UDK: 628.312.5:677

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PRISUSTVO TEKSTILNIH MIKROPLASTIČNIH VLAKANA U OTPADNIM VODAMA I NJIHOV UTICAJ NA ŽIVOTNU SREDINU

The presence of textile microplastic fibers in the wastewater and their impact on the environment

IZVOD

Prisustvo sintetičkih mikroplastičnih vlakana (MPF) otkriveno je u različitim vodenim ekosistemima širom sveta. Mikroplastična vlakna u otpadnoj vodi uglavnom potiču iz veša koji se pere u veš mašinama, a najčešće uključuju sintetičke materijale poput poliestera, akrila, najlona itd. Mali broj studija se bavio ispitivanjem prisustva mikroplastičnih vlakana u otpadnim vodama, kao i o metodama izolovanja mikroplastike iz vode koja se ispušta iz domaćinstava, odnosno iz mašina za pranje i sušenje veša. Stoga, javlja se sve veće interesovanje naučne i stručne javnosti u pogledu budućeg istraživanja ovog fenomena. U ovom radu dat je pregled literature o količini, vrsti i oblicima mikroplastičnih vlakana u otpadnim vodama poreklom iz uređaja za pranje veša, kao i problemima koji nastaju njihovim ispuštanjem u životnu sredinu. Na osnovu dostupnih informacija, zaključeno je da se sintetička mikroplastčna vlakna mogu detektovati u vazduhu, zemljištu, slatkovodnim ekosistemima, okeanima itd., što predstavlja značajan ekološki problem čak i u minimalnim koncentracijama. Dostupna literatura takođe naglašava važnost u pogledu sprovođenja dodatnih istraživanja na temu optimizacije tehnologija za uklanjanje mikroplastike u postrojenjima za prečišćavanje otpadnih voda.

Ključne reči: mikroplastika, sintetička vlakna, mašina za pranje veša, otpadne vode

ABSTRACT

The presence of synthetic microplastic fibers (MPFs) has been detected in various aquatic ecosystems around the world. The microplastic fibers are mainly generated from domestic and commercial laundering, from the washing machine, and they most often include synthetic materials such as polyester, acrylic, nylon, etc. However, only a few studies have focused on examining the presence of microplastic fibers in wastewater, as well as on methods of isolating microplastics from water discharged from households, ie from washing and drying machines. Therefore, there is a growing interest of the scientific and professional community for future research. This paper provides an overview of the literature on the amount, type and forms of microplastics laundry fibers in household wastewater, as well as the problems arising from their release into the environment. Based on the available information, it was concluded that synthetic microfibers can be detected in various matrices such as the atmosphere, soil, fresh water, oceans, etc., posing a significant environmental problem even in minimal concentrations. All this requires additional research in terms optimizing the technologies for microplastic removal in wastewater treatment plants.

Keywords: micropastics, synthetic fibers, washing machine, wastewater

1. UVOD

Plastika je kao materijal postala sveprisutna zbog svoje jeftine cene, izdržljivosti i jednostavne obrade tokom proizvodnje plastičnih proizvoda. Dodatno, u isto vreme plastika izaziva zabrinutost jer njena proizvodnja, upotreba i odlaganje potencijalno predstavlja rizik po životnu sredinu i zdravlje ljudi. Plastika se proizvodi od petrohemijskih jedinjenja, često u kombinaciji sa aditivima kao što su punila, plastifikatori, boje, stabilizatori, maziva i sredstva za penjenje. Približno 30% ukupno proizvedene

1. INTRODUCTION

Plastics have become ubiquitous because they are cheap, durable and easily adaptable to the production of many plastic products, but at the same time there is a growing concern that the production, use and disposal of plastics may pose a risk to the environment and human health. Plastics are made from petrochemical compounds, usually in combination with additives such as fillers, plasticizers, dyes, stabilizers, lubricants and foaming agents (*Cole et al., 2011*). Approximately 30% of the total plastic

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plastike je još uvek u upotrebi, a plastika koja se ne koristi, dospeva u različite vodene sisteme kao otpad. Plastični otpad može biti u obliku malih čestica poznatih kao mikroplastika (MP) (*Cole i dr., 2011*). Pojam mikroplastika prvi put je upotrebljen nakon istraživanja u morskim ekosistemima, ali je ubrzo ustanovljeno njeno prisustvo i u slatkovodnim i kopnenim ekosistemima, kao i u gradskoj prašini (*Thompson i dr., 2004; Horton i dr., 2017; Dehghani i dr., 2017*).

Mikroplastiku čine plastične čestice manje od 5 mm koje se prema poreklu dele na „primarnu" i „sekundarnu" mikroplastiku. Primarne mikroplastične čestice se direktno ili kao prekursori upotrebljavaju za proizvodnju drugih plastičnih proizvoda, dok „sekundarna" mikroplastika nastaje raspadanjem većih plastičnih materijala u životnoj sredini (*De Falco i dr., 2020*).

Jedan od najčešćih izvora mikroplastike u životnoj sredini su komunalne otpadne vode koje, između ostalog, sadrže mikroplasična vlakna poreklom iz tekstila i proizvoda za ličnu negu (*Sillanpaa i Sainio, 2017*). Sintetička mikroplastična vlakna (*eng. Microplastics fibers*-MPFs) su plastične niti veličine manje od 5 mm poreklom iz različitih materijala, odeće, automobilskih guma, mreže za pecanje, opušaka od cigareta, patosnica, kravata, čipke itd. (*Mishra i dr., 2019*). Do 60% ukupno proizvedenog tekstila je sintetičkog porekla, pri čemu se najčešće vrste polimera koriste poliester, akril i najlon (*Barrows i dr., 2018*). Rana istraživanja pokazuju da se čak 35% čestica mikroplastike iz domaćinstava ispušta u životnu sredinu, a većina potiče od tekstila. Sintetička vlakna su uobičajena u otpadnim vodama i komunalnim otpadnim vodama, a dokumentovana su i u urbanim područjima u blizini postrojenja za prečišćavanje otpadnih voda.

Sintetička mikroplastična vlakna se pored toga što su detektovana u otpadnim vodama i komunalnim otpadnim vodama, mogu pronaći i u urbanim područjima u blizini postrojenja za prečišćavanje otpadnih voda. Sintetička mikroplastična vlakna detektovana su u vazduhu, zemljištu i vodenim ekosistemima. U domaćinstvu sintetička mikroplastična vlakna čine oko (70%) tekstila - uglavnom poliester (28%) i najlon (23%) (*Beton i dr., 2014*). Poliester se često koristi u kombinaciji sa drugim vlaknima, poput pamuka od kog se prave bluze i košulje. Zbog svoje sveprisutnosti i niske cene, upotreba poliestera izazvala je trend „brze mode", koji se temelji na jeftinoj proizvodnji, trendovima koji se brzo menjaju i kraćem veku trajanja tekstilnih proizvoda. Kao posledica ovakvog trenda, tekstilni proizvodi postaju otpad u vrlo kratkom vremenskom periodu (*Niinimaki i dr., 2020*). Sa druge strane, najlon (poliamid) se uglavnom koristi za pletenu odeću, poput čarapa i donjeg veša, kao i za tehničke tkanine

produced is still in use, and plastic that is not in use, mainly in the form of waste, reaches marine and other water systems. A proportion of this plastic waste is in the form of small particles known as microplastics (MPs) (*Freeman et al., 2020*). Microplastic pollution has nowadays become a topic of emerging concern. The term microplastic first came into popular use following research in the marine environment but it was quickly noticed that microplastics are also present in freshwater and terrestrial systems, as well as urban dust (*Thompson et al., 2004; Horton et al., 2017; Dehghani et al., 2017*).

Microplastics are defined as plastic particles smaller than 5 mm and are further divided, based on their origin, as "primary" and "secondary" microplastics. Primary microplastics are plastic particles which are intentionally produced either for direct use or as precursors to other products, and "secondary" microplastics if they are formed in the environment from the breakdown of larger plastic materials (*De Falco et al., 2020*).

One of the most common sources of microplastics in the environment are municipal wastewaters containig, among other, textile fibers and personal care products (*Sillanpää and Sainio, 2017*). Synthetic microplastic fibers (MPFs) are tiny plastic threads of various textiles including clothes, tires, fishing nets, cigarette butts, floor mats, tie and lace, having a diameter less than 5 mm widely distributed in the environment (*Mishra et al., 2019*). Up to 60% of textiles produced globally are synthetic, with the main polymers used being polyester, acrylic and nylon (*Barrows et al., 2018*). Early global estimates indicate that as much as 35% of microplastics from households are released into the environment, and most of them come from domestic textile laundry. Synthetic fibers are common in wastewater and municipal wastewater and have been documented in urban areas near wastewater treatment plants.

Synthetic microfibers have been found in various environmental matrices, such as air, land, rivers, lakes and oceans. Synthetic microfibers have been found in various environmental matrices such as air, soil, rivers, lakes and oceans. In the household, synthetics make up around (70%) of textiles – mainly polyester, (28%), and nylon (23%) (*Beton et al., 2014*). Polyester is often used in blends with other fibers, such as cotton which is often used in blouses and shirts. Due to its versatility and low price, the use of polyester has induced the fast fashion trend, which is based on cheap manufacturing, fast-changing trends and shorter lifetimes of textile products, which is why they are becoming waste in a very short time (*Niinimäki et al., 2020*). On the other hand, nylon (polyamide) is mainly used for knitted apparel, such as hosiery and underwear, and for technical woven fabrics including airbags, ropes and carpets. Carpet manufacturing accounts for about 17% of global uključujući vazdušne jastuke za automobile, užad i tepihe. Oko 17% ukupne upotrebe najlona koristi se za proizvodnju tepiha. Međutim, direktno poređenje studija o oslobađanju ovih vlakana u životnu sedinu je teško zbog nedostatka standardnih metoda za praćenje njihovog oslobadjanja kao i izveštavanje podataka (*Cesa i dr., 2020; Freeman i dr., 2020*).

Cilj ovog rada je pregled prisustva sintetičkih mikroplastičnih vlakana u otpadnim vodama koja potiču od pranja veša, kao i njihov potencijlni uticaj na životnu sredinu.

2. PRISUSTVO MIKROPLASTIKE IZ TEKSTILA U VODI

Mikroplastčna vlakna koja ulaze u vodene ekosisteme predstavljaju skup vlakana koji se razlikuju po morfologiji i hemijskom sastavu. Kao posledica ljudske aktivnosti dospevaju u vodene ekosisteme direktnim ili indirektnim putem (npr. bacanjem ribolovnog pribora, mazanjem čamaca i brodova kako bi izbegli koroziju i prljavštinu itd.) Na ovaj način se ispušta značajna količina MPFs-a koji su nastali njihovom upotrebom i odlaganjem. Ovaj ekološki problem ima veliki uticaj, s obzirom na efikasan doprinos pranja odeće od sintetičkog tekstila. Sintetička vlakna koja se koriste u proizvodnji odeće bez ikakve dalje obrade, smatraju se primarnim mikrovlaknima. Sa druge strane, sekundarna mikrovlakna predstavljaju fragmente koji nastaju od velikih primarnih komada tekstila proizvedenih u tekstilnoj i odevnoj industriji (*Mishra i dr., 2020*).

2.1. Vrsta i količina mikroplastike iz tekstila u vodenim ekosistemima

Mikroplastika koja dospeva u vodene sisteme može se taložiti u vidu suspendovanih čestica, u zavisnosti od njene gustine, sastava i oblika. Gustina mikroplastike može se dodatno povećati njenim vezivanjem za glinu ili biotu što za posledicu ima nakupljanje mikroplastike u svim vrstama vodenih ekosistemima. Mnoge studije ukazale su na to da se najveća količina mikroplastike najčešće nalazi u urbanim i industrijskim područjima, usled intenzivnih antropogenih aktivnosti, dok se kao najčešći izvori mikroplastike navode otpadne vode, smeće i atmosfersko taloženje (*Eriksen i dr., 2013; Horton i dr., 2017; Rodrigues i dr., 2018*).

Prisustvo sintetičkih mikroplastičnih vlakana, njihova veličina, koncentracija i sastav najčešće su detektovani uzorcima morske vode što je navedeno u tabeli 1. *Mishra i dr. (2020)* ukazali su na to da do ispuštanja mikroplastičnih sintetičkih vlakana u životnu sredinu najčešće dolazi putem komunalnih otpadnih voda. Zbog mnogih prednosti sintetičkih vlakana (čvrstoća, mekoća, otpornost na mrlje, cena itd.), u poslednje dve decenije proizvodnja i potrošnja odeće značajno

nylon usage. However, direct comparison of fibers release studies is difficult due to a lack of standard methods for following fiber release and for reporting data (*Cesa et al., 2020*; *Freeman et al., 2020*).

The aim of this papir is to give an overwiew of the presence of synthetic microfibers in the wastewater from laundry washing as well as their potential impact on the environment.

2. THE PRESENCE OF TEXTILE MICROPLASTICS IN WATER

Microfibers that enter water systems are a collection of fibers that differ in morphology and chemical composition. They often deliberately enter aquatic ecosystems by human activities (for example, fishing gear, boats and ships to avoid corrosion and dirt, etc.) and are discharged directly or indirectly into the water. In this way, a huge amount of MPFs is discharged, which were created by use and disposal. This environmental problem is of great importance, considering the efficient contribution of washing clothes made of synthetic textiles. Synthetic fibers used in the production of clothing without any further processing are considered primary microfibers, and secondary microfibers are fragments of large primary microfibers produced in the textile and clothing industry (*Mishra et al., 2020*).

2.1. Type and amounts of textile microplastics in aquatic ecosystems

Microplastic released into the aquatic environment can be suspended in the water column or sink into the sediment, depending on its density, composition and shape. The density of microplastics can be further increased by its binding to clay or bio, and thus leads to sinking in all types of aquatic ecosystems. Many studies have found that the largest amount of microplastics is usually found in urban and industrial areas, where the most intense anthropogenic activities occur, and the most common sources of microplastics are wastewater, garbage and atmospheric deposition (*Eriksen et al., 2013; Horton et al., 2017; Rodrigues et al., 2018*).

The presence of synthetic microplastic fibers, their size, concentration and composition were found in many seawater samples and are listed in Table 1. According to research, the amount of microplastic fibers present in different types of microplastics was determined. The discharge of microplastic synthetic fibers from domestic sewage has recently been reported and characterized as a problem (*Mishra et al., 2020*). Due to the many advantages of synthetic fibers (strength, softness, stain resistance, price, etc.), in the last two decades, the production and consumption of clothing has been significantly linked (*Moore et al. 2011; Leslie et al. 2017; Lahens et al. 2018; Lin et al. 2018*).

su povezane (*Moore i dr., 2011; Leslie i dr., 2017; Lahens i dr., 2018; Lin i dr., 2018*).

Iako se većina studija fokusirala na karakterizaciju količine mikroplastike u okeanima, nedavne studije ukazuju na to da su slatkovodni ekosistemi zagađeni na sličnom ili većem nivou od morskog okruženja. Na primer, u Velikim jezerima, pronađeno je prosečno 43000 čestica/km^2 (*Eriksen i dr., 2013*), što premašuje količine koje se nalaze u morskim sistemima. Pored toga, reke su važan vektor za transport mikroplastike u morsko okruženje zbog čega se podrazumeva da se na ovaj način između 1,15 i 2,41 miliona tona plastike godišnje transportuje u okeane (*Lebreton i dr., 2017*). Dodatno, studije su ukazale da dnevno 6 milijardi čestica mikroplastike preko reke Dunav ulazi u Crno more, 1,9 milijardi mikroplastičnih čestica iz reke Po u Sredozemno more i 0,7 milijardi čestica iz reke Rajne u Severno more (*Van der Val, 2015*). Zbog toga je potrebno utvrditi nivo zagađenja mikroplastike u rekama i upopuniti nedostatke kada su izvori, sudbina i efekti mikroplastike u vodenim sistemima u pitanju (*Tien i dr., 2020*).

Iako primarni izvori MPFs-a još uvek nisu istraženi, pretpostavlja se da su otpadne vode, dobijene nakon pranja veša u domaćinstvima, najčešći izvor ovih čestica. Dodatno, nivo oslobađanja MPF -a zavisi od faktora kao što su tip polimera, vrsta tkanine (uključujući vlakna, predivo, tkanje i dorada), vrstu mašine za pranje veša, program pranja i vrsta deterdženta (*De Falco i dr., 2018; Cesa i dr., 2020, Vassilenko i dr., 2021*).

Štaviše, mikroplastika se u skladu sa materijalima koji se koriste u odeći redovno detektuje u visokim koncentracijama nizvodno od postrojenja za prečišćavanje vode (*Eriksen et al., 2013; Hoellein et al., 2014*) što ukazuje na to da standardna filtracija otpadnih voda nije uvek efikasna u zaustavljanju mikroplastike koja dolazi do okeanskih ekosistema. Procenjuje se da jedan sintetički odevni predmet može osloboditi približno 730.000 MPFs prilikom jednog pranja veša Nekoliko studija je predložilo različite metode za kvantifikaciju odvojenih MPF-ova. To su obično indirektne metodologije, na primer, procena količine MPFs-a na osnovu njihove težine i dužine. Međutim, tačnost ovih studija je još uvek niska, a jedinice koje se koriste za izražavanje rezultata su različite, što dodatno otežava njihovo poređenje (*Henri i dr., 2019; Vassilenko i dr., 2019*; *Jonsson i dr., 2018*).

2.2. Izvor mikroplastičnih vlakana u otpadnim vodama

Nekoliko studija ukazalo je na to da se po domaćinstvu jednim pranjem veša od 5-6 kg može osloboditi hiljade mikrovlakana u otpadne vode tokom pranja sintetičke odeće, koristeći različite postupke pranja (*Napper i dr., 2016; De Falco i dr., 2020*).

Although most studies have focused on characterizing quantities of microplastics in the oceans, recent studies indicate that freshwater ecosystems are contaminated at similar or greater levels than marine environments. For example, an average of 43 000 particles/km^2 were found in the Great Lakes (*Eriksen et al. 2013*), which exceeds quantities found in open water marine environments. Additionally, rivers are an important vector for the transport of microplastics to the marine environment, and it is implied that between 1.15 and 2.41 million tons of plastic are transported to the oceans via rivers annually (*Lebreton et al. 2017*). Additionally, research has shown that 6 billion microplastic particles from the Danube River flow into the Black Sea daily, 1.9 billion microplastic particles from the Po River into the Mediterranean Sea, and 0.7 billion particles from the Rhine River into the North Sea (*Van der Wal, 2015*). Therefore, it is necessary to determine the level of pollution of microplastics in rivers and fill gaps in knowledge about the sources, fate and effects of microplastics in water systems (*Tien et al., 2020*).

Even though primary sources of MPFs have not been yet investigated, it is extensively assumed that household laundry wastewaters are the most important source, although the level of MPF release is dependent on factors such as polymer type, fabric type (including fiber, yarn, weave and finishing), type of washing machine, washing program and type of detergent (*De Falco et al., 2018; Cesa et al., 2020, Vassilenko et al., 2021).* However, direct comparison of fiber release studies is difficult due to a lack of standard methods for testing fiber release and for reporting data (*Cesa et al., 2020*; *Freeman et al., 2020*).

Furthermore, microplastics consistent with materials used in clothing are regularly reported in high concentrations downstream of water treatment facilities (*Eriksen et al., 2013; Hoellein et al., 2014*) indicating that the standard filtration of wastewater is not always effective in stopping microplastics from domestic laundry reaching ocean ecosystems. It is estimated that a single synthetic garment can release approximately 730,000 MPFs from a single laundry wash (*Henry et al., 2019; Vassilenko et al., 2019*). Some researchers suggest that textiles are the most important source of microplastics, with discharge of 500,000 t/year, while other studies suggest that textiles are only a marginal contributor to the plastic pollution of water bodies (*Jonsson et al., 2018*). A few studies have proposed different methods to quantify detached MPFs. These are usually indirect methodologies, for example, estimating the amount of MPFs from their weight and length. However, the accuracy between these studies is still low, and the units used to express the results are different, making their comparison even more difficult..

Table 1: Koncentracije sintetičkih mikroplastičnih vlakana u uzorcima morske vode iz različitih regija (izmenjeno *Mishra et al., 2020*)

Lokacije	Veličina MPFs (mm) (dužina)	Prijavljen opseg koncetracija	Procenat mikroplastičnih vlakana u uzorcima vode (%)	Hemijska kompozicija	Reference
Severnozapadni Pacifički okean	0,5 – 2,5	$6{,}4 \times 10^{2} – 4{,}2 \times 10^{4}$ čestica km^{-2}	Nije precizirano	PE, PP i PA	*Pan et al., 2019*
Arapski poklon	Nije precizirano	$4{,}4 \times 10^{4} – 1{,}5 \times 10^{6}$ čestica km^{-2}	93,8	PE, PP i PET	*Abayomi et al., 2019*
Severozapadno Sredozemno more	1,48 ± 0,88	$6 \times 10^{3} – 1 \times 10^{6}$ čestica km^{-2}	Nije precizirano	Nije precizirano	*Schmidt et al., 2017*
Južno Kaspijsko more	0,333 - 1	34,490 čestica km^{-2}	Nije precizirano	PE i PP	*Matati et al., 2019*
Severni ledeni okean	250 - 7710	$2{,}8 \times 10^{4}$ čestica km^{-2}	95	Nije precizirano	*Lusher et al., 2015*
Severnoistični Pacifički okean	64,8 to 5810	8 to $9{,}2 \times 10^{3}$ čestica/m^{3}	75	Nije precizirano	*Desforges et al., 2014*
Istočnoazijska mora oko Japana	<500	$1{,}7 \times 10^{6}$ čestica km^{-2}	Nije precizirano	PP, PE,	*Isobe et al., 2015*
Istočnoseverni Pacifik	Nije precizirano	156,800 čestica km^{2}	Nije precizirano	Nije precizirano	*Law et al., 2014*
Severozapadni Pacifički okean	<300	60 - 2000 čestica/m^{2}	75	Nije precizirano	*Fischer et al., 2015*
Severnoistočno Sredozemno more	<5	$18{,}6 \pm 17{,}9 \times 10^{3}$ čestica/m^{3}	Nije precizirano	Nije precizirano	*Guven et al., 2016*
Severno žuto mre, Kina	<5	545 ± 282 čestica/m^{3}	39,1 ± 22,3	PE, PP	*Zhu et al., 2018*
Baltičko more, Evropa	0,3 – 0,63	0,07 ± 0,02 čestica/m^{3}	≥ 50	Nije precizirano	*Tamminga et al., 2018*
Severni Meksički zaliv	<0.1	5,0 – 18,4 čestica/m^{3}	84,6	Nije precizirano	*Mauro et al., 2017*
Severnozapadni Pacifički okean	1,56 ± 0,89	0,13 ± 0,11 čestica/m^{3}	95,9	PET, PP, PA, PE , AC	*Mu et al.,*
Centralni arktički bazen	1 – 2	0,7 čestica/m^{3}	94	PE, PET, PA, PVC	*Kanhai et al., 2018*
Severnozapadna Evropa	0,355 - 5	0-1,5 čestica/m^{3}	Nije precizirano	PET, PP, PE	*Maes et al., 2017*
Jugoistočna obala Južne Afrike	0,08 - 5	257,9 ± 53,36 -3308 ± 1449 čestica /m^{3}	90	Nije precizirano	Nel and Froneman, 2015

Table 1: Concentrations of synthetic microfibers in seawater samples from different regions of marine environment (modified *Mishra et al., 2020*)

Locations	Size range of MPFs (mm) (in length)	Reported concentrations range	Percentage of microplastic fibers in water samples (%)	Chemical composition	Reference
Northwestern Pacific Ocean	0.5 - 2.5	$6.4 \times 10^2 – 4.2 \times 10^4$ items km^{-2}	Not specified	PE, PP and PA	*Pan et al., 2019*
Arabian Bay	Not specified	4.4×10^4 - 1.5×10^6 items km^{-2}	93.8	PE, PP and PET	*Abayomi et al., 2019*
Northwestern Mediterranean Sea	1.48 ± 0.88	$6 \times 10^3 – 1 \times 10^6$ items/km^{-2}	Not specified	Not specified	*Schmidt et al., 2017*
Southern Caspian Sea	0.333 - 1	34,490 items km^{-2}	Not specified	PE and PP	*Matati et al., 2019*
Arctic Ocean	250 - 7710	2.8×10^4 items km^{-2}	95	Not specified	*Lusher et al., 2015*
Northeastern Pacific Ocean	64.8 to 5810	8 to 9.2×10^3 items/m^3	75	Not specified	*Desforges et al., 2014*
East Asian seas around Japan	<500	1.7×10^6 items km^{-2}	Not specified	PP, PE,	*Isobe et al., 2015*
Eastern North Pacific	Not specified	156,800 pieces/km^2	Not specified	Not specified	*Law et al., 2014*
Northwest Pacific Ocean	<300	60 - 2000 particles/m^2	75	Not specified	*Fischer et al., 2015*
North-eastern Mediterranean Sea	<5	$18.6 \pm 17.9 \times 10^3$ particles/m^3	Not specified	Not specified	*Guven et al., 2016*
North Yellow Sea, China	<5	545 ± 282 particles/m^3	39.1 ± 22.3	PE, PP	*Zhu et al., 2018*
Baltic Sea in Europe	0.3 - 0.63	0.07 ± 0.02 particles/m^3	≥ 50	Not specified	*Tamminga et al., 2018*
Northern Gulf of Mexico	<0.1	5.0 - 18.4 particles/m^3	84.6	Not specified	*Mauro et al., 2017*
Northwestern Pacific Ocean	1.56 ± 0.89	0.13 ± 0.11 particles/m^3	95.9	PET, PP, PA, PE & AC	*Mu et al.,*
Arctic Central Basin	1 - 2	0.7 particles/m^3	94	PE, PET, PA & PVC	*Kanhai et al., 2018*
Northwest Europe	0.355 - 5	0-1.5 particles/m^3	Not specified	PET, PP & PE	*Maes et al., 2017*
South-eastern coastline of South Africa	0.08 - 5	257.9 ± 53.36-3308 ± 1449 particles/m^3	90	Not specified	*Nel and Froneman, 2015*

Ova vlakna se zbog svoje veličine često ne mogu zaustaviti na filterima u postrojenjima za prečišćavanje otpadnih voda i i na taj način dospevaju direktno u vodovodne ekosisteme. Zbog toga se poslednjih godina javlja potreba za kvantifikacijom efekata ispuštanja mikroplastičnih vlakana vodene sisteme prilikom pranja sintetičke odeće. *Napper i Thompson (2016)* ispitivali su oslobađanje mikrovlakana iz džempera od poliestera, pamuka i akrila tokom ciklusa pranja na temperaturi od 30°C i 40°C primenom gravimetrijske metode u prisustvu i odsustvu deterdženta i omekšivača. *Hartline i dr., (2016)*, su takođe ispitivali oslobađanje mikrovlakana gravimetrijskom metodom uz procenu vrste mašine za pranje veša, tržišta i starosti odeće. Sličan pristup su koristili *Pirc i dr. (2016)*, gde se određena količina mikroplastčnih vlakana ispuštala u vodu prilikom pranja poliesterskih ćebadi u prisustvu i odsustvu detrdženta i omekšivača. Ove studije su sprovedene radi procene uticaja nekoliko parametara (kao što je uloga praha i gorionika u procesima, omekšivača, izbeljivača i parametara poput tvrdoće vode, temperature i mehaničkih svojstava) na oslobađanje mikroplastike iz sintetičkih vlakana tokom pranja. Da bi se postigao ovaj cilj, razvijena je nova procedura za utvrđivanje na koji način dolazi do oslobađanja mikrovlakana tokom ovog procesa u domaćinstvima. Ovaj postupak se sastoji od filtriranja vode dobijene ispiranjem čestica koje nastaju i analize filtera skenirajućom elektronskom mikroskopijom (SEM). Na ovaj način je dobijena direktna kvantifikacija broja i dimenzija oslobođenih mikroplastičnih vlakana (*Napper i Thompson, 2016; Hartline i dr., 2016; Pirc i dr., 2016; De Falco i dr., 2018*).

3. UTICAJ MIKROPLASTIKE IZ TEKSTILA U ŽIVOTNOJ SREDINI

Pod uticajem različitih hemijskih i fizičkih faktora, dejstvom abrazije i fotodegradacije, plastični polimerni materijali se fragmentacijom raspadaju na manje komade plastike koje je teško analizirati (*Bouvmeester i dr., 2015*). Plastika je generalno otporna na biorazgradnju, ali se nova istraživanja zasnivaju na stvaranju enzima koji imaju dovoljno veliki kapacitet razgradnje polimera, kao što je na primer polietilen tereftalat, oblik poliestera. Zbog činjenice da je ova oblast nedovoljno istražena, velika količina mikroplastičnih vlakana je i dalje u životnoj sredini i tu se akumulira godinama i vekovima.

Ispuštanjem otpadnih voda koje nastaju pranjem odeće iz domaćinstava, mikroplastična vlakna dospevaju u reke, a samim tim i u organizme koji naseljavaju vodene sisteme i često zamenjuju hranu sitnim mikroplastičnim česticama. Slika 1 pokazuje da je oslobađanje mikroplastičnih vlakana podeljeno na nekoliko tačaka u lancu dospevanja tekstila do životne sredine kao i da može uticati na zdravlje

2.2. The source of microplastic fibers in wastewater

Several studies have investigated the release of microfibers to wastewater from the washing of synthetic clothes, using different washing procedures, and estimated that thousands of microfibers could be released by a single household wash of 5– 6 kg (*Napper et al., 2016; De Falco et al., 2020*).

Due to their size, these fibers can stop on filters in wastewater treatment plants and thus reach aquatic ecosystems. Therefore, in recent years, there has been a need to quantify the effects of microfiber release into the water system when washing synthetic garments. *Napper and Thompson (2016)*, examined the release of microfibers from sweaters made of polyester, cotton and acrylic, during the household wash cycle at a temperature of 30° and 40° using the gravimetric method in the presence and absence of detergent and softeners. *Hartline et al. (2016),* also examined the release of microfibers by gravimetric method with the assessment of the type of washing machine, market and age of clothes. A similar approach was used by *Pirc et al. (2016),* where a certain amount of microfibers is released into the water when washing polyester blankets in the presence and absence of crackers and fabric softeners. These studies were performed to evaluate the influence of several parameters (such as the role of powder and process burners, softeners, bleaches and parameters such as water hardness, temperature and mechanical properties) on the release of microplastics from synthetic fibers during washing. To achieve this goal, a new procedure has been developed for the determination of microfiber release during this process in households. This procedure consists of filtering the water obtained by rinsing the bead and analyzing the filter by scanning electron microscopy (SEM). In this way, direct quantification of the number and dimensions of released microfibers was obtained (*De Falco et al., 2018*).

3. THE IMPACT OF TEXTILE MICROPLASTICS ON THE ENVIRONMENT

Under the influence of various chemical and physical forces, by the action of abrasion and photodegradation, plastic polymeric materials are reduced to smaller and smaller particles that are difficult to detect and analyze (*Bouwmeester et al., 2015*). Plastics are generally resistant to biodegradation, but new research is based on the creation of new enzymes that have a sufficiently large capacity to degrade plastic polymers such as polyethylene terephthalate, a form of polyester. Due to the fact that this area is insufficiently researched, a large amount of microfibers is still in the environment and accumulates there for years and centuries.

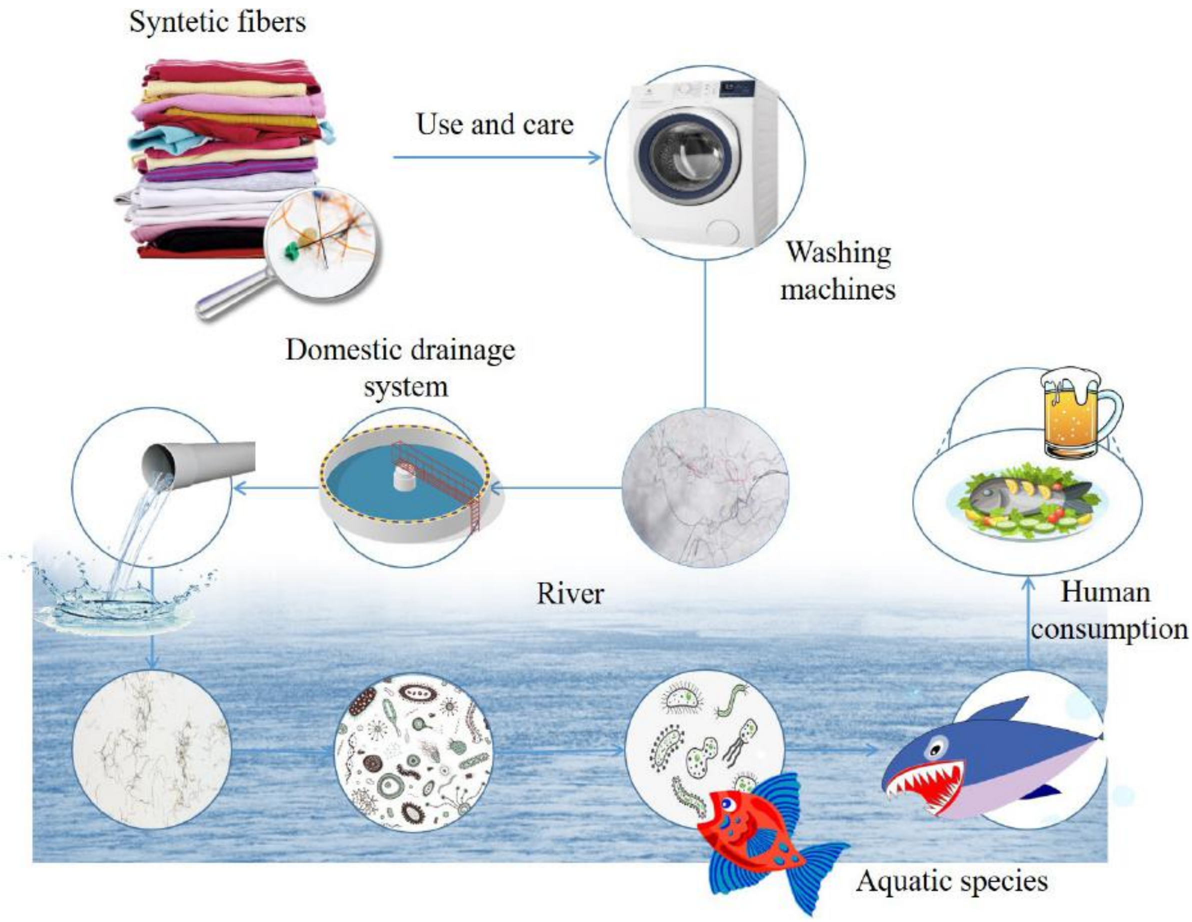
ljudi preko organizama koji naseljavaju morske i slatkovodne sisteme (*Henri i dr., 2019*).

Zbog svoje male veličine i plutajućih svojstava, mikroplastika često služi kao zamena za hranu vodenim organizmima. Ovi organizmi često nenamerno unose ili gutaju mikroplastiku i deponuju je u svom telu. Shodno tome, mikroplastika je otkrivena u različitim organizmima kao što su zooplankton, školjke, ribe i drugi (*Farrell i Nelson, 2013; Setala i dr., 2014*). Kada mikroplastika uđe u vodene ekosisteme, ona postaje potencijalni vektor za adsorpciju organskih polutanata kao što su, na primer, polihlorovani bifenili, policiklični aromatični ugljovodonici, polibromovani difenil etri, metali itd. Osim što obezbeđuje mesta za sorpciju polutanata, mikroplastika takođe može biti izvor zagađujućih materija u vodenim sistemima (*Tien i dr., 2020*). Kako mikroplastična vlakna predstavljaju vrstu mikroplastike prethodno navedene karakteristike odnose se i na pamučna vlakna koja dospevaju u životnu sredinu, iako nisu postojana u obliku poliestera.

Za razliku od sintetičkih, prirodni polimeri su kompostabilni i biorazgradivi od strane mikroorganizama, što se može primetiti posmatranjem od nekoliko dana na visokim

Microfibers enter the environment in two ways: the 5 mm wet mass that forms in textile fabrics and the microfibers that form in the environment by absorbing most of the parts, and the discarded ones are rejected. Figure 1 shows that the release of microfibers is separated at several points in the textile supply chain and that it can affect human health through an organization from marine and freshwater systems. By discharging wastewater from washing clothes from households, microplastic fibers reach rivers and thus organisms that inhabit water systems and often replace food with tiny microplastic particles (*Henry et al., 2019*).

Due to its small size and floating properties, microplastics often serve as a substitute for food for aquatic organisms. Benthos organisms often inadvertently ingests or swallow deposited microplastics in their body. Accordingly, microplastics have been discovered in various organizations such as zooplankton, shellfish, fish and others (*Farrell and Nelson, 2013; Setälä et al., 2014*). When microplastics enter aquatic ecosystems, they become a potential vector for the adsorption of organic pollutants such as, for example, polychlorinated biphenyls, polycyclic aromatic hydrocarbons, polybrominated diphenyl ethers, metals, etc. In addition to providing sorption sites for pollutants, microplastics can also act as



Slika 1: Jedan od puteva mikroplastičnih vlakana u životnu sredinu
Fig. 1: The possible transmission pathway of microfiber particles into the environment

temperaturama (*Arshad i dr., 2014*). Pored dostupnih informacija o biorazgradivosti prirodnih polimera, ova tema je slabije istražena kada su u pitanju mikroplastična vlakna. Stoga, potrebno je izvršiti dodatna istraživanja kako bi se razumela stopa biorazgradnje mikroplastičnih vlakana u različitim uslovima životne sredine, uključujući i morske ekosisteme.

S obzirom na to da se plastika i dalje akumulira u životnoj sredini, jedan od izazova bi takođe moglo biti praćenje ponašanja mikroplastičnih tekstilnih vlakana tokom dužeg vremenskog perioda. Široka distribucija ovih čestica je dokazana na različitim lokacijama, čak i na velikim dubinama. U morskim sistemima na dubini od 2000 m pronađena su čak tri tipa organizama koji unose hranu zajedno sa mikroplastičnim vlaknima od polipropilena, viskoze, poliestera i akrila (*Tailor i dr., 2016*). Takvi uticaji nisu ograničeni samo na morske sisteme, već i na različite slatkovodne sisteme (*Henri i dr., 2019*).

4. ADITIVI U PLASTICI I NJIHOV UTICAJ NA ŽIVOTNU SREDINU

Više vrsta jedinjenja se meša sa polimerima prilikom proizvodnje plastike. Vrsta dodatog jedinjenja, odnosno aditiva, zavisi od plastičnog polimera i zahteva finalnog proizvoda. Hemijski aditivi se dodaju polimerima kako bi se postigla željena fizička, hemijska, pa čak i biološka (npr. antimikrobna) svojstva, u cilju poboljšanja performanse i povećanja funkcionalnosti polimera (*Checker i dr., 2013; Cole, 2016; Sait i dr., 2021*). Ova jedinjenja obično nisu kovalentnom vezom vezana za polimerni matriks što potencijalno, za posledicu može imati njihovo lakše oslobađanje u vodeno okruženje (*Hermabessiere i dr., 2017*). Zbog toga je praćenje curenja aditiva iz mikroplastike u vodenu sredinu jedna od glavnih problema današnjice. Jedan od najčešćih tipova aditiva koji se koristi u procesima proizvodnje plastike u istraživanjima vezanim za životnu sredinu, jesu bromovani usporivači gorenja, ftalati koji se koriste kao plastifikatori, nonilfenoli, bisfenol A itd.

Bromovani usporivači gorenja (*eng. Brominated flame retardants-BFR*) su klasa aditiva koji se koriste u plastičnim proizvodima za smanjenje zapaljivosti. Ovi BFR se koriste u raznim potrošačkim proizvodima, od elektronskih uređaja do izolacionih pena. BFR-i uključuju širok spektar hemikalija, od kojih polibromovani difenil etri, heksabromociklodekan i tetrabromobisfenol A predstavljaju glavne BFR-ove koji se koriste u industriji plastike (*Hermabessiere i dr., 2017*). U plastici polibromovani difenil etri deluju kao usporivači gorenja. Najčešće se primenjuju penta-, okta- i dekabromovani difenil etri. Ovi aditivi su sveprisutni, toksični, postojani i bioakumuliraju se u životnoj sredini, a takođe predstavljaju opasnost po zdravlje ljudi (*Engler, 2012*).

a source of pollutants in aquatic systems (*Tien et al., 2020*). All mentioned previously is valid also for the cotton fibers discharged into the environment, though they are not as persistent as polyester.

In contrast of synthetic, natural polymers are compostable and biodegradable by microorganisms, which can be observed within a few days at high temperatures (*Arshad et al., 2014*). More research is needed to understand the rate of biodegradation of microfibers in different environmental conditions, including in marine ecosystems.

Given that plastics continue to accumulate in the environment, one of the challenges could be to monitor the behavior of textile fibers over a longer period of time. The wide distribution of these particles has been proven in various locations, even at great depths. In marine systems at depths of 2000 m, as many as three types of organisms have been found that enter food into their body together with microfibers made of polypropylene, viscose, polyester and acrylic (*Tailor et al., 2016*). Such impacts are not limited to marine systems, but to various freshwater systems (*Henry et al., 2019*).

4. ADDITIVES IN PLASTICS AND THEIR INFLUENCE ON THE ENVIRONMENT

Multiple types and categories of chemicals are mixed with polymers to produce plastics. The type of additive depends on the plastic polymer and the requirements of the final product. Chemical additives are added to polymers to achieve desirable physical, chemical and even biological (e.g. antimicrobial) properties, improve performance and increase functionality (*Chequer et al., 2013; Cole, 2016; Sait et al., 2021*). These chemicals are typically not covalently bonded to the polymer matrix and are therefore expected to leach more readily into the aquatic environment (*Hermabessiere et al., 2017*). Therefore, microplastic additive leakage monitoring into the water environment is one of the main concerns nowadays. One of the most common additive types used in the manufacturing processes that have been reported in macro-and microplastic debris collected in environmental surveys are brominated flame retardants, phthalates used as plasticizers, nonylphenols, bisphenol A etc.

Brominated flame retardants (BFR) are a class of additives used in plastic products to reduce flammability. This BFR are used in a variety of consumer products ranging from electronic devices to insulation foams. BFRs include a wide range of chemicals, of which polybrominated diphenyl ethers, hexabromocyclododecane and tetrabromobisphenol A (*Hermabessiere et al., 2017*) represent the main BFRs used in the plastic industry. Polybrominated diphenyl ethers are hydrophobic substances that include numerous formulations used in plastics

Estri ftalne kiseline (*eng. Phthalic acid esters-PAE*) ili ftalati su plastični aditivi koji se koriste kao plastifikatori, uglavnom u proizvodnji PVC -a. Kao rezultat toga, PVC može sadržati 10% - 60% ftalata po težini. Kako ftalati nisu hemijski vezani za polimerni matriks, oni se lako ispiranjem mogu ispuštati u životnu sredinu tokom proizvodnje, upotrebe i odlaganja (*Net i dr., 2015*).

Bisfenoli i benzofenonski UV-filteri su dva aditiva velikog obima proizvodnje. Bisfenoli se široko koriste u proizvodnji različitih vrsta plastike i uključuju nekoliko analoga od kojih je najistaknutiji bisfenol A (*Asimakopoulos i dr., 2014*). U proizvodnji tekstila, bisfenol A se koristi kao mazivo u proizvodnji boja i antioksidanata, a nedavno je detektovan i u nekoliko odevnih predmeta (*Vang i dr., 2019; Ksue i dr., 2017*). Dok su istraživanja bisfenol A široko zastupljena, koncentracije drugih bisfenola i mogući putevi njihovog izlaganja nisu dovoljno proučeni.

Benzofenonski UV filteri se često primenjuju kao UV filteri u plastičnim proizvodima kako bi se sprečila ili smanjila degradacija izazvana UV zračenjem (*Asimakopoulos i dr., 2014*) zbog čega se koriste u tekstilnoj industriji za produženje veka trajanja proizvoda (*Ksue i dr., 2017*). Iako mikroplastika može biti inertna u svom početnom obliku, ona obično sadrži potencijalno štetne aditive, poput omekšivača ili antibakterijskih agenasa koji se mogu ispustiti u okolinu (*Brovne i dr., 2013; Siberg i dr., 2015*). Ona takođe ima potencijal da adsorbuje štetne hidrofobne supstance i samim tim postane vektor u transportu takvih polutanata u vodenu sredinu (*Sillanpaa i Sainio, 2017; Teuten i dr., 2009*).

U nedavnim istraživanjima o bromovanim jedinjenjima u kućnoj prašini, *Peng i dr. (2016)* ukazali su da većina bromovanih jedinjenja nisu usporivači plamena, već azo-boje koje se koriste kao boje za tekstil. *Turner i dr. (2019)* pretpostavili su da je Br u uzorcima odeće koja je analizirana u njihovom radu takođe rezultat složenog asortimana boja koje se koriste i u prirodnim i u sintetičkim materijalima. Prisustvo Sb i Br među preostalim uzorcima može se u velikoj meri pripisati ispuštanju vlakana tokom pranja i sušenja. Osim toga, Br i Sb mogu biti prisutni u sušilici kao bromovani usporivači plamena ali takođe i zajednički usporivači plamena, indirektnim ispuštanjem iz aditiva dodatih mekom kućnom nameštaju, kao što su sofe, dušeci, tepisi i zavese (*Stapleton i dr., 2005*).

Preliminarni zaključci bi se trebali usredsrediti ka osmišljavanju razvoja i uspostavljanju proizvodnih procesa koji bi pomogli u smanjenju oslobađanja mikroplastičnih prirodnih i sintetičkih vlakana. Dodatno, smanjenje upotrebe deterdženta bi moglo smanjiti emisiju oslobođene količine vlakana, kao i smanjenje uzastopnog ispiranja veša. Filter

as flame retardants. Indeed, there are three main commercial formulations called penta-, octa- and deca- brominated diphenyl ethers. These additives are ubiquitous, toxic, persistent and bioaccumulate in the environment and are of great concern for human health (*Engler, 2012*).

Phthalic acid esters (PAE) or phthalates are a family of plastic additives used as plasticizers, mainly in PVC production. As a result, PVC can contain 10%-60% phthalates by weight. As phthalates are not chemically bound to the polymer matrix, they can easily leach into the environment during manufacturing, use and disposal (*Net et al., 2015*).

Bisphenols and benzophenone UV-filters are two high production volume additive chemicals. Bisphenols are widely used in the manufacture of various plastics and include several analogues; the most prominent being bisphenol A (*Asimakopoulos et al., 2014*). In textile manufacturing, bisphenol A is used as a coating and intermediate chemical in the manufacture of dyes and antioxidants and was recently detected in a range of garments (*Wang et al., 2019*; *Xue et al., 2017*). While bisphenol A is extensively researched, concentrations of other bisphenols and possible exposure pathways remain largely understudied.

Benzophenone UV filters are frequently applied as UV filters in plastic products to prevent or reduce UV-induced degradation (*Asimakopoulos et al., 2014*) and are used for this reason in the textile industry to increase product lifetime (*Xue et al., 2017*). Additionally, while microplastics may be inert in their original form, they commonly contain potentially harmful additives, such as softeners or antibacterial agents that could be released into the environment (*Browne et al., 2013; Syberg et al., 2015*), while also having the potential to adsorb harmful hydrophobic substances and subsequently become a vector in the transport of such contaminants to the water environment (*Sillanpää and Sainio, 2017;Teuten et al., 2009*).

In a recent study of brominated compounds in household dust, *Peng et al. (2016)* indicated that the majority of brominated compounds were not flame retardants but azo dyes employed as textile colourants. Additionally, *Turner et al. (2019)* surmised that Br in clothing samples analyzed in their study are also results from a complex assortment of dyes used in both natural and synthetic materials. The presence of Sb and Br among the remaining samples may be largely attributed to the shedding of fibers during washing and drying. In addition, both Br and Sb may be present in dryer lint as brominated flame retardants and flame retardant synergists, derived indirectly from formulations added to soft household furnishings like sofas, mattresses, carpets and curtains (*Stapleton et al., 2005*).

u mašinama za pranje veša se takođe pokazao kao važna komponenta, te je u tu svrhu potrebno sprovesti više istraživanja (*Henri i dr., 2019*).

5. ZAKLJUČAK

Zbog velike sveprisutnosti i štetnih efekata na vodenu biotu, zagađenje mikroplastičnim vlaknima postalo je sve više zabrinjavajuće. Upotreba sintetičke odeće donela je ogromne usluge ljudima, ali i ozbiljne probleme životnoj sredini. Oslobođena sintetička mikroplastična vlakna iz odeće na različite načine dospevaju u vodene sisteme, usled čega se danas veliki akcenat stavlja na otpadne vode iz domaćinstava, koje nastaju pranjem odeće u mašinama za veš. Zbog svoje male veličine, često se dešava da filteri u postrojenjima za prečišćavanje otpadnih voda ne zadržavaju ove čestice, pa se one ispuštaju direktno u životnu sredinu. Nalaze se u različitim matriksima, ali najčešće dopiru do vodenih sistema različitim antropogenim aktivnostima. Kroz hranu, vodu ili konzumiranje morskih plodova, mikrplastična vlakna mogu doći i do čoveka.

Mikroplastična vlakna takođe mogu imati mogućnost potencijalnog vezivanja određenih komponenti za mikroplastiku. Takođe, činjenica da se u mikroplastičnim vlaknima mogu naći jedinjenja koja se koriste u svrhe aditiva, ukazuje na to da može doći do njihovog potencijalnog curenja u životnu sredinu.

S obzirom na nedostatak informacija o metodama izolovanja mikroplastičnih vlakana iz otpadnih voda mašina za pranje veša kao i potencijalnu mogućnost adsorpcije različitih vrsta jedinjenja, poput aditiva, proizvoda za ličnu negu, metala itd., cilj daljih istraživanja trebalo bi da bude fokusiran na razvoj direktnih i pouzdanih metoda za izolovanje i određivanje mikroplastičnih vlakana u otpadnim vodama nakon pranja tekstilne odeće, kao i ispitivanje mogućeg curenja aditiva koji se koriste za poboljšanje karakteristika sintetičkog tekstila (bisfenoli, ftalati, bromirani usporivači plamena) ili ostataka sastojaka za ličnu negu čija je adsorpcija na mikroplastiku potvrđena.

Zahvalnica. Istraživanja je finansiralo Ministarstvo prosvete, nauke i tehnološkog razvoja Republike Srbije (Ev.br. 451-03-9/2021-14/ 200125)

Preliminary conclusions should assist future studies in designing the development and establishment of manufacturing processes that would help reduce the release of microplastic fibers, including natural and synthetic ones. As for the laundry itself, reducing the use of detergent could reduce the emission of the released amount of fibers as well as reduce the successive rinsing off the laundry. Also, the filter in washing machines has proven to be an important device, so more research is needed for that purpose (*Henry et al., 2019*).

5. CONCLUSION

Due to the high ubiquity and harmful effects on aquatic biota, microplastic fiber pollution has become increasingly worrying. The use of synthetic clothing has brought enormous services to people, but also serious problems of environmental pollution. Released synthetic fibers from clothing reach water systems in various ways, and today much emphasis is placed on household wastewater, which is generated by washing clothes in washing machines. Due to their small size, it often happens that filters in wastewater treatment plants fail to retain these particles, so they are released directly into the environment. They are found in different matrices, but most often reach water systems, most often through anthropogenic activities. Through food, water or consuming seafood, these microfibers can reach humans.

Microplastic fibers can also have the possibility of potential binding of components to microplastics, as well as the fact that in microplastics can be found compounds used for the purpose of additives, but when leaking plastic can adversely affect the environment.

Given the lack of information on methods of isolating microplastic fibers from the wastewater of washing machines and the potential adsorption of various types of emerging compounds, such as additives, personal care products, metals, the aim of further research should be to develop a direct and reliable method for isolation and determination of microfibers in wastewater after washing textile clothes, as well as testing for possible leakage of additives used to increase the characteristics of synthetic textiles (bisphenols, phthalates, brominated flame retardants) or residues of personal care ingredients whose adsorption on microplastics is confirmed.

Acknowledgments. The authors acknowledge financial support of the Ministry of Education, Science and Technological Development of the Republic of Serbia (Grant No. 451-03-9/2021-14/ 200125)

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