The ecological impacts of discarded cigarette butts

Dannielle S. Green*[†], Andrew D.W. Tongue[†] and Bas Boots

Applied Ecology Research Group, School of Life Sciences, Faculty of Science and Engineering, Anglia Ruskin University, Cambridge CB1 1PT, UK

* Correspondence: @Dr_DSGreen, dannielle.green@aru.ac.uk (Dannielle S. Green)

[†]Equal first authors.

Keywords: Applied Ecology, Cigarette Butts, Ecotoxicology, Microplastic, Litter, Pollution.

Glossary

Cellulose acetate: The overwhelming majority of cigarette filters currently in use are made of cellulose acetate. It is derived from plant-based cellulose but converted into a plastic by industrial processes (acetylation, hydrolysis and the application of a plasticiser). Modelling suggests that cellulose acetate cigarette butts may take up to 14 years to decompose in the environment.

Cigarette butts: The filter or end through which cigarettes have been smoked. Machine-manufactured cigarettes have contained filters for over 70 years and we define "butt" as the used filter once the cigarette is smoked. Cigarette butts present a unique challenge because they are ubiquitous and resistant to decomposition when littered. The smoked butt may contain paper, unsmoked and scorched tobacco, ash and contains chemicals some of which can exert deleterious effects on biota.

Ecotoxicology: The study of the presence and impacts of toxic (usually synthetic) substances in non-human biota.

Leachate: Technically defined as water that has percolated through a substance or substrate, we use the term in this review to refer to water in which cigarette butts have been soaked for the purpose of ecotoxicological research. Cigarette butt leachate has typically (though not exclusively) been used to evaluate the impacts of discarded butts in aquatic organisms, but compounds can be leached from cigarette butts in terrestrial habitats as well.

Single-use plastics: Plastic items intended to be used once before they are disposed of or recycled. Given that cellulose acetate cigarette butts are made of plastic, they constitute single-use plastics.

Xenobiotics: Chemicals detected in the environment or in organisms that would not naturally be present in substantially higher concentrations than would otherwise be expected. Cigarette butts have been found to contain hundreds of chemicals. When cigarette butts are littered, these xenobiotic chemicals may potentially enter the environment and have been shown to affect biota.

Abstract

Cigarette butts, one of the most littered items globally present a unique challenge to ecosystems due to their ubiquity, persistence and potential for harm. Over 35 studies have examined the toxicity of cigarette butts in biota from aquatic and terrestrial habitats from microbes to mice, but many organisms and habitats have not been tested. Two thirds of studies are on aquatic organisms and lethal effects were common. Research on the impacts on terrestrial life is lagging behind. Cigarette butts can affect the growth, behaviour and reproductive output of individual organisms in all three habitats, but research on wider effects on biodiversity and ecosystem functioning is lacking. Here we summarise the ecotoxicological concerns and identify important knowledge gaps for future research.

A unique and ubiquitous combination of physical and chemical pollution

Given the ubiquity, toxicity and persistence of discarded **cigarette butts**, the poorly understood contribution of cigarette butts to microplastic pollution [1] and the global biodiversity crisis, there is a growing interest in the potential impacts of cigarette butt pollution in terms of toxicity on biota and, ultimately, how it may affect ecosystems. Approximately 1.13 billion smokers worldwide consumed 7.41 trillion tobacco-equivalents [2], which comprised of more than 6 trillion cigarettes in 2019, with up to three-quarters of them littered [3]. Discarded cigarette butts can be carried via surface run-off, ultimately entering watercourses and oceans [3-5]). Cigarette butt litter is recognised as a problem globally [4, 6-9] with recently reported maximum densities of 130 butts per m^2 in some cities, 150 per km of suburban road and 1600 per 100 m of beach [10-12]. The Ocean Conservancy, a US-based non-profit organisation, routinely reports cigarette butts as the most encountered item of beach litter during its annual 'International Coastal Clean-up' [3], and cigarette butts comprise up to 33%, 24% and 15% of all litter in Argentinian coastal cities, on Brazilian beaches and in Balinese coastal villages respectively [6, 13-14].

Cigarette butts are made of tightly packed microfibre bundles of **cellulose acetate** [15]. Cellulose acetate is categorised as a 'bioplastic' because it is based on plant-derived cellulose which has been treated with acetic acid [16-17]. Although machine-measured levels of tar in simulated smoking experiments are lowered when filters are added to cigarettes [18], epidemiological data do not support them as beneficial to human health [19-20]. The effectiveness of filters at reducing the exposure of smokers to harmful substances is at best dubious and at worst potentially responsible for minimising public perceptions of the health risks of smoking [16, 21-22]. Cigarette filters are not regarded by the global public health authority to be a protective device [3]. Since the 1950s, most machine-manufactured cigarettes have contained filters, although the proportion of 'roll-your-own' smokers adding standalone filters to their cigarettes is not well understood [23].

Modelling suggests that cigarette butts take up to 14 years to fully decompose, likely due to the resistance to microbial degradation imparted by acetylation, and influenced by conditions such as temperature, moisture, the nature of the substrate and potentially also by the nitrogen content of smoked cigarette butts [24-25]. What makes cigarette butt pollution unique as an environmental challenge is that, in addition to the plastic pollution posed by its considerable persistence and ubiquity, butts can also be highly toxic. Smoked cigarette butts are infused with chemicals from smoking, >40 of them harmful to aquatic organisms. These include polycyclic aromatic hydrocarbons (PAHs), metals, phthalates, nicotine and volatile organic compounds [26], which can be released as **leachate** in water. The physicochemical properties of water (e.g.

pH, salinity, ionic strength) affect the leaching rate of some potentially toxic metals [27]. This phenomenon could lead to differential effects on marine and freshwater organisms.

Inappropriately disposed cigarette butts, therefore, are **single-use plastics** of questionable human health benefit which are contaminated with various **xenobiotics**. The impacts on biota following exposure to cigarette butts are wide-ranging and include lethal (i.e. increased mortality) and sublethal effects (e.g. affecting growth, reproduction and behaviour). Since the first published and peer-reviewed study in 2006 [28], a total of 36 investigations have been published in the scientific literature to date investigating the **ecotoxicology** of cigarette butts across a range of endpoints and on various biota (Supplemental information online). The biota studied include microbes, plants, invertebrates, fish, amphibians, birds and mice (Figure 1) and current evidence indicates that cigarette butts potentially exert more deleterious impacts in aquatic systems compared to terrestrial environments. For example, investigations into aquatic life have reported relatively greater acute effects including mortality, and the toxicity of cigarette butts in water may exceed that of littered cigarette butts in terrestrial environments possibly due to the slower release of toxicants in terrestrial environments, e.g. [29-30]. However, to date, aquatic biota has been subject to greater ecotoxicological investigation than terrestrial systems.

It is important that research on the environmental toxicity of cigarette butts is done as environmentally realistic as possible. For example, studies on organisms inhabiting lotic or marine aquatic environments should be subjected to flow-through experiments as opposed to static tanks to more accurately represent the flow of water that occurs in such habitats. Much research has been done in standardised, static simulations within laboratories, which provided valuable information, but is difficult to translate “to the field”. In this review, we highlight the current gaps of knowledge to fully understand how cigarette butts affect aquatic and terrestrial ecosystems. The findings are summarised in a heatmap (Figure 2) to provide a colour-coded graphical depiction of the intensity of research effort and significant findings thus far.

How has the ecotoxicity of cigarette butt litter been assessed?

Published research has focussed on different levels of biological organisation, from experiments using molecular analyses to observations of species assemblages (Figure 2), which we have categorised: for each publication, we recorded (i) which endpoints were measured, (ii) in which category/categories of organism/s and, out of those, (iii) whether the responses were statistically significant, compared to controls (i.e., conspecific subjects not exposed to cigarette butts). Although not displayed in the heatmap, it should be emphasised that any synthesis of the literature on ecotoxicological research on cigarette butts undertaken to date is compounded by differences in study design, particularly concentrations used and exposure duration. In addition, some studies have compared effects of: (i) smoked *vs*. unsmoked cigarettes, (ii) whether remnant tobacco was retained alongside the cigarette butt or removed, (iii) 'regular' *vs*. flavoured (e.g. mentholated) cigarettes, (iv) different cigarette brands and (v) cigarettes containing conventional cellulose acetate butts *vs*. those containing alternative, biodegradable butts (supplemental information online). Examples of such studies are discussed in this review. Freshwater organisms have been commonly used as ecotoxicological research subjects: 26 aquatic-only, peer-reviewed studies with 15 freshwater, seven marine and four covering both freshwater and marine and ten terrestrial-only studies (supplemental information online). The four most important take-home messages from Figure 2 are: (i) There has been a greater research focus on aquatic (particularly freshwater) organisms, compared to terrestrial life, with deleterious effects following cigarette butt exposure regularly reported in aquatic systems. (ii) The majority of research has used cigarette butt leachate rather than whole butts, thus the physical component of this contaminant is understudied (iii) Very few studies have examined wider ecological effects of cigarette butts such as communities and those that did were on microbes and ectoparasites. No studies thus far have addressed their wider impacts on ecosystem functioning and services. (iv) sublethal effects are still understudied, including changes in behaviour and reproduction.

How toxic are cigarette butts and associated substances for aquatic biota?

Most aquatic tests have focused on invertebrates (crustaceans, molluscs and freshwater insect larvae) and vertebrates (fish and amphibians), with a smaller number of studies involving microbes, algae and plankton (Figure 2). Cigarette butts may exert greater lethal effects in aquatic life in comparison with terrestrial biota: mortality for treatment subjects has been observed in most of the aquatic studies, i.e., in foraminifera [31], invertebrates [1, 29, 32-37] and vertebrates [38-40], with many significant effects reported. Mosquitoes have an aquatic and terrestrial life stage, and six studies have reported lethal effects of cigarette butt leachate on mosquitos during their aquatic life stages, but not much is known on their terrestrial life cycle. As mosquitoes are vectors of zoonotic disease, this research effort has implications for the use of collected cigarette butts as vector control [32-34, 41], but also as to whether the global ubiquity of cigarette butts may facilitate selection pressure for nicotine resistance in mosquitoes [37].

Aside from lethal effects, cigarette butts can illicit important sublethal effects such as alterations to behaviour and changes to reproductive output of a range of aquatic organisms. Animal behaviour is a sensitive and important variable in research to aquatic organisms [42] and, indeed, significant alterations to behaviour were found in most studies which tested it in response to cigarette butt leachate. The movement of marine [29] and freshwater [35] gastropods was reduced when exposed to high concentrations of cigarette butt leachate. Marine polychaetes [43] and freshwater bivalves [44] took longer to create burrows and, in the case of the bivalves, also dug shallower burrows. Behavioural endpoints are, however, often overlooked in ecotoxicological assessments [45], but alterations to behaviour can impact the fitness of an individual (e.g. via predator avoidance and feeding), with consequences for population dynamics, species interactions and ecosystem functioning [46].

Lima *et al*. [47] found that the reproductive rates of marine copepods (*Nitokra* sp.) exposed to leachate of just 0.1 or 0.01 butts L^{-1}, in water or sediment respectively, were reduced by >50% relative to controls. The effects of cigarette butts on reproduction, however, have predominantly been assessed in mosquitos with mixed results (either decreases in hatching success; [32]; no effect on hatching success of fecundity; [34] or some increases in hatching success; [37]). Given the link of reproductive success to the stability of populations, we need to understand the effects of cigarette butts on reproduction of a broader range of organisms.

Differences between aquatic studies may occur due to differing experimental set up. Realistic exposure durations are important for any environmentally-relevant assessment of ecotoxicity. Conditions for animals inhabiting large and dynamic aquatic environments (e.g., rivers and oceans) can be simulated using realistic flow-through, as opposed to static, water systems or in-situ experiments. To date, however, there are only two studies that has used continuously flowing water: Green *et al* [48] reported that smoked conventional butts decreased clearance rates of blue mussels (*Mytilus edulis*) (at 1 butt L^{-1}) 2.5 times and reduced the biomass of benthic microalgae (at 0.25 and 1 butt L^{-1}) by up to 3 times. On the contrary, Werdel *et al* [49] found that biofilm formation, in terms of algal biomass and diatom health, was unaffected in an experiment using a flowing stream with agar plates made with various concentrations of cigarette butt leachate. Such systems are relevant to understand ecoctoxicological effects of cigarette butts, but standardisation is required to facilitate comparison between different ecosystems.

Given that cigarette butts can persist in the environment for many years, a better understanding is needed of how their ecotoxicological impacts can change over time. An apparent temporal decline in cigarette butt toxicity has also been observed for marine bacteria [25], terrestrial snails [30] and mosquito larvae [32]. Notably, an experiment which tested the effects of leachate from cigarette butts which had been aged for 5 years found that the growth of a freshwater microalga (*Raphidocelis subcapitata*) was the most strongly inhibited by recently smoked cigarette butts (i.e., less than 30 days post-smoking) [25]. In this long-term experiment, after 30 days most compounds in leachate they had detected earlier were no longer detectable and there was a rapid decline in nicotine concentrations. However, despite this apparently fast decline in toxicity, leachate of butts that had been decomposing for five years were still toxic to *R. subcapitata* [25]. It is also possible that microfibres, a type of microplastic, are released during degradation. There is a growing body of evidence of how microplastics affect aquatic biota [50], including animals and primary producers [51]. Studies assessing the impact of cigarette butts on primary producers, however, have been limited with only three studies on microalgae [25, 49, 52], one study on a marine macroalga [48] and no studies on plants in either habitat. Understanding impacts at the base of aquatic food webs would enable better predictions of impacts across multiple trophic levels in both freshwater and marine systems, but also in terrestrial habitats.

Studies of impacts of cigarette butts in terrestrial systems are limited

Amongst terrestrial biota, three studies to date have focused on plants (Figure 2) [11, 53-54]. The effects reported in terrestrial plants include physiology: chlorophyll [11], root water content [54], growth (root [54] and shoot length/biomass [11]; cell growth and overall toxicity, comprising cytotoxicity, i.e., cell toxicity and mutagenicity [53]. Green *et al*. [11] investigated effects on perennial ryegrass (*Lolium perenne*) and white clover (*Trifolium repens*) following exposure to regular *vs*. mentholated cigarette butts including smoked butts with remnant tobacco attached and unsmoked filters. The germination of *T. repens* was especially negatively impacted: 27% fewer seeds germinated with smoked cigarette butts present. Reductions in shoot length, root biomass and changes to chlorophyll content in both plants occurred regardless of whether butts were unsmoked, smoked or contained remnant tobacco. The plants used are model organisms for important grassland ecosystems where they are at the basis of the food web. Another example of detrimental effects on plant health is reported by Mansouri *et al*. [54] who found that almost 50% seeds of *Vicia faba* did not germinate when exposed to leachate from cigarette butts, and ash had even a stronger impact with no seeds able to germinate. Furthermore, the uptake of chemicals associated with cigarettes, such as nicotine, into plant tissues as found by Selmar *et al*. [55] could lead to cascading effects on foodwebs, including plant communities which are important for sustaining biodiversity and for supporting insect pollinators.

Three studies [56-58] so far have investigated the effects of cigarette butts directly on terrestrial vertebrates. Cardoso *et al*. [56] examined predator avoidance behaviour in laboratory mouse (*Mus musculus*), growth and physiological responses (food and water consumption, locomotor activity, visual, auditory and olfactory functions) following provision drinking water containing leachate. A significant reduction in avoidance behaviour in response to the presence of domestic cats (*Felis catus*) or corn snakes (*Pantherophis guttatus*) was observed for exposed mice. For example, when a snake was present the mice spent ~ 50% more time in a safe place when not exposed to cigarette butt leachate (an avoidance response) than when exposed to environmentally realistic concentrations of leachate, suggesting that the cigarette butt leachate may make them more prone to predation. Another ecotoxicological concern is the interaction of birds with cigarette butts. House finches (*Carpodacus mexicanus*) were found to incorporate littered cigarette butts into the lining of their nests [58-59]. The reasons for this are not fully established, but levels of nicotine and other chemicals in butts correlate with reduced numbers of parasitic arthropods in nests [58-59]. Hatching/fledging success and nestling immune response of house finches were positively correlated with the proportion of cigarette butt material in the nest. However, long-term genotoxic harm in nestlings increased with the proportion of cigarette butts in nest material, indicating that nestlings were at heightened risk of DNA damage, but lower parasite burden [57-59]. Despite potential positive impacts outlined above, the possibility of chicks ingesting cigarette butt litter introduced into their nests is of concern. Due to their small size and fast metabolism, birds absorb chemicals faster, meaning they require less toxins to cause harm and so are at particular risk from ingestion of cigarette butts [60], although research on ingestion rates is lacking.

Not many studies have investigated the effects of cigarette butts on terrestrial invertebrates, but research has been done on ectoparasites in nests [58-59], snails [30]and earthworms [61]. Gill *et al*. [30] reported short-term behavioural changes in snails (*Anguispira alternata*) in the presence of smoked mentholated cigarette butts. At the start of a three-week experiment, six times more snails were associated with sections of mesocosms containing no cigarette butts and were less likely to occupy those sections containing the maximum quantity of butts. However, this difference was not there at the end of the experiment. Given that food provision did not differ between sections, it is possible that the toxicity of butts declined over time (as suggested previously). Similarly, despite a relatively lengthy experiment period of 70 days, Korobushkin *et al*. [61] reported no mortality effects for earthworms (*Eisenia fetida*) in experimental microcosms containing both smoked and unsmoked butts. Total worm biomass in microcosms containing smoked butts was, however ~2 times greater than that for controls, with the presence of worms correlating with lower quantities of cigarette paper, thus worms appeared to consume the cigarette paper wrapping, though not the cellulose acetate butt itself.

Material matters: cigarette butts are complex pollutants and more than just leachate

Most ecotoxicological studies have focused on the chemical component of cigarette butts, using extracted leachate (28 of a total of 36 peer-reviewed studies), with five studies using whole butts, and two exposing organisms to a combination of leachate and microfibres from butts. In addition, just one study has compared the impact of leachate from cigarette ash *vs*. that of smoked butts, reporting higher phytotoxicity associated with leachate from ash [54]. When a cigarette butt is littered, the used plastic filter, ash, remnant tobacco, microfibres and leachate all enter the environment. By only testing the effect of leachate we are missing crucial information about the wider impact of this unique pollutant. For example, when cellulose acetate microfibres were present in smoked cigarette butt leachate, it was more toxic to water fleas (*Daphnia magna*) with 50% immobilisation (as a proxy for mortality) occurring at 0.017 butts L^{-1} compared to 0.067 butts L^{-1} in leachate without microfibres [1]. On the contrary, Wright *et al*. [43] found no significant effects on growth rates, burrowing time and DNA damage in ragworms (*Hediste diversicolor*) when exposed to smoked cigarette microfibres in sediment, with subjects accumulating 13 times less nicotine following fibre exposure compared to those which were exposed to leachate. Ragworms exposed to leachate in seawater had >30% weight loss, twice the DNA damage and >10 times longer burrowing times compared with controls. Investigations into the effects of cigarette butt microfibres in a greater range of taxa is desirable given their importance as a form of microplastic litter. Belzagui *et al*. [1] reported that smoked butts in water release approximately 100 microfibres (<0.2 mm) per day, equating to 0.3 million tons of microfibres released per year.

The plastic (cellulose acetate) filter itself, even when unsmoked, can cause detrimental effects possibly due to plasticizers, such as diethyl phthalate (a known toxicants to plants [62] and animals [63]). Leachate from unsmoked cellulose acetate filters can be toxic to marine and freshwater fish [38], amphibians [39] and freshwater microalgae [25] and unsmoked filters can decrease germination and growth of plants [11] and alter microbial communities in marine sand [64].

Current moves to reduce single-use plastics may lead to a shift to alternative butts composed of biodegradable cellulose instead of cellulose acetate. There have been concerns in the past that biodegradable filters would not be acceptable to smokers due to poor taste, short shelf life and physical instability during smoking [4]. However, recent advances in filter technology, combined with shifting consumer opinions [65], may improve uptake of biodegradable filters in the future as pressure to reduce plastic litter mounts. The decomposition rates and ecotoxicological impacts of biodegradable cigarette butts remain largely unknown. It was estimated that smoked biodegradable cellulose butts would take 2.3–13 years to disappear in compost and at the soil surface, respectively, whilst smoked conventional cellulose acetate butts would take 7.5–14 years to disappear [24]. As well as uncertainty of the persistence of biodegradable butts, there is also very little known about their ecotoxicological impacts. An experiment simulating a marine environment found that smoked biodegradable butts caused no significant impacts, whilst smoked conventional butts affected clearance rates of *M. edulis* and reduced the biomass of benthic microalgae [48]. On the contrary, leachate from either biodegradable or conventional smoked butts caused equal mortality of freshwater pond invertebrates at 5 butts L^{-1} and a reduction in their movement at 1 butt L^{-1}[35]. In addition, leachate from biodegradable butts may have relatively higher concentration of metals than conventional butts possibly leading to alterations to microbial communities [66]. Whether biodegradable filters play an important role in the future or not, they contain toxic compounds from smoking, and it is possible they will be preferentially littered due to their perceived biodegradability [67], therefore they pose a similar threat to the environment as conventional butts do.

Concluding Remarks and Future Directions

The majority of studies investigating cigarette butt ecotoxicity have focused on individual organisms from aquatic habitats and many have found lethal effects in enclosed systems. In contrast, sub-lethal endpoints (e.g. reproduction, behaviour, physiology) have received less attention, but there is evidence that ecosystem engineers (such as bivalves and plants) can be affected by environmentally realistic concentrations of cigarette butts and this could lead to wider ecological impacts. Very few investigations have been made into the wider ecological effects of cigarette butts on populations or species diversity, and no studies have focused on ecosystem functioning. Whilst evidence of ecological impacts is often needed to justify policy reform, there is already strong evidence from lower levels of biological organisation that cigarette butts pose a hazard to the environment and require tighter legislation. Finally, study design is important; to accurately predict the impacts of cigarette butts in the real environment we need environmentally realistic experiments in relation to exposure duration, contaminant concentrations and the use of flow-through systems for biota associated with habitats containing moving water.

Acknowledgements

The authors gratefully acknowledge the award of Research England Quality-Related (QR) research funding awarded to DSG and BB by the Faculty of Science and Engineering, Anglia Ruskin University.

Supplemental Information

Supplemental information associated with this article can be found online.

Tables

Table 1. Definitions of the endpoint categories used in this review to summarise the cigarette waste (i.e., butts, leachate, microfibres and ash) ecotoxicological tests reported in the literature to date

Endpoint category	Study Definition
Mortality	Tested whether subjects died/were immobilised.
Toxicity	Tested whether sublethal responses such as cytotoxicity, immunotoxicity, genotoxicity and mutagenicity were expressed.
Physiological	Tested physiological responses, such as feeding rates, filtering rates, or chlorophyll content of plants/algae.
Reproduction	Tested whether the subject's reproductive output was altered. This included germination for plants and hatching success for egg-laying organisms.
Growth/Malformation	Tested whether growth rates were affected or malformation occurred during development.
Behavioural	Tested whether the subject's behaviour in terms of movement (speed, frequency of movement, latency to move, predator avoidance, burrowing) were altered.
Population/Diversity	Tested impacts at the population level of a species or at the level of species diversity.

Figure captions

Figure 1. Diagram to illustrate exemplar organisms and their habitats (1: terrestrial, 2: freshwater, 3: marine; organisms not to scale) in which the effects of cigarettes butts have been studied at various endpoints. 1a: The songbird house finch (*Haemorhous mexicanus*)*;* 1b: The earthworm *Eisenia fetida*) 1c: the plant white clover (*Trifolium repens*); 1d: the grass *Lolium perenne*; 1e: the snail *Anguispira alternata*; 1f: terrestrial bacteria (various strains); 1g: the mouse *Mus musculus*; 2a: the freshwater fish Nile tilapia (*Oreochromis niloticus*); 2b: the freshwater shrimp *Thamnocephalus platyurus*; 2c: freshwater bacteria (various strains); 2d: the freshwater microalgae *Raphidocelis subcapitata*; 2e: the frog species *Hymenochirus curtipes*; 2f: the zebra mussel (*Dreissena polymorpha*); 3a: marine bacteria (various strains); 3b: the marine microalgae *Dunaliella teriolecta*; 3c: the copepod (genus *Nikotra*); 3d: the marine fish topsmelt (*Atherinops affinis*); 3e: the marine snail *Austrocochlea porcata*; 3f: the blue mussel *Mytulis edulis.*

Image credits: Earthworm icon: naakila.blogspot.com (CC BY 4.0); Clover icon Piotr Siedlecki (CC BY 4.0); Land snail silhouette Piotr Siedlecki (CC BY 4.0); bacteria icon Metro Science Natural Sciences Icons (Icons8); Microalgae icon Hanna Vernydub (CC BY 4.0); Copepod icon Pham Thanh Loc (CC BY 4.0); Fish icon The Noun Project (CC BY 4.0); Sea snail icon iconsout (licence); Mussel icon The Noun Project (CC BY 4.0); Shrimp icon Free Icons Library; Frog icon SVG SILH (CC BY 4.0). All other images are free for commercial use with no attribution required.

Figure 2. Heatmap summarising research focus to date on the effects of cigarette butts in different habitats. The colour of the columns headed as "Tested" relates to the top left value, which is the number of overall experiments/tests done as reported in the literature, and the colour of the column headed "Sig." is based on the number of tests which were reported significantly different from a concurring control. The bold value in the middle of a cell in the "Tested" column represent the number of papers published which report a test in a particular habitat measuring a response variable in the corresponding category. Many papers report multiple independent observations, thus

the number of tests is often greater than the number of papers. For example, there were 22 tests done on freshwater invertebrates, of which 16 reported significant differences from the control, but the results have been published in nine papers.

References

1. Belzagui, F. *et al*. (2021) Cigarette butts as a microfiber source with a microplastic level of concern. Sci. Total Environ. 762, 144165.

2. GDB 2019 Tobacco Collaborators (2021) Spatial, temporal, and demographic patterns in prevalence of smoking tobacco use and attributable disease burden in 204 countries and territories, 1990–2019: a systematic analysis from the Global Burden of Disease Study 2019. The Lancet. 397, 2337-2360.

3. Novotny, T.E. and Slaughter, E. (2014) Tobacco product waste: an environmental approach to reduce tobacco consumption. Curr. Environ. Health Rep. 1, 208-216.

4. Novotny, T.E. *et al*. (2009) Cigarettes butts and the case for an environmental policy on hazardous cigarette waste Int. J. Environ. Res. Public Health. 6, 1691-1705.

5. Patel, V. *et al*. (2013) Cigarette butt littering in city streets: a new methodology for studying and results. Tob. Control. 22, 59-62.

6. Pon, J.P.S and Becherucci, M.E. (2012) Spatial and temporal variations of urban litter in Mar del Plata, the major coastal city of Argentina. Waste Manage. 32, 343-348.

7. Curtis, C. *et al*. (2017) Tobacco industry responsibility for butts: a Model Tobacco Waste Act. Tob. Control. 26, 113-117.

8. Metcalfe, S. *et al*. (2017) A kick in the butt: time to address tobacco waste in New Zealand. N. Z. Med. J. 130, 65-69.

9. Qamar, W. *et al*. (2020) Cigarette waste: Assessment of hazard to the environment and health in Riyadh city. Saudi J. Biol. Sci. 27, 1380-1383.

10. Moriwaki, H. *et al*. (2009) Waste on the roadside, 'poi-sute' waste: Its distribution and elution potential of pollutants into environment. Waste Manage. 29, 1192-1197.

11. Green, D.S. *et al*. (2019) Cigarette butts have adverse effects on initial growth of perennial ryegrass (gramineae: *Lolium perenne* L.) and white clover (leguminosae: *Trifolium repens* L.). Ecotoxicol Environ. Saf. 182, 109418.

12. Asensio-Montesinos, F. *et al*. (2021) Abundance and distribution of cigarette butts on coastal environments: examples from southern Spain J. Mar. Sci. Eng. 9, 129.

13. Ribeiro, V.V. *et al*. (2021) Marine litter on a highly urbanized beach at Southeast Brazil: A contribution to the development of litter monitoring programs. Mar. Pollut. Bull. 163, 111978.

14. Smith, S.D.A. and Bernal, E. (2021) Quantifying mismanaged waste in a small Balinese coastal village: Comparisons of standing stock in different habitats. Ocean Coast. Manage. 202, 105433.

15. Davis, D.L. *et al*. (1999) Cigarette design and materials. in Tobacco: production, chemistry and technology. eds Davis, D.L. and Nielsen M.T. (Blackwell Science, Inc, Malden, Massachusetts), pp 353–387.

16. Pauly, J.L. *et al*. (2002) Cigarettes with defective filters marketed for 40 years: what Philip Morris never told smokers. Tob. Control. 11, 51-61.

17. Cheng, H.N. *et al*. (2010) Synthesis of cellulose acetate from cotton byproducts. Carbohydr. Polym. 80, 449-452.

18. Hoffmann, D. *et al*. (1997) The Changing Cigarette. Prev. Med. 26, 427-434.

19. Ito, H. *et al*. (2011) Nonfilter and filter cigarette consumption and the incidence of lung cancer by histological type in Japan and the United States: Analysis of 30-year data from population-based cancer registries. Int. J. Cancer. 128, 1918-1928

20. Stigler Granados, P. *et al*. (2019) Global health perspectives on cigarette butts and the environment. Int. J. Environ. Res. Public Health. 16, 1858.

21. Hastrup, J.L. *et al*. (2001) Consumers' knowledge and beliefs about the safety of cigarette filters. Tob. Control. 10, 84.

22. Evans-Reeves, K. *et al*. (2021) The 'filter fraud' persists: the tobacco industry is still using filters to suggest lower health risks while destroying the environment. Tob. Control. In Press.

23. Young, D. *et al*. (2006) Prevalence and attributes of roll-your-own smokers in the International Tobacco Control (ITC) Four Country Survey. Tob. Control. 15, 76-82.

24. Joly, F.-X. and Coulis, M. (2018) Comparison of cellulose vs. plastic cigarette filter decomposition under distinct disposal environments. Waste Manage. 72, 349-353.

25. Bonanomi, G. *et al*. (2020) The fate of cigarette butts in different environments: Decay rate, chemical changes and ecotoxicity revealed by a 5-years decomposition experiment. Environ. Pollut. 261, 114108.

26. Venugopal, P.D. *et al*. (2021) No butts on the beach: aquatic toxicity of cigarette butt leachate chemicals. Tob. Regul. Sci. 7, 17-30.

27. Akhbarizadeh, R. *et al*. (2021) Potentially toxic elements leachates from cigarette butts into different types of water: A threat for aquatic environments and ecosystems? Environ. Res. 202, 111706.

28. Micevska, T. *et al*. (2006) Variation in, and causes of, toxicity of cigarette butts to a cladoceran and microtox. Arch. Environ. Contam. Toxicol. 50, 205-212.

29. Booth, D.J. *et al*. (2015) Impact of cigarette butt leachate on tidepool snails. Mar. Pollut. Bull. 95, 362-364.

30. Gill, H. *et al*. (2018) Cigarette butts may have low toxicity to soil-dwelling invertebrates: Evidence from a land snail. Sci. Total. Environ. 628-629, 556-561.

31. Caridi, F. *et al*. (2020) Cigarette butts, a threat for marine environments: Lessons from benthic foraminifera (Protista). Mar. Environ. Res. 162, 105150.

32. Dieng, H. *et al*. (2011) Discarded cigarette butts attract females and kill the progeny of *Aedes albopictus*. J. Am. Mosq. Control Assoc. 27, 263-271

33. Dieng, H. *et al*. (2013) Turning cigarette butt waste into an alternative control tool against an insecticide-resistant mosquito vector. Acta Trop.128, 584-590

34. Dieng, H. *et al*. (2014) Indirect effects of cigarette butt waste on the dengue vector *Aedes aegypti* (Diptera: Culicidae). Acta Trop. 130, 123-130

35. Green, D.S. *et al*. (2020) Smoked cigarette butt leachate impacts survival and behaviour of freshwater invertebrates. Environ. Pollut. 266, 115286.

36. de Souza Abessa, D. *et al*. (2021) Acute toxicity of cigarette butts leachate on nauplii of *Artemia sp*. Braz. J. Anim. Environ. Res. 4, 659-670.

37. Oliver, S.V. (2021) The effect of larval cigarette exposure on the life history of the major malaria vector *Anopheles arabiensis* (Diptera: Culicidae). Trans. R. Soc. S. Afr. In press

38. Slaughter, E. *et al*. (2011) Toxicity of cigarette butts, and their chemical components, to marine and freshwater fish. Tob. Control. 20, 25-29.

39. Lawal, M.S. and Ologundudo, S.O. (2013) Toxicity of cigarette filter leachates on *Hymenochirus curtipes* and *Clarias Gariepinus* in Nigeria J. Env. Ext. 11, 7–14.

40. Parker, T.T. and Rayburn, J. (2017) A comparison of electronic and traditional cigarette butt leachate on the development of *Xenopus laevis* embryos. Toxicol. Rep. 24, 77-82

41. Murugan, K. *et al*. (2018) Managing wastes as green resources: cigarette butt-synthesized pesticides are highly toxic to malaria vectors with little impact on predatory copepods. Environ. Sci. Pollut. Res. 25, 10456-10470.

42. Melvin, SD and Wilson, SP (2013) The utility of behavioral studies for aquatic toxicology testing: A meta-analysis. Chemosphere, 93(10): 2217-2223.

43. Wright, S.L. *et al*. (2015) Bioaccumulation and biological effects of cigarette litter in marine worms. Sci. Rep. 5, 14119.

44. Montalvao, M.F. *et al*. (2019) How leachates from wasted cigarette butts influence aquatic life? A casestudy on freshwater mussel *Anodontites trapesiali*. Sci. Tot. Environ. 689, 381-389.

45. Ågerstrand, M. *et al*. (2020) Emerging investigator series: use of behavioural endpoints in the regulation of chemicals. Environ. Sci. Process. Impacts 2020, 22, 49– 65.

46. Candolin, U. and Wong, B.B.M. (2019) Mate choice in a polluted world: consequences for individuals, populations and communities. Philos. Trans. R. Soc., B 374, 20180055.

47. Lima, C.F. *et al* (2021) Occurrence, characterization, partition, and toxicity of cigarette butts in a highly urbanized coastal area, Waste Management, 131: 10-19.

48. Green, D.S. *et al*. (2021) Effects of cigarette butts on marine keystone species (*Ulva lactuca* L. and *Mytilus edulis* L.) and sediment microphytobenthos. Mar. Pollut. Bull. 165, 112152.

49. Werdel, G.M. *et al.* (2021) Cigarette butt effects on diatom health in a stream ecosystem. Aquatic Ecology, 1-12.

50. Bucci, K. *et al*. (2020) What is known and unknown about the effects of plastic pollution: A meta-analysis and systematic review. Ecol. Appl. 30, e02044.

51. Yokota, K. *et al.* (2017) Finding the missing piece of the aquatic plastic pollution puzzle: Interaction between primary producers and microplastics. Limnol. Oceanogr., 2: 91-104.

52. Oliva, M. *et al*. (2021) Bioassay-based ecotoxicological investigation on marine and freshwater impact of cigarette butt littering. Environ Pollut. 288, 117787.

53. Montalvão, M.F. *et al*. (2019) An insight into the cytotoxicity, genotoxicity, and mutagenicity of smoked cigarette butt leachate by using *Allium cepa* as test system. Environ. Sci. Pollut. Res. 26, 2013-2021.

54. Mansouri, N. *et al*. (2020) Genotoxicity and phytotoxicity comparison of cigarette butt with cigarette ash. Environ. Sci. Poll. Res. 27, 40383-40391.

55. Selmar, D. *et al*. (2018) Uptake of nicotine from discarded cigarette butts–A so far unconsidered path of contamination of plant-derived commodities. Environmental Pollution 238 (2018): 972-976.

56. Cardoso, L.S. *et al*. (2018) The exposure to water with cigarette residue changes the anti-predator response in female Swiss albino mice. Environ. Sci. Poll. Res. 25, 8592-8607.

57. Suárez-Rodríguez, M. and Garcia, C. (2014) There is no such a thing as a free cigarette; lining nests with discarded butts brings short-term benefits, but causes toxic damage. J. Evol. Biol. 27, 2719-2726.

58. Suárez-Rodríguez, M. and Garcia, C.M. (2017) An experimental demonstration that house finches add cigarette butts in response to ectoparasites. J. Avian Biol. 48, 1316-1321.

59. Suárez-Rodríguez, M. *et al*. (2013) Incorporation of cigarette butts into nests reduces nest ectoparasite load in urban birds: new ingredients for an old recipe? Biol. Lett. 9, 20120931

60. Novotny T.E., *et al*. (2011) Tobacco and cigarette butt consumption in humans and animals. Tobacco Control, 20:17-20.

61. Korobushkin, D.I. *et al*. (2020) The earthworm species *Eisenia fetida* accelerates the decomposition rate of cigarette butts on the soil surface. Soil. Biol. Biochem. 151, 108022.

62. Cheng, S. (2012) The toxic effects of diethyl phthalate on the activity of glutamine synthetase in greater duckweed (*Spirodela polyrhiz*a l.). Aquat. Toxicol. 124–125, 171–178.

63. Liu, Y. *et al*. (2009). Toxicity of seven phthalate esters to embryonic development of the abalone *Haliotis diversicolor* supertexta. Ecotoxicology 18, 293–303.

64. Quéméneur, M. *et al* (2020). Impact of cigarette butts on microbial diversity and dissolved trace metals in coastal marine sediment. Estuarine, Coastal and Shelf Science, 240: 106785.

65. Hoek, J. *et al*. (2020) Butting out: an analysis of support for measures to address tobacco product waste. Tob Control, 29:131–137.

66. Koroleva, E. *et al*. (2021) Impact of cigarette butts on bacterial community structure in soil. Environ. Sci. Pollut. Res. In press.

67. Klöckner, C.A. (2013). A Comprehensive Model of the Psychology of Environmental Behaviour-A Meta-Analysis. Glob. Environ. Change 23 (5), 1028–1038.

Figures

Figure 1

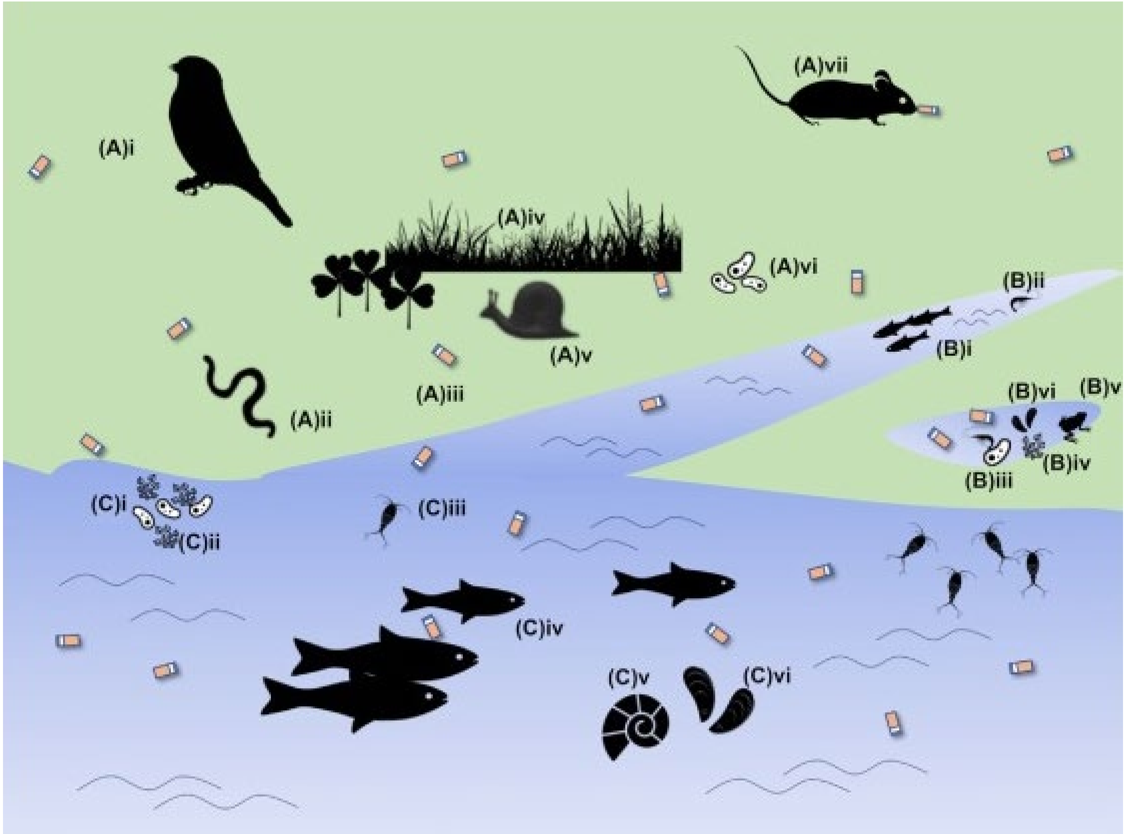

Figure 2

Habitat	Taxa	Mortality Tested	Mortality Sig.	Toxicity Tested	Toxicity Sig.	Physiological Tested	Physiological Sig.	Reproduction Tested	Reproduction Sig.	Growth/Malfor. Tested	Growth/Malfor. Sig.	Behavioural Tested	Behavioural Sig.	Pop./Diversity Tested	Pop./Diversity Sig.	Count
Freshwater	*Microbe*									2 2	2					0
	Algae/plant					2 2	0			3 2	1					1
	Invertebrate	22 9	16	3 1	3	8 7	6	4 4	3	2 2	1	5 2	5			2
	Vertebrate	5 3	5			5 2	5			5 2	5	1 1	1			3
Marine	*Microbe*	3 1	3			6 2	6							3 1	3	4
	Algae/plant									4 3	3					5
	Invertebrate	8 4	8	1 1	1	5 2	4	2 1	2	5 4	3	7 2	6			6
	Vertebrate	1 1	1													7
Terrestrial	*Microbe*													2 1	0	8
	Plant			8 2	7	7 2	7	3 2	3	8 2	5					16
	Invertebrate	2 2	0			1 1	0			2 2	1	1 1	1	1 1	1	22
	Vertebrate			2 1	2	5 1	0	2 1	2	2 2	1	5 2	4			