An Investigation into the Effectiveness of Zebra Mussel Control Methods

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Executive Summary

Since their arrival in North America in the 1980s, zebra mussels have spread rapidly throughout the U.S. and Canada using waterways such as lakes and rivers. The growing zebra mussel population has caused more than $250 million of damages to water reliant facilities from 1989-2004 by impeding water flow to these facilities and reducing efficiency. As a result, zebra mussels must be controlled and eradicated. This report will analyze and compare the zebra mussel control methods of chlorine dispersal and toxin encapsulation. Although chlorine dispersal is effective in removing zebra mussels, it is both costly and harmful to the surrounding environment. Toxin encapsulation is not only more effective at removing zebra mussels than chlorine dispersal, but also more cost-effective and environmentally friendly. Therefore, it should take the place of chlorine dispersal as the most widely used zebra mussel control method.

Zebra mussels have a valve-closing response that allows them to survive for three weeks without feeding based on anaerobic metabolism. This renders many control methods ineffective as zebra mussels can simply close their valves and wait for any harmful chemicals around them to diminish or dissipate completely. One particular solution to this problem is toxin encapsulation since it surrounds a toxin core inside a Biobullet covered with edible particles and fools a zebra mussel into ingesting the deadly active ingredient. Chlorine dispersal is another solution as chlorine has the ability to kill zebra mussels, but only over an extended period of time.

A comparison of both toxin encapsulation and chlorine dispersal confirmed that toxin encapsulation is a more viable zebra mussel control method. Of the four chlorine dispersal methods examined, automated irrigation management system was most effective as it achieved 100% zebra mussel mortality in 14 days. On the other hand, toxin encapsulation reached 100% zebra mussel mortality in just 3-5 days. From 1989-2004, the combined total cost of chlorine dispersal for all drinking water treatment and power generation facilities in North America rose to $29,506,932. Toxin encapsulation monopolizes the filtration abilities of zebra mussels to place toxins deep inside zebra mussels. This reduces costs as low amounts of active ingredients need to be purchased and placed within the Biobullet.

Chlorine dispersal has extremely negative impacts on surrounding aquatic organisms since it involves discharging large amounts of chlorine into to the environment. The EPA even attempted to limit the severe environmental impacts of chlorine by establishing an exposure limitation of 1 part per million or 3 milligrams as described in the Clean Air Act of 1990. Toxin encapsulation can use both extremely low amounts of potentially harmful active ingredients as well as active ingredients that rapidly degrade and disperse after being ingested by the zebra mussel.

Toxin encapsulation is superior to chlorine dispersal in that it is more effective at removing zebra mussels in a short amount of time, more cost-effective, and less harmful to the surrounding environment. Toxin encapsulation should replace chlorine dispersal as the most widely used

zebra mussel control method. This will not help minimize the already vast costs associated with zebra mussels in North America, but it will also reduce the damaging environmental impact of chlorine dispersal.

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1.0 Introduction

The zebra mussel has developed a strong presence in North America since entering in the 1980s. Zebra mussels are known for their ability to survive via anaerobic metabolism for extended periods of time. This increased difficulty in removing zebra mussels has led to severe economic and environmental costs as zebra mussels reduce the efficiency of water reliant facilities. Control methods such as chlorine dispersal used in excess lead to negative environmental impacts through the spread of chlorine in aquatic ecosystems. As a result, improved control methods must be developed in order to limit high costs associated with controlling zebra mussels. This paper will compare the control methods of chlorine dispersal and toxin encapsulation.

Figure 1: Zebra Mussel Invasion. Figure 1 details the zebra mussel invasion in North America from 1988-1997.

1.1 History of Zebra Mussels in North America

Since their discovery in North America in June 1988, zebra mussels have quickly spread to all of the Great Lakes and entered eight river systems as seen in Figure 1 above. It is widely believed that the zebra mussel was introduced in 1985 or 1986 in ballast water discharged from foreign shipping (Ludyanskiy, McDonald, & MacNeill, 1993). From there the native species of southern Russia has spread rapidly throughout waterways of both the United States and Canada, impacting utilities, industrial and municipal water consumers, and even fisheries (Ludyanskiy et al., 1993).

1.2 Physiological Characteristics of Zebra Mussels

Zebra mussels have the ability to sustain themselves on anaerobic metabolism for several days, rendering numerous control methods ineffective (Rajagopal, Van der Velde, Van der Gaag, & Jenner, 2003). Chlorine, for example, is often used to attack organisms at organ, cellular, and subcellular levels. Zebra mussels are able to sense chlorine and other toxins in their surrounding environment and respond by closing their valves, thus allowing them to avoid the toxic effects resulting from control methods for nearly three weeks (Aldridge, Elliott, & Moggridge, 2006). A picture of a zebra mussel's valves can be seen in Figure 2. Their notorious nature of being nearly impossible to eradicate completely is one of the key reasons behind the enormous costs associated with zebra mussels.

Figure 2: Zebra Mussel Physical Features. Figure 2 provides a close-up of a zebra mussel's shell as well as its valves within the shell.

Another characteristic that makes zebra mussels resistant to elimination besides their avoidance response in the presence of toxins is their filtration capabilities. Zebra mussels are able to filter as much as 600 milliliters of water per hour while sorting out extremely small particles of food based on sensory quality (Costa, Aldridge, & Moggridge, 2011). This enables zebra mussels to quickly sort through materials for ingestion while also bypassing harmful chemicals or toxins. The harm inflicted by zebra mussels combined with their self-sustaining ability cause zebra mussels to be viewed as a serious problem that can severely hinder facilities that use water on a daily basis.

1.3 Zebra Mussel Control Methods to Be Analyzed

Chlorine dispersal and toxin encapsulation are two zebra mussel control strategies that will be researched and discussed in this paper. Chlorination is mainly practiced in continuous, intermittent, and pulse modes. Intermittent and pulse chlorination employ low doses of chlorine at specific time segments while continuous chlorination distributes an uninterrupted stream of chlorine into zebra mussel infested waters (Rajagopal et al., 2003). Toxin encapsulation features a Biobullet that contains toxins covered by edible materials, thereby tricking the zebra mussel into feeding on deadly toxins it would otherwise avoid as a result of its filtration system and valve-closing response (Aldridge et al., 2006).

2.0 Damages Inflicted By Zebra Mussels

Zebra mussels are responsible for both negative economic and environmental impacts. Their arrival in the Great Lakes in the 1980s continues to be a problem for both water reliant facilities and ecosystems surrounding those facilities. Aside from drinking water treatment and power generation facilities in North America, zebra mussels have also caused $1-5 billion each year for nuclear power plants experiencing fouling and blockage of heat exchange pipes, screen houses, steam condensers, and trash bars (Aldridge et al., 2006). On top of those costs, zebra mussels also negatively alter ecosystems by removing key aquatic species. The rapid spread of zebra mussels combined with their natural resistance to numerous control methods has led to enormous economic and environmental costs.

2.1 Economic Costs: Water Reliant Industrial Facilities

The zebra mussel is famous for efficiently removing large amounts of phytoplankton and detritus, leading to the destruction of planktonic food webs and the rise of food webs reliant upon and near the shore (Strayer, 2008). The invasion of zebra mussels in North America caused phytoplankton and small zooplankton populations in the Great Lakes region to fall by more than 50% in just a few months (Strayer, 2008). This rapid decline emphasizes their extreme efficiency as filter feeders. No other mussel can match the efficiency of the zebra mussel as a filter feeder.

Another issue related to zebra mussels invading lakes, rivers, streams, and reservoirs is their reputation as an efficient biofouler. This means that zebra mussels are capable of reproducing in a short amount of time and rapidly degrading underwater equipment and surfaces (Ludyanskiy et al., 1993). This results in the damage and destruction of marine structures such as bridges, docks, and buoys (MacIsaac, 1996). Known as an efficient filter feeder and biofouler, zebra mussels have continued to negatively impact industries reliant upon water since their arrival in North America.

The negative impacts brought about by the presence of zebra mussels have been particularly felt by industrial facilities that require the use of raw water. Zebra mussels have affected surface water dependent electric power generation and drinking water treatment facilities since their arrival in North America by fouling intake pipes and other pieces of equipment, leading to severely impeded flows of water into these different facilities (Connelly, O’Neill, Knuth, & Brown, 2007). One third of such facilities in North America have reported finding zebra mussels. 36% of those facilities experienced an annual economic impact of $30,000 per facility (Connelly et al., 2007).

Zebra mussels also negatively impact irrigation systems by adhering to pipelines and hydraulic infrastructure. This leads to high maintenance costs and a loss of efficiency through blocked filters and ineffective hydrants (Seral, Garcia, Aliod, Pano, & Faci, 2012). These high costs are detailed in Figure 3 below. Power generation facilities, drinking water treatment facilities, and irrigation systems all represent and emphasize the substantially negative impact that zebra mussels have had over the past 25 years.

Table 4

Mean and total economic impacts caused by zebra mussels, 1989–2004 by expenditure category

Expenditure category	Mean per facility with some type of expenditures	Estimated total for study area
Prevention efforts	$186,557	$87,308,676
Lost production and revenues	$124,110	$58,083,480
Chemical treatment	$63,049	$29,506,932
Planning, design, and engineering	$58,459	$27,358,812
Retrofit and/or reconstruction	$48,314	$22,610,952
Filtration or other mechanical exclusion	$22,061	$10,324,548
Monitoring and inspection	$21,398	$10,014,264
Mechanical removal	$13,897	$6,503,796
Nonchemical treatment	$9,786	$4,579,848
Research and development	$4,208	$1,969,344
Personnel training	$2,976	$1,392,768
Customer education	$1,831	$856,908
Other	$14,360	$6,720,480

Figure 3: Zebra Mussel Removal Costs. Figure 3 details the cost of zebra mussel removal for drinking water treatment and power generation facilities in North America from 1989-2004.

2.2 Environmental Impacts

In addition to significant biofouling mitigation expenses, zebra mussels are also responsible for negative biotic impacts upon an ecological community. By removing a large percentage of primary producers such as zooplankton, phytoplankton, and fisheries, zebra mussels reduce much of the food and energy available for pelagic food webs near the bottom of lakes or seas and adjacent to land (Ludyanskiy et al., 1993). Not only do zebra mussels reduce the amount of food present, but they also remove contaminants from water and concentrate them on lake floors and shorelines (Ludyanskiy et al., 1993). While zebra mussels inflict a large amount of damage through their potential to foul raw water intakes, they can also cause negative environmental impacts.

3.0 Review of Control Method #1: Chlorine Dispersal

A widely used zebra mussel control method is chlorine dispersal. This method involves dosing a zebra mussel with chlorine in order to quickly kill and remove the zebra mussel in a short period of time. Chlorine dispersal is effective in removing zebra mussels, but often requires large amounts of chlorine which then in turn harm the surrounding ecosystem and aquatic life.

3.1 Worldwide Popularity

Chlorine dispersal is the most commonly used method of zebra mussel control in Europe, Asia, and North America (Rajagopal, Van der Velde, & Jenner, 2002). Compared to other oxidizing biocides, chlorine is effective at low concentrations and against zebra mussels. The issue remains that although chlorine dispersal is impressive when attempting to reduce economic impacts related to zebra mussels, too much chlorine is released into the environment when targeting zebra mussels (Rajagopal et al., 2002).

3.2 Application to Zebra Mussels

Chemical products such as chlorine are regularly used to control or eradicate zebra mussels in pressurized irrigation pipes (Seral et al., 2012). In order to limit costs as well as harmful effects on crops or the surrounding environment, an optimum application of chlorine must be developed in order to reach maximum effectiveness. As a result, software applications for managing pressurized irrigation networks are being combined with water quality simulation modules to facilitate the dispersion of chlorine throughout all points within a pressurized irrigation network (Seral et al., 2012). One such example of this type of collaboration is between GESTAR and EPANET.

GESTAR, a computer program for hydraulic engineering in pressurized irrigation systems, has been converted to an EPANET format, which is a program used for analyzing water quality in drinking water supply networks (Seral et al., 2012). The conversion to the EPANET format has allowed for the GESTAR format network to serve as an irrigation management system that automatically regulates the concentrations of chlorine and contact times needed for each specific point in a network of pipelines and hydraulic infrastructure (Seral et al., 2012). Application dose, duration of the treatment, temperature, pH of the water, pipe materials, and the presence of organic and inorganic compounds are all accounted for in order to ensure that the application of chlorine will be effective, economical, and environmentally friendly. (Seral et al., 2012).

A shock treatment was tested in order to determine the effectiveness of the strategy. Shock treatments require individual additions of chlorine to control or eradicate zebra mussels, leading to high levels of chlorine (Seral et a., 2012). Over the course of 14 days, 100% zebra mussel mortality was achieved using a chlorine concentration of 1.00 mg/l. Chlorine decay was extremely noticeable, however, meaning that doses must be administered frequently in order to prevent chlorine levels in the pressurized network from falling below 1.00 mg/l. Preventative treatments involving the continuous application of sodium hypochlorite as well as 0.25 mg/l of chlorine were also conducted (Seral et al., 2012). Only residual chlorine concentrations below 0.25 mg/l and above 0.1 mg/l were discovered.

Although the shock treatment proved to be more effective, its use of excessive amounts of chlorine is problematic. Preventative treatments use less chlorine, but are less effective in removing zebra mussels. More research must be conducted in order to determine the optimal level of chlorine application. The results from this study should be used in order to gather information about the concentrations, mortality percentages, and contact times needed for each treatment (Seral et al., 2012). Each of these variables will be altered until the most effective, economical, and environmentally friendly application of chlorine is developed.

3.3 Intermittent vs. Pulse Chlorination

In addition to the creation of an automated chlorine dispersal system, other strategies for applying chlorine have been developed such as pulse chlorination. Intermittent chlorination has proved to be widely ineffective. 100% mortality of zebra mussels can be achieved after 588 hours of continuous chlorination of 1 mg l^{-1} (Rajagopal et al., 2003). The same concentration of chlorine applied in a cycle of 4 hours on and 4 hours off results in only 5% mortality during that period (Rajagopal et al., 2003). This disparity is also shown in Figure 4 below.

As a result, pulse chlorination has been developed. This is a zebra mussel control method in which chlorination is resumed just before a zebra mussel begins to feed following a previous bout of chlorination (Rajagopal et al., 2003). By immediately dispersing chlorine just before the zebra mussel needs to feed, zebra mussels experience the total period as continuous chlorination, even though it is actually still intermittent chlorination (Rajagopal et al., 2003). This control method increases the effectiveness of chlorine dispersal while also reducing the amount of chlorine used along with the economic and environmental impacts resulting from greater doses of chlorine.

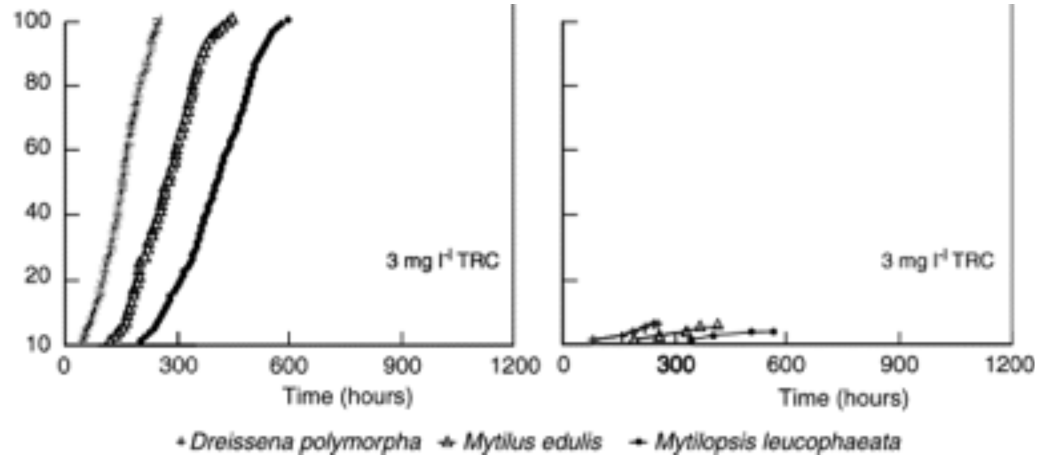

Figure 4: Effectiveness of continuous and intermittent chlorination. Figure 4 shows three different tests that illustrate the ineffectiveness of intermittent chlorination (on the right) as compared to continuous chlorination (on the left) using a concentration of 1mg/l of chlorine over 100 hours. The y-axis represents the percentage of zebra mussel mortality.

3.4 Negative Environmental Impacts

There is growing environmental concern regarding the discharge of chlorinated water into aquatic environments. Despite the effectiveness of chlorine at low levels, the presence of trihalomethanes in chlorinated water used to remove zebra mussels has led to increasingly strict water quality standards (Rajagopal et al., 2002). Chlorine dispersal can also lead to the formation of haloacetonitriles, halophenols, and bromochloromethanes. Each of these highly volatile compounds is especially concerning due to their toxicity towards aquatic life. (Allonier, Khalanski, Bermond, & Camel, 2000).

3.5 National Water Quality Standards

As stated by the U.S. Environmental Protection Agency (EPA), chlorine can have a negative effect upon humans and animals. For humans, drinking water concentrations of greater than 90 parts per million of chlorine cause irritation of throat and mouth membranes (Office of Pollution Prevention and Toxics [PPT], 1994). Chlorine has high acute toxicity to aquatic organisms as many toxicity values are less than or equal to 1 milligram. For example, brook trout has a 48 hour toxicity value of 0.1 to 0.18 milligrams per liter (PPT, 1994). This low value highlights the tremendous amount of damage inflicted upon aquatic species by chlorine. A small sample of chlorine has the ability to kill or severely hinder many aquatic species within a time-frame of just one or two days as indicated by the toxicity value (PPT, 1994).

The severe environmental impact of chlorine dispersal upon aquatic species has forced the EPA to create standards in relation to the amount of chlorine allowed in the environment. The permissible exposure limit is 1 part per million or 3 milligrams as described in the Clean Air

Act of 1990. (PPT, 1994). These high exposure ceilings have allowed the destruction of environmental ecosystems and aquatic species to take place at an alarming rate in favor of reducing the economic impacts tied to zebra mussels. Emphasis continues to be placed on zebra mussel removal effectiveness and cost, rather than environmental impact.

3.6 Cost

Growing demands for more effective chlorine distribution methods are not only spurred on by negative environmental impacts, but also economic costs. Surface water dependent drinking water treatment and electric power generation facilities in North America have continuously dealt with rising costs related to zebra mussel removal via chlorination. Facilities that used less than one million gallons of water per day spent an average of $26,618 on chemical treatment consisting of chlorination from 1989-2004. The costs rose to $64,736 for facilities that used more than 11 million gallons of water per day (Connelly et al., 2007).

The total average cost when combining all the drinking water treatment and electric power generation facilities in North America reaches $29,506,932 (Connelly et al., 2007). Despite its wide availability and use, chlorine is an expensive zebra mussel control method that, when used inefficiently, is even more detrimental to the long-term success of water reliant facilities. Effective chlorine dispersal methods are crucial since they have the ability to lower economic and environmental impacts related to the purchase and release of excess chlorine.

4.0 Review of Control Method #2: Toxin Encapsulation

Toxin encapsulation is a relatively new zebra mussel control method that has only been used for a decade. This zebra mussel control method involves the creation of a Biobullet, which contains an active ingredient that is toxic to a zebra mussel. The Biobullet is covered with edible particles so that the zebra mussel ingests the toxins and is quickly killed.

4.1 Frequency of Use

Introduced in 2003 by Cambridge University lecturers Dr. David Aldridge and Dr. Geoff Moggridge, the zebra mussel control method of toxin encapsulation via the use of a biobullet is a relatively new idea (Aldridge et al., 2006). Due to their high levels of mortality and quick dissolving nature, the popularity of the Biobullet will continue to spread to all zebra mussel infested waters. The ability of Biobullets to overcome the limitations of chlorine in relation to high costs and environmental impacts has led to extremely high rates of success in treating mussel fouling of UK drinking water treatment plants (Aldridge & Moggridge, 2011).

As a result, Biobullets have been licensed by the UK Drinking Water Inspectorate as a potential method by which to remove zebra mussels from water reliant facilities within the UK (Aldridge & Moggridge, 2011). Aldridge and Moggridge hope to build off this success and branch off into new markets dealing with the issue of zebra mussels.

4.2 Description of Biobullets

Toxin encapsulation is the other zebra mussel control method that this research will evaluate and analyze. The Biobullet is one way in which toxin encapsulation is used to effectively kill zebra mussels. This approach involves the microencapsulation of an active ingredient that is toxic to zebra mussels, but covered with particles that are edible to zebra mussels (Aldridge et al., 2006). By encapsulating the toxins with normally edible materials, Biobullets have the potential to overcome the rejection and valve-closing response generally seen when zebra mussels are exposed to toxic substances (Aldridge et al., 2006). This process is also described below in Figure 5.

Figure 5: Process of Toxin Encapsulation. Figure 5 uses images to describe the benefits of and steps involved in toxin encapsulation via Biobullets. The figure also includes a graph emphasizing the superior effectiveness of encapsulated active ingredients as opposed to non-encapsulated active ingredients.

Zebra mussels are extremely efficient filter feeders capable of processing water at rates as high as 600 milliliters per hour while ingesting particles such as algae in the size range of 5–35 micrometers (Costa et al., 2011). Therefore, Biobullets must be the appropriate size in order to allow the zebra mussels to actively filter the edible materials from the water column, concentrating the toxins within themselves (Costa et al., 2011).

4.3 Constructing a Biobullet

Before a Biobullet is put together, the active ingredient included in the encapsulated particle must first be chosen. A number of different active ingredients can be used due to the effectiveness associated with toxin encapsulation (Aldridge & Moggridge, 2011). Since Biobullets have the ability to enter a zebra mussel via ingestion, their ability to kill the zebra mussel is very high. One of the most commonly used active ingredients is potassium chloride, which interferes with membrane integrity, respiration, and the gill activity of zebra mussels (Aldridge et al., 2006). This is particularly harmful when considering the low body fluid concentrations of zebra mussels. Any ingredient that is toxic to zebra mussels can be used in order to achieve maximum zebra mussel mortality (Aldridge et al., 2006). Biobullets are created using a spray drying process. A premix slurry containing the encapsulate and active ingredient is prepared. The premix is then pumped into an ultrasonic atomizing nozzle at the top of a cooling chamber. When cooling, these atomized particles then form perfect spheres and fall to the bottom of the cooling chamber. More cooling takes place before the particles are released via a cyclone to a fluid bed processor. (Aldridge et al., 2006). After the particles are coated with nonionic surfactant to increase movement in water, they are then cooled once more in the fluid bed in order to remove all heat from the encapsulated particles (Aldridge et al., 2006). A close-up of finished Biobullets can be seen in Figure 6.

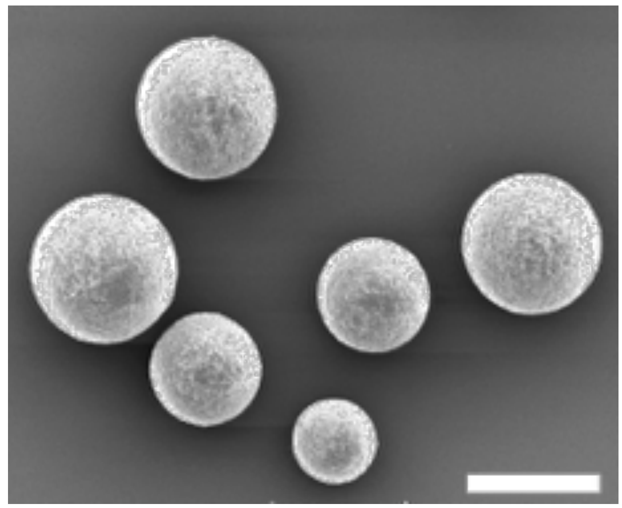

Figure 6: Close-up of Biobullets. Figure 6 is a scanning electron micrograph (SEM) of Biobullets. The scale is set to 100 micrometers.

4.4 Zebra Mussel Mortality

Aldridge and Moggridge, the two founders of the Biobullet, conducted a test in which they compared two formulations of microencapsulated active ingredients on fouled pipes in an irrigation system in Mora La Nova, Spain. One product consisted of a concentration of 150mg/l, while the second product had a concentration of 30mg/l. These two products have regulatory approval for use in UK drinking water supplies (Aldridge & Moggridge, 2011). The two products were dosed along two different supply lines for eight hour periods on two consecutive days. The active ingredient in the first product with a concentration of 150mg/l was a quaternary ammonium compound. The second was a salt-based product known to be toxic to zebra mussels (Aldridge & Moggridge, 2011).

The second concentration of active ingredients measured at 30mg/l achieved 100% zebra mussel mortality three days after releasing the Biobullets into the water. The first concentration of 150mg/l yielded 100% mortality four days after dosing ceased. In each case, the same result was reached with only minimal differences in the time it took for each concentration to obtain 100% mortality (Aldridge & Moggridge, 2011). There was also no size selectivity in the zebra mussels that were killed, emphasizing the notion that Biobullets could be used to control all zebra mussel populations. Zebra mussels within the pipe dosed with 150mg/l ranged in length from 8 to 27 mm while the second pipe dosed with 30mg/l showed different sizes of zebra mussels ranging from 8 to 28 mm (Aldridge & Moggridge, 2011). Despite the differences in size, all zebra mussels were killed in a similar time period.

Although both trials highlighted the success of Biobullets in quickly eliminating zebra mussels regardless of size, a different study involving the active ingredient potassium chlorine achieved 60% mortality following a 12 hour dosing of Biobullets. An additional 12 hour dosing raised the mortality rate to 84% (Aldridge et al., 2006). 100% mortality was reached after two days following the two separate dosings. This study points out the small variability in the time it takes to kill all zebra mussels depending on the active ingredient used. More effective active ingredients have a higher mortality rate within a shorter period of time.

Annual implementation of Biobullets would in turn then lead to the steady decline of zebra mussel populations that continue to threaten water reliant facilities across the world. Supported by their ability to remove any zebra mussels within a short period of time, Biobullets can serve as a viable control method for zebra mussels in any location.

4.5 Environmental Impact

The idea of self-ingestion of toxins through Biobullets is extremely beneficial when considering economic and environmental costs. Biobullets offer a viable alternative to chlorination since they only require one treatment instead of continuous or intermittent dosing which leads to increased environmental and economic impacts (Aldridge et al., 2006). While chlorine dispersal doses the water directly, Biobullets use nontoxic active ingredients that do not support the production of trihalomethanes as seen with chlorine (Aldridge et al., 2006).

The fact that Biobullets use a zebra mussel's impressive filtering ability to place a toxin deep within a zebra mussel dramatically reduces the amount of a toxin required and increases the possibility of employing less expensive toxins that might have otherwise been deemed ineffective as a result of a zebra mussel's valve closing response (Costa et al., 2011). Biobullets emphasize the efficiency of toxin encapsulation at controlling zebra mussels with relation to high mortality, cost, and the minimization of environmental impact.

Aside from the effectiveness of Biobullets in maximizing zebra mussel removal effectiveness while also limiting environmental impact, Biobullets have a small impact on the survival rate of other filter feeders. The impact of Biobullets on nontarget biota was assessed by exposing unionid mussels to Biobullets (Aldridge et al., 2006). 120 unionid mussels were placed within 12, 500ml aquariums dosed with Biobullets at the same concentration used to measure the effectiveness of Biobullets in removing zebra mussels. 12 other aquariums without Biobullets were used as a control method. After 7 days of exposure, no unionid mussel in either the experimental or control aquariums died (Aldridge et al., 2006).

Known for being some of the most sensitive filter-feeding organisms, the unionid mussels were not impacted by the amount of potassium chloride within the Biobullets (300 mg/l). The negative impact was nonexistent due to the fact that potassium chloride is particularly toxic to zebra mussels. The same amount of potassium chloride also produced no mortality in mosquitofish or snails despite the fact that they were exposed to concentrations of potassium chloride that caused severe mortality in zebra mussels (Aldridge et al., 2006). The microencapsulation of Biobullets allows for low doses of potassium chloride since its effectiveness is being maximized by the zebra mussel's filtration system which ingests the toxins deep within the zebra mussel itself.

Although the Biobullets were ingested by the unionid mussels in the experiment, there was no mortality among the unionid mussels as a result of their low toxicity to potassium chloride. Potassium chloride was chosen as the active ingredient within the Biobullet due to the fact that potassium chloride is highly toxic to zebra mussels. As a result of the zebra mussel's efficient filtration system that allows Biobullets to go deep within a zebra mussel, the dose of each active ingredient can be minimized. This leads to a combination of low doses of active ingredients along with the flexibility of being able to use numerous different active ingredients with varying levels of toxicity as a result of the structure of a Biobullet. Both of these factors ensure that the impact of Biobullets on nontarget filter feeders is practically non-existent.

4.6 Cost

The exact cost of Biobullets is difficult to measure due to the ability to use numerous different active ingredients within the encapsulate known as a Biobullet. More expensive and toxic ingredients have the ability to speed up the time it takes to reach 100% zebra mussel mortality. It is clear, however, that the production of Biobullets is less expensive than chlorine dispersal. The main issue with chlorine dispersal is the ion hypochlorite. This ion is expensive and hazardous to transport, store, and handle (Aldridge et al., 2006). Hypochlorite can cost upwards of $1,500 per ton (Aldridge et al., 2006). This high cost is extremely problematic when dealing with large zebra mussel populations that require constant chlorination.

As the most common form of zebra mussel control, chlorine dispersal is well-known across most countries. Biobullets serve as a cost-effective alternative that was developed in order to defray the immense costs brought about by the zebra mussel invasion. In North America alone, zebra mussels are estimated to cost the nuclear power plant industry $1-5 billion each year (Aldridge et al., 2006). The introduction of Biobullets will serve as a cost-effective alternative to chlorine and minimize the high costs associated with zebra mussels despite the common use of chlorine to control zebra mussels.

5.0 Zebra Mussel Control Method Comparison and Recommendation

The zebra mussel control methods of chlorine dispersal and toxin encapsulation will be compared on the assets of zebra mussel removal effectiveness, economic cost, and environmental impact. These characteristics are crucial when attempting to determine the success, affordability, and sustainability of a zebra mussel control method. The best control methods will take into account all three categories.

5.1 Zebra Mussel Removal Effectiveness

A high zebra mussel mortality rate is the key goal for each zebra mussel control method. Enhanced effectiveness in removing zebra mussels results in greater use among facilities attempting to eliminate zebra mussels. There are four methods in which chlorine can be applied to zebra mussels. The use of an automated irrigation management system via GESTAR and EPANET reaches 100% zebra mussel mortality in 14 days using a chlorine concentration of 1.00 mg/l (Seral et al., 2012). Intermittent chlorination involves applying doses of chlorine for four hour periods at a time. Applying chlorine in a cycle of four hours on and four hours off resulted in just 5% zebra mussel mortality after 588 hours or 24.5 days (Rajagopal et al., 2003). Continuous chlorination consists of constantly dosing zebra mussels with chlorine. In 588 hours, continuous chlorination reached 100% zebra mussel mortality (Rajagopal et al., 2003). Finally, pulse chlorination disperses chlorine shortly before a zebra

Chlorine Dispersal Method	**100% Zebra Mussel Mortality**
Automated Irrigation Management System	14 Days
Intermittent Chlorination	490 Days
Continuous Chlorination	24.5 Days
Pulse Chlorination	24.5 Days
Toxin Encapsulation Method	**100% Zebra Mussel Mortality**
Biobullets	3-5 Days

Figure 7: Summary of Zebra Mussel Removal Effectiveness. Figure 7 provides a comparison between chlorine dispersal and toxin encapsulation with regards to their effectiveness in removing zebra mussels.

mussel begins to feed, resulting in the experience of continuous chlorination despite the fact that 50% less chlorine is used as compared to continuous chlorination (Jenner, Whitehouse, Taylor, & Khalanski, 1998).

Toxin encapsulation via Biobullets has experienced tremendous success as compared to chlorine dispersal. Since the concentrated structure of a Biobullet allows for the direct injection of toxins inside a zebra mussel, the toxins are more effective in a short amount of time. A concentration of 30mg/l of active ingredients results in 100% zebra mussel mortality in three days (Aldridge & Moggridge, 2011). Changes in the concentrations of active ingredients only minimally affect the time needed to reach 100% zebra mussel mortality by a few days.

From the data presented and summarized in Figure 7 above, toxin encapsulation through the use of Biobullets is far more effective in achieving a high zebra mussel mortality rate within a short period of time. Being able to remove zebra mussels quickly is extremely beneficial to facilities that experience reduced efficiency as a result of zebra mussels impeding the flow of water to intake pipes. Toxin encapsulation is able to effectively eliminate zebra mussels within a 3-5 day period while chlorine dispersal requires upwards of two weeks. This fact supports the recommendation that toxin encapsulation should be used to achieve a high zebra mussel mortality rate as soon as possible.

5.2 Economic Cost

In addition to having the ability to effectively remove zebra mussels in a limited amount of time, successful zebra mussel control methods must also be affordable. The zebra mussel invasion in North America has caused millions of dollars in damages. As a result, the most cost-effective zebra mussel control method needs be used in order to minimize already high costs brought about by zebra mussels. Surface water dependent drinking water treatment and power generation facilities in North America that use less than one million gallons of water per day have spent an average of $26,618 on chemical treatment consisting of chlorination from 1989-2004. Those costs rose to $64,736 for facilities that used more than 11 million gallons of water per day (Connelly et al., 2007). From 1989-2004, the combined total cost of chlorination for all drinking water treatment and power generation facilities in North America skyrockets to $29,506,932 (Connelly et al., 2007). These high costs only add to the continued negative economic impact introduced by zebra mussels.

The structure of Biobullets allows for toxin encapsulation to be a much more cost-effective zebra mussel control method. Biobullets can hold almost any active ingredient that is toxic to zebra mussels (Aldridge & Moggridge, 2011). This flexibility enables cheaper toxins to be used depending on how quickly zebra mussels need to be removed. The edible particles surrounding a Biobullet also make it easier to use extremely deadly toxins that a zebra mussel would otherwise reject via its vale-closing response (Aldridge et al., 2006). The ability of a Biobullet to travel deep within the digestive system of a zebra mussels also increases the effectiveness of the toxins used (Aldridge et al., 2006). Although determining the costs of Biobullets is difficult as a result of its limited use, the flexibility and increased effectiveness offered by a Biobullet makes it easy to create a cost-effective Biobullet.

The data presented in this section indicates that toxin encapsulation is superior to chlorine dispersal when examining cost. Although chlorine dispersal has been widely used, the recent introduction of Biobullets has proven to be a zebra mussel control method that is more lethal to zebra mussels, but also less expensive. Chlorine dispersal is a rigid control method that involves the spread of chlorine while toxin encapsulation allows consumers to choose different toxins in order to balance cost. The flexibility and effectiveness of Biobullets through toxin encapsulation overcomes the traditional use of chlorine when considering cost.

5.3 Environmental Impact

Environmental impact is another key characteristic to consider when examining zebra mussel control methods. Although it is important to eliminate zebra mussels, doing so in an irresponsible manner can lead to severe environmental impacts. Chlorine dispersal in particular can lead to the formation of trihalomethanes, haloacetonitriles, halophenols, and bromochloromethanes. Each of these compounds are highly toxic and can negatively impact almost any aquatic species (Allonier et al., 2000). Chlorine itself has a high acute toxicity to aquatic organisms and can kill or severely hinder many aquatic species in just one or two days (PPT, 1994). In fact, the EPA attempted to limit the severe environmental impacts of chlorine by establishing an exposure limitation of 1 part per million or 3 milligrams as described in the Clean Air Act of 1990 (PPT, 1994).

Toxin encapsulation inflicts much less environmental damage due to its ability to place toxins within zebra mussels. Toxin encapsulation allows for the concentration of toxins, but also expands the type of toxins used in order to employ more water soluble products that would normally be rejected by a zebra mussel's valve closing response (Aldridge et al., 2006). Toxin encapsulation can use active ingredients that are designed to rapidly degrade and disperse before entering the water and after being ingested by the zebra mussel, thereby minimizing the pollution of the surrounding ecosystem (Aldridge et al., 2006).

Another benefit of toxin encapsulation is its minimal impact on other filter feeders in the surrounding environment. A Biobullet allows for the selection of numerous active ingredients that are all highly toxic to zebra mussels, but harmless against other filter feeders in low doses (Aldridge et al., 2006). Since a Biobullet is ingested by a zebra mussel, it is extremely effective. This means that only low doses of active ingredients are required in order to remove zebra mussels. Even if a Biobullet were to be ingested by a filter feeder other than a zebra mussel, the low doses of active ingredients within a Biobullet combined with the toxicity of the active ingredient to zebra mussels specifically ensures that other filter feeders will not be negatively influenced by Biobullets in their surrounding environment.

The information concerning the environmental impacts of chlorine dispersal and toxin encapsulation clearly reveals the fact that toxin encapsulation is much better at minimizing negative environmental impacts. Chlorine is notoriously toxic. Continuous chlorination places aquatic life at risk. The environmental impacts were so severe that the EPA intervened. Toxin encapsulation provides the flexibility to use environmentally friendly toxins that dissolve quickly. The data analyzed supports the belief that toxin encapsulation should be used in the place of chlorine dispersal when attempting to limit negative environmental impacts.

6.0 Conclusion

After first being observed in North America in 1988, zebra mussels have spread rapidly through waterways in Canada and the U.S., reaching densities as high as 750,000 in some regions of the Great Lakes (MacIsaac, 1996). This has led to massive economic costs for water reliant facilities that are experiencing decreased efficiency as a result of impeded water flow. To alleviate this high economic cost, zebra mussel removal methods are being developed in order to minimize the zebra mussel population along with the negative economic effects that accompany them. Two such zebra mussel removal methods are chlorine dispersal and toxin encapsulation. Chlorine dispersal periodically doses zebra mussels with chlorine, thereby exposing zebra mussels to the harmful ion hypochlorite. The problem with chlorine dispersal is that large amounts of chlorine must be distributed for extended periods of time in order to achieve 100% zebra mussel mortality. This leads to high costs and negative environmental impacts as a result of the highly toxic nature of chlorine.

Toxin encapsulation is another zebra mussel control method that uses Biobullets. Toxin encapsulation can reach 100% zebra mussel mortality within a few days while also using water soluble active ingredients that dissolve quickly upon entry into the water. This rapid dispersal aids in reducing environmental impacts resulting from chlorine dispersal. Biobullets also have the ability to hold any active ingredient that is toxic to zebra mussels, allowing for flexibility that can lead to decreased removal costs. Finally, Biobullets monopolize the filtration abilities of zebra mussels to place toxins deep inside zebra mussels, thereby increasing the effectiveness of any toxin used. As a result of its ability to achieve 100% zebra mussel mortality more quickly, minimize economic costs, and reduce environmental impacts, toxin encapsulation is a better zebra mussel control method than chlorine dispersal and should take the place of chlorine dispersal as the most widely used zebra mussel control method.

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