpensive mealworm farm containing millions of mealworms. Our projected costs have mealworms degrading polystyrene for as little as $0.122/kg by the end of the first two years of the facility's establishment, making this process competitive with those of recycling and waste incineration. Finally, although the initial facility would begin with mealworms, the ultimate goal would be to research the mealworms bioprocesses to develop a genetically engineered process to degrade polystyrene, and other plastics, with high efficiency and low costs.

The Issue

Within the last couple of decades, the accumulation of plastic waste has become a global concern. On average about 300 million tons of plastic is thrown out per year, where a majority of it is sent to landfills to take up space, causing groundwater and environmental contamination, while the remainder is incinerated and becomes greenhouse gases, or is recycled.[1] Approximately 30% of this plastic waste is due to packaging, a single-use plastic which is discarded with no environmental concern. Creating and disposing of this plastic is also a large source of pollution and energy, due to the manufacturing process and transportation that is needed to make it readily available to consumers.

Polystyrene (C_8H_8), Styrofoam, is one of the most popular materials used when packaging a product, as it is cheap, readily available, and easy to manipulate. Additionally, it has a melting temperature between 210 and 249 °C, and is very inert.[2] Due to these properties, it has a long degradation period and does not degrade in the presence of acids or bases. For these reasons, it has become a desirable packaging material, but an undesirable waste stream.

Rutgers University currently has 50,254 enrolled students, undergraduate and graduate, with 43 %, or 21,609 students, living on-campus.[3] According to Columbia University, the average American generates around 7 lb of material waste every day, which totals approximately 16 million lb of waste generated by Rutgers on campus living per semester.[4] Polystyrene averages around 9% of all waste, resulting in 1.5 million lb of polystyrene generated by Rutgers on campus living per semester. In addition to waste from on campus living, Rutgers is home to a large number of research laboratories, which receive daily packages likely fortified with polystyrene packaging materials. The same assumption can be made about the food delivered to dining halls and the various cafes throughout the 5 campuses. With all these streams considered, Rutgers generates a significant amount of plastic waste.

Currently, polystyrene waste is disposed of via waste incineration or is sent to landfills. Polystyrene is made from oil and gas so it holds significant energy potential within its chemical bonds, and creates significant amounts of heat when burnt, which can be captured and used to decrease the net energy footprint of the burning process. The energy generated from this process of plastic incineration is also used as a substitute for burning oil. However, burning plastic is only 21% efficient, compared to gas-fired power stations which are 55% efficient, resulting in significant amounts of heat loss while also emitting CO_2 and toxic gases, such as NO_x and SO_x, into the atmosphere.[5] There is also ash being emitted from incombustible materials, water vapor and toxic metals such as chlorofluorocarbons that are present in the polystyrene. The greenhouse gas emissions from plastic production and incineration have been projected to account for 56 gigatons of carbon-based greenhouse gases between now and 2050. This is equal to almost 50 times the annual emissions of all coal power plants in the US.[6]

As previously stated, about 9% of all collected waste is polystyrene, which amounts to at least 1,429,435 lb of polystyrene, or 715 tons, from Rutgers. For this waste to be processed in the municipal waste stream, it costs about $62/ton just for collecting the waste and then another $139/ton to incinerate the waste, which is only 21% efficient and results in about 1.8 million kg of CO_2 being emitted.[7] This totals to at least $143,715 in capital cost for Rutgers University to incinerate the polystyrene being disposed of, without considering the costs of environmental damage and pollution caused by sending waste to landfills or incinerating it and generating greenhouse gases. Although recycling seems like a promising alternative, only about 9% of all plastics are recycled. Of that 9%, approximately 75% of the plastic is recovered, leading to a net market cost around $64/ton. For Rutgers, that amounts to at least $45,760 with around 193,765 kg of CO_2 being generated by the recycling processes required to sanitize and make the plastic appropriate for reuse.[7]

While landfills may seem to be a more environmentally favorable alternative to plastic incineration, because there are little to no emissions of greenhouse gases, it has a more direct impact on environmental and human health. The first issue with plastics in landfills is that they are extremely stable, and will only degrade after centuries, resulting in overfilled landfills which present environmental and health risks. As a result, many countries have resorted to dumping plastic into the ocean; in the US alone, the equivalent of 65 trucks per day of plastic waste are dumped into the ocean via land, rivers and coasts.[8] This equates to 40-110 million kg/yr of plastic in the ocean. The trash that ends up in the ocean is harmful to marine life, both through physical methods, such as the choking of marine animals, and also through the toxic chemicals which accompany the plastic waste dumped into the ocean. These toxic chemicals can also have detrimental effects for human communities when plastic waste is dumped into regular landfills, as these fluids can contaminate soil and leach into water supplies, resulting in contamination of water supplies.[9]

Our Solution

To reduce the carbon footprint of Rutgers University from plastic waste disposal, we are proposing the establishment of Rutgers' own plastic waste disposal facility, which would utilize mealworms to degrade polystyrene, in a matter of days, to CO_2 and nutrient-filled biomass.[10] Mealworms, which are the larvae of *Tenebrio molitor* Linnaeus, have the ability to degrade polystyrene into 47.7% CO_2, and 49.2% nutrient-filled feces. They are considered to be pests, and are often used as an animal food source.[11] Additionally, they can be easily reared on inexpensive food sources such as oats, bran, and grains, and have four life stages: egg, larva, pupa and adult.

Multiple studies have found that mealworms can live off a diet of polystyrene and other types of plastic, due to microorganisms inside the mealworms' guts which are able to biodegrade the material. About 34-50 mg of polystyrene can be degraded a day by 100 mealworms, 1.25-2.5 cm in length each. They are able to operate as efficiently on this diet as on a normal diet of bran.[12]

While this consumption per 100 mealworms is negligible compared to the daily amount of polystyrene waste from Rutgers University, the cost of raising these mealworms can be as low as $0.10 per 1000 mealworms.[13] Additionally, mealworms can exist in limited amounts of space, with the ability to have millions of mealworms in a single warehouse space. Thus, the facility we are proposing be established at Rutgers would consist of millions of mealworms in a building the size of a warehouse, on Rutgers Cook-Douglass campus, resulting in the ability to process the daily capacity of Rutgers plastic waste.

To create this facility, we are suggesting using undeveloped land, which costs about $6,500 per acre, on one of Rutgers University campus, minimizing waste transportation costs.[14] Another aspect of the starting costs would be purchasing the mealworms, which can easily be done from Amazon with a price ranging from $6-$16 for 1000 mealworms. Once the first batch of mealworms have been allowed to reproduce, the mealworm farm will be able to sustain itself without the addition of newly purchased mealworms. As previously stated there are 4 stages to mealworms lives': egg (incubation period ranging from 4-20 days), larva (10-week period), pupa (6-18 days) and finally the beetle (8-12 weeks) which lay 40 eggs per day for about 3 months allowing population of mealworm to grow without having to buy new ones. Both the larvae and the beetles can eat polystyrene, with the larvae eating the largest quantity.

The way the different stages of mealworms will be separated is laid out in Figure 1. Each level will contain a different stage of mealworms, allowing them to be separated to ensure an organized facility which minimizes the mealworm death rate. This facility would also require a ventilation system that acts as a kind of greenhouse, to capture the CO_2 produced by the mealworms, and to control the temperature within the mealworm farm between 15-25 °C. The structure the mealworms are put in will be made out of a non-adhesive surface to ensure that they remain within their respective stage, and do not climb up to other stages. When distributing the polystyrene within the mealworm farm, we propose layering the polystyrene into each level to create structures which increase the surface area of the polystyrene available to the mealworms, and to allow them to create a network throughout the waste. Oats will be used as a supplementary nutrient source, with a water delivery system along the exterior of each mealworm stage. This system will also be designed to prevent the formation of mold within the structure, and will be accompanied by a protein source to supplement the mealworm diet and ensure a healthy mealworm farm.

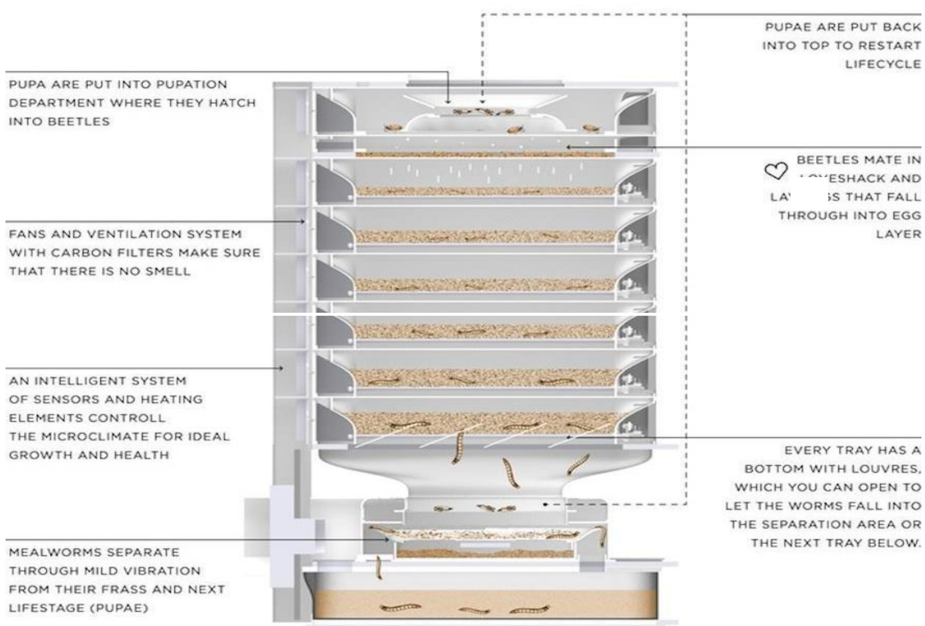

Figure 1- Proposed mealworm farm structure

Calculation of Mealworm Productivity and Proposed Timeline

If we assume that 50% of the polystyrene is converted to CO_2 by the mealworms then about 1.54 kilogram to CO_2 will be produced for every kilogram of polystyrene consumed. The processing costs have been calculated as follows:

Assuming that 100 mealworms can process 35 mg polystyrene/day = $3.5*10^{-5}$ kg/day

$$\therefore \frac{100 \text{ mealworms}}{3.5 * 10^{-5}\text{kg} * \text{day}} = 2{,}857142 \ \frac{\text{mealworms}}{\text{kg}} * \text{day}$$

Assuming 3,000,000 mealworms, once an initial population has been established:

$$\frac{\$0.10}{1000 \text{ mealworms}} * 3{,}000{,}000 \text{ mealworms} = \frac{\$300}{\text{kg polystyrene}}$$

Assuming mealworms can process polystyrene as larva (worms) and adults (beetles), this gives an active life of:

$$70 + 84 = 154 \text{ days}$$

Cost of processing polystyrene per day

$1.95/kg polystyrene for first 154 dayls

However, once the initial mealworm population has been cultivated, they will reproduce and grow exponentially, further decreasing the cost of processing.

Assuming that the population doubles every lifecycle (~150 days), after the first 150 days, the cost of processing will halve and continue to halve each reproduction cycle.

$0.975/kg polystyrene for second 154 days

$0.488/kg polystyrene for third 154 days, and so forth.

Thus, the timeline we have proposed to reach competitive plastic degradation capacity would be after the first two years of operation. By this time, it has been projected that the process costs for mealworms will be between $0.122 and $0.244/kg, making the process competitive to those of recycling ($0.288/kg) and waste incineration ($0.199/kg).

The major differences between recycling polystyrene, incinerating it and using mealworms is summarized in Table 1. Over time the process time decreases as the population of mealworms grows by reproduction, minimizing the university's cost of new mealworm batches. As detailed in this table, excluding energy required to maintain facility conditions, to degrade the polystyrene amounts to 0 kwh/kg when using a natural process like mealworms.

Table 1. Comparison of costs of recycling, waste incineration and mealworms

	Recycling	Waste Incineration	Mealworms
CO_2 emissions kg/kg polystyrene	0.271	2.60	1.54
Energy efficiency	-	21%	-
Process costs ($/kg)[1]	0.288	0.199	Cycle 1 = 1.95 Cycle 2 = 0.975 Cycle 3 = 0.488 Cycle 4 = 0.244 Cycle 5 = 0.122
Energy requirement (kwh/kg)[2]	1.347	7.95	0

[1]Excluding upfront operational costs
[2]Excluding general electricity costs (heat, light etc.)

Finally, the initial facility that has been proposed will not immediately solve the Rutgers waste issue. There are still extensive improvements which must be made to the process to increase its efficiency and further reduce the costs of processing polystyrene waste via mealworms. However, we believe that this facility could be the start of a novel method for processing plastic waste. Thus, in addition to creating this waste facility, we would also like to have this facility connected with the Rutgers EcoComplex, and have it linked to numerous research groups. Understanding the process within the mealworm gut would allow the genetic engineering of the key components which allow the mealworms to degrade polystyrene waste. This could allow for the genetic engineering of a significantly more efficient, streamlined process to degrade polystyrene, and an understanding of the active bacteria or enzymes within this process could also potentially lead to technologies which could also degrade other plastics, such as polyethylene.

Conclusion

Finding new natural ways to get rid of plastics like polystyrene will allow for savings in both energy and money, while also reducing the amount of pollution generated by plastic waste disposal at Rutgers. Our facility proposes mealworms as a novel method to convert polystyrene waste into CO_2 and nutrient-filled biomass, with the facility structured in such a way that the CO_2 can be captured and prevented from entering the atmosphere. In addition to reducing the energy and pollution costs of Rutgers plastic waste processing, our facility would also provide students with job opportunities, both within the facility and within the research groups that we would partner with to expand on this research, which would reduce the costs of operating the facility at Rutgers. Finally, this facility would be initiated as a pilot plant, with the ultimate goal being to understand the bioprocesses occurring within the mealworms gut so that a more efficient, streamlined process for plastic waste degradation could be genetically engineered and be implemented to replace the mealworm farm. With this goal in mind, it is our hope that Rutgers University will be able to process all of its polystyrene waste via mealworm derived technology.

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