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Effects of Personal Care Product Residues on the Development of Aquatic Insect Communities

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Abstract: Triclosan, parabens, and ultraviolet (UV) filters are released into freshwater systems as personal care products (PCPs) via domestic wastewater, treatment plant effluent, and recreational activities. Conventional treatment does not completely remove these residues and they remain in the water and sediment and are ingested, contacted and absorbed by benthic insects. In this paper, evidence concerning the occurrence of PCP and its impact on insects, particularly development and survival and community structure, is evaluated; a field and laboratory testing framework for these impacts is presented. Reported concentrations in water matrices range from 0.029 ng/L to 7.811×10^6 ng/L and in sediment of the Hooghly River, concentrations of triclosan, parabens and musk ketone range from 2 to 593 ng/g. Triclosan, at 10-1000 µg/L, disrupted transcription of ecdysone receptor, ultraspiracle, estrogen-related receptor, E74, and hsp70 genes in C. riparius larvae, suggesting that triclosan interferes with moulting pathways. There is limited direct evidence that ties realistic concentrations to community change, and evidence is synthesized from studies, with site-level data not yet collected. The proposed design incorporates four categories of sites, two seasons, solid-phase extraction with LC-MS/MS, diversity and EPT indices, benthic sampling, and a controlled lab bioassays using Chironomus, analysed. Chronic low dose testing is a priority as well as mixture studies, and paired chemical and biological monitoring.

Keywords: Personal Care Products; Triclosan, Parabens; Benzophenone-3; Aquatic Insects; Chironomus Riparius; Endocrine Disruption; Macroinvertebrates.

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I. Introduction

1.1. Personal Care Products and Aquatic Entry

Personal care products (PCPs) are soaps, shampoos, cosmetics, perfumes, sun protection products and antimicrobial products. These active and inactive ingredients (including preservatives, antimicrobials, UV filters, musks, etc.) enter water bodies via household drains, industrial effluents, urban run-off, swimming, and disposal of unused products. The primary pathway is treatment-plant effluents: based on the review of 141 articles, 72 PCPs reported, 64 found in treatment-plant effluent, 43 found in surface water and 23 in ground water in 30 countries (Montes-Grajales et al., 2017). A study of over 5,000 detections found that antimicrobials, UV filters and polycyclic musks were priorities for treatment and monitoring (Hopkins & Blaney, 2016).

1.2. Ecological Importance of Aquatic Insects

Energy is passed from algae and detritus to fish and terrestrial predators by aquatic insects (mayflies, stoneflies, caddisflies, dragonflies, true flies, and beetles). Shredders and collectors - break down leaf litter and small organic matter, maintaining decomposition and nutrient cycling. There are different groups that are sensitive, making insects useful bioindicators of water quality; the richness and dominance of Ephemeroptera, Plecoptera and Trichoptera (EPT) are some of the most widely used riverine metrics in the world (Eriksen et al., 2021).

1.3. Research Gap

Most of the PCP studies report levels in surface water and wastewater, or acute toxicity to algae, crustaceans and fish. Insects are seldom studied in more than one of these ways. The effects of chronic exposure, larval growth, metamorphosis and emergence success and community-level change in insects are

generally not studied together. The correlation between realistic PCP concentrations and insect diversity should be investigated in detail due to sublethal effects reducing fitness without immediate mortality.

1.4. Research Question, Objectives, and Hypotheses

Research question: How do PCP residues in freshwater affect the development, survival, abundance, diversity, and composition of aquatic insect communities?

Objectives: (i) identify common PCP compounds in freshwater; (ii) quantify them in water and sediment; (iii) assess effects on insect survival and development; (iv) describe changes in abundance, diversity, and composition; (v) relate chemical contamination to biological indicators; (vi) recommend monitoring and control measures.

The paper consists of 6 main sections. Personal care products (PCPs), aquatic insect importance, research gaps and objectives are introduced in section 1. This section 2 covers the residues and toxicity of PCP. In Section 3, the proposed study framework, sampling and statistics are described. Data on concentrations and toxicity are reviewed in Section 4. The findings and mechanism are discussed in Section 5 and the recommendations and control measures are given in Section 6.

II. Background and Literature Review

2.1 PCP Residues in Rivers, Lakes, and Wastewater-Affected Habitats

Triexhlorohydrobenzene (triclocarban) and trichloroethylene (triclosan) are two common antimicrobials found in plants treating domestic sewage according to Indian reviews (Balakrishna et al., 2017). Among 14 targeted compounds, caffeine, triclosan, bisphenol A, and diethyl phthalate were detected in wastewater samples collected from the Vichoor village in Tamil Nadu with variations in concentration in different seasons (Ravichandran et al., 2021). Triclosan (2–84 ng/g), musk ketone (2–26 ng/g), and parabens (87–593 ng/g) were found to be accumulating in sediment in the Hooghly River (Chakraborty et al., 2019). The mean concentrations of summed PPCP in river water along Ganges were in the range of 54.7 to 826 ng/L, which were found to be highest in the middle and lower reaches of the Ganges River, and the estimated risk to aquatic organisms was found to be moderate (Sharma et al., 2019). Another survey conducted in the Ganga for two years found PPCPs and endocrine-disrupting compounds ranging from not detected to 5,850.04 ng/L in water and 1,080.41 ng/g in sediment and included triclosan, triclocarban and methylparaben as the most prevalent (Singh & Suthar, 2021).

2.2 Chemical Stressors and Insect Development

Ecdysteroid signalling controls insect growth and moulting and can be disrupted by xenobiotics, which may lead to effects on development, survival, reproduction and behaviour. Chironomus riparius, the species investigated, is a reference species for toxicology. Exposure to triclosan for 24 hours at 10, 100, and 1,000 µg/L altered the transcription of the genes ecdysone receptor, ultraspiracle, estrogen-related receptor, and E74 and increased the expression of hsp70, suggesting a mode of action that mimics an ecdysteroid (Martínez-Paz et al., 2017). A number of other UV filters also altered the expression of genes encoding hormonal receptors in embryos and larvae of C. riparius (Ozaez et al., 2016).

2.3 Toxicity and PCP-Related Effects

The toxicity of compounds and taxa varies considerably. The 48-h LC50 value of Daphnia magna was 1.09mg/L for BP-3 and 47.47mg/L for BP-4, while the predicted no effect concentration was 1.8µg/L for BP-3 and 0.47mg/L for BP-4, and the BP-3 survival concentration in Nanjing surface water ranged from 3.63 ng/L to 164 ng/L, which was lower than the predicted no effect value (Du et al., 2017). Ethylhexyl methoxycinnamate affected the reproduction of snails in sediment tests with infaunal invertebrates, butyl methoxydibenzoylmethane and octocrylene had no effects in any of the tested invertebrates (Kaiser et al., 2012).

2.4 Limitations of Earlier Research

Existing studies typically expose algae or crustaceans to a single compound, expose for short periods (acute exposure) and are conducted under controlled conditions, and may not include insects in their testing. There are no links between gene-expression changes and emergence or population-level results, and few datasets exist that correlate chemical concentration with indices of insects in the field.

III. Methods

3.1 Study Sites

Four site categories are suggested for urban to peri-urban freshwater reaches in Tamil Nadu, India: S1 (reference sites with little or no domestic wastewater influence); S2 (urban sites with domestic wastewater and runoff); S3 (sites downstream of wastewater-treatment facility discharge); and S4 (agricultural/ peri-urban sites with mixed runoff). Final selection will be based on hydrological connectivity, access and preliminary water-quality screening (at least three independent reaches are selected within each category). This is not an observed observation, but design parameters for the sites and sample numbers.

3.2 Sampling and Analysis

Sampling is done for the pre-monsoon and the post-monsoon season for 12 months and three replications per site and per season. Water samples are collected monthly at a depth of 10-20cm below the surface in pre-cleaned amber glass bottles (1L) in the field, stored at 4°C and accompanied by field blanks, laboratory blanks, duplicates and matrix spikes. Surface sediments 0–5 cm (200–500 g) are taken at 2-month intervals. At each visit, temperature, pH, dissolved oxygen, conductivity and turbidity are recorded.

The targets are triclosan, methylparaben, propylparaben, BP-3, octocrylene, galaxolide and tonalide. Solvent extraction of dissolved fractions and solid phase extraction of water and subsequent analysis by LC-MS/MS or GC-MS using certified standards; solvent extraction of sediment, followed by cleaning and analysis. Internal standard, calibration curve, detection limit and quantification limit, and percentage recovery are examples of quality control.

Insects are collected with a D-frame net or Surber sampler at all riffles, pools and vegetated margins using standard effort and preserved in 70-80% ethanol, then sorted under a stereomicroscope and identified to family and/or genus using recognised keys.

Figure 1 starts with four site categories sampled across pre- and post-monsoon periods. Three parallel streams of data are collected: the collection of water and sediments for residue analysis, collection of benthic insects for community indices, and a controlled Chironomus riparius bioassay for developmental endpoints. The in-situ variables are measured during each sampling trip. The three streams merge in statistical integration (ANOVA, correlation, regression, PERMANOVA and PCA). The final product is exposure-response evidence to support the recommendations for monitoring and measures to control pollution in a wastewater-influenced freshwater system.

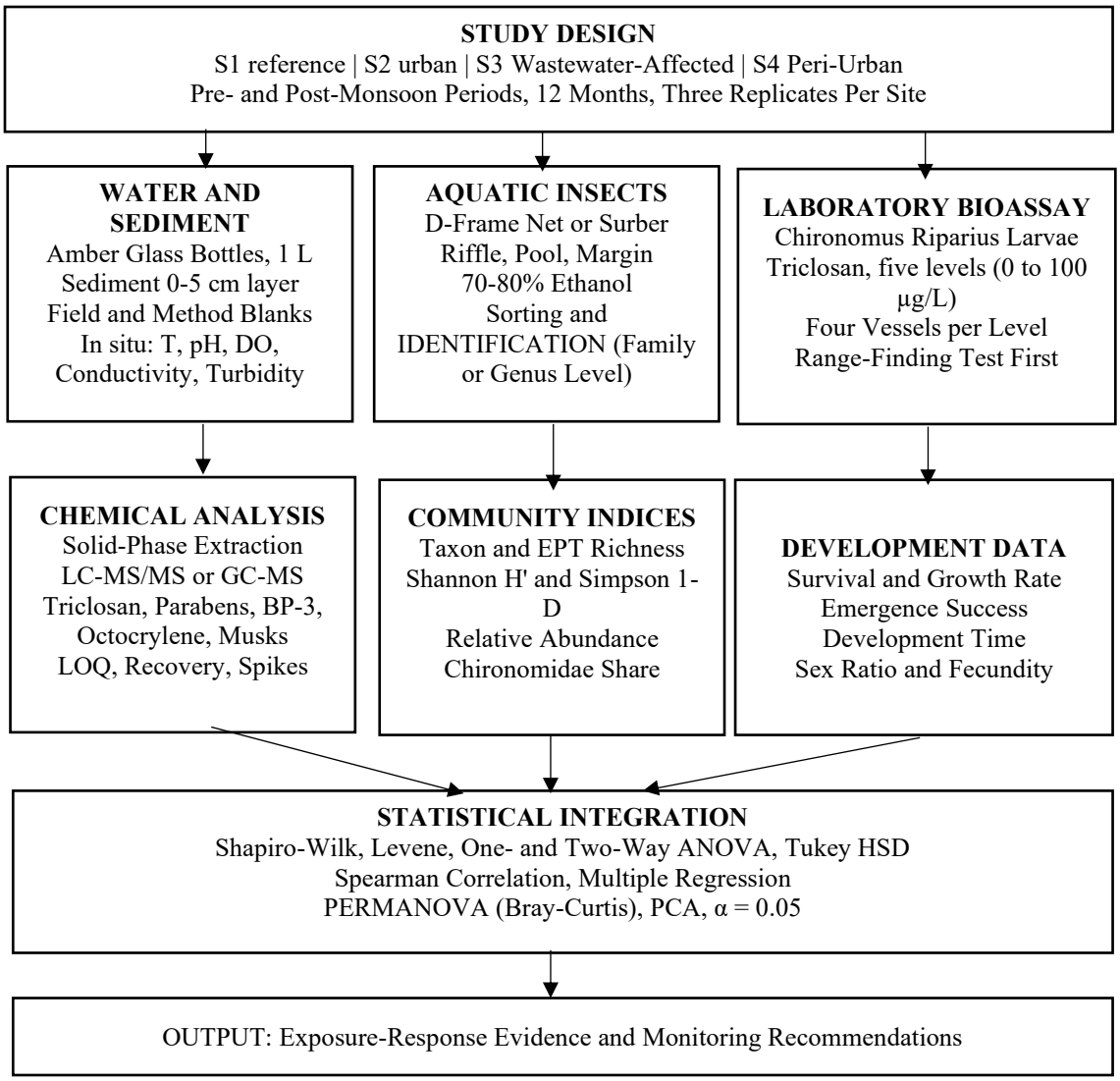


Figure 1: Methodological Flow of the Proposed Field and Laboratory Study

3.3 Community measures and developmental indicators

The mathematical formulas and community/developmental endpoints equation (1) to (5):

Community Diversity Indices

Shannon Diversity Index

$$H' = -\sum p_i \ln p_i \qquad (1)$$

(Where p_i is the proportion of individuals in taxon i)

Simpson Diversity Index

$$1 - D = 1 - \sum p_i^2 \qquad (2)$$

(Where p_i is the proportion of individuals in taxon i)

Laboratory Bioassay Endpoints

Survival Percentage

$$\text{Survival (\%)} = \frac{N_f}{N_i} \times 100 \quad (3)$$

(where N_f is final number and N_i is initial number)

Growth Rate

$$\text{Growth rate} = \frac{W_f - W_i}{t} \quad (4)$$

(where W_f is final weight, W_i is initial weight, and t is time)

Emergence Percentage:

$$\text{Emergence (\%)} = \frac{\text{Emerged adults}}{\text{Initial larvae}} \times 100 \quad (5)$$

3.3 Statistical Analysis

Shapiro–Wilk and Levene tests are used to test for normality and variance homogeneity. One-way ANOVA compares sites or treatments, two-way ANOVA tests season and site effects, and Tukey HSD tests for differences among groups. Spearman correlation and multiple regression test the residuals for correlation with biological indices after controlling for dissolved oxygen, nutrients and habitat. PERMANOVA of Bray–Curti's dissimilarity test is used to examine community composition, and PCA is used to examine chemical and ecological gradients ($\alpha = 0.05$). There is no evidence of causation if it is based on correlation.

IV. Results

4.1 Concentrations and Distribution of PCP Residues

The following results represent values combined for compounds and habitats as defined in Section 3. The number of residues in water matrices ranges from sub-ng/L to mg/L, highest in wastewater. The parabens showed a higher concentration in the sediment samples of the Hooghly River (87 – 593 ng/g) than the musk ketone (2 – 26 ng/g) and triclosan (2 – 84 ng/g). sediment of the Ganga River showed a peak concentration of 1,080.41 ng/g for the PPCP and endocrine-disrupting group.

Table 1: Concentrations of PCP-Related Residues in Aquatic Matrices

Compound or Group	Matrix	Location	Reported Concentration
72 PCPs (141 articles)	Water Matrices	30 Countries	0.029 – 7.811 × 10^6 ng/L
Triclosan	Sediment	Hooghly River	2 – 84 ng/g
Parabens	Sediment	Hooghly River	87 – 593 ng/g
Musk Ketone	Sediment	Hooghly River	2 – 26 ng/g
PPCPs and EDCs	Water	Ganga River	ND – 5,850.04 ng/L
PPCPs and EDCs	Sediment	Ganga River	ND – 1,080.41 ng/g
Benzophenone-3	Surface water	Nanjing, China	3.63 – 164 ng/L

Table 1 consolidates reported concentration ranges used in this paper. The water values range over eight orders of magnitude for compounds and matrices, due to differences in chemistry, wastewater inputs, and sampling design. Sediment levels of triclosan, parabens and musk ketone in the Hooghly River are examples of hydrophobic persistence in benthic habitat. The data from the Ganga River are a combination of

pharmaceuticals, personal care products, and endocrine disrupting compounds. ND = below the reporting limit or not detected. Values are derived from studies as mentioned.

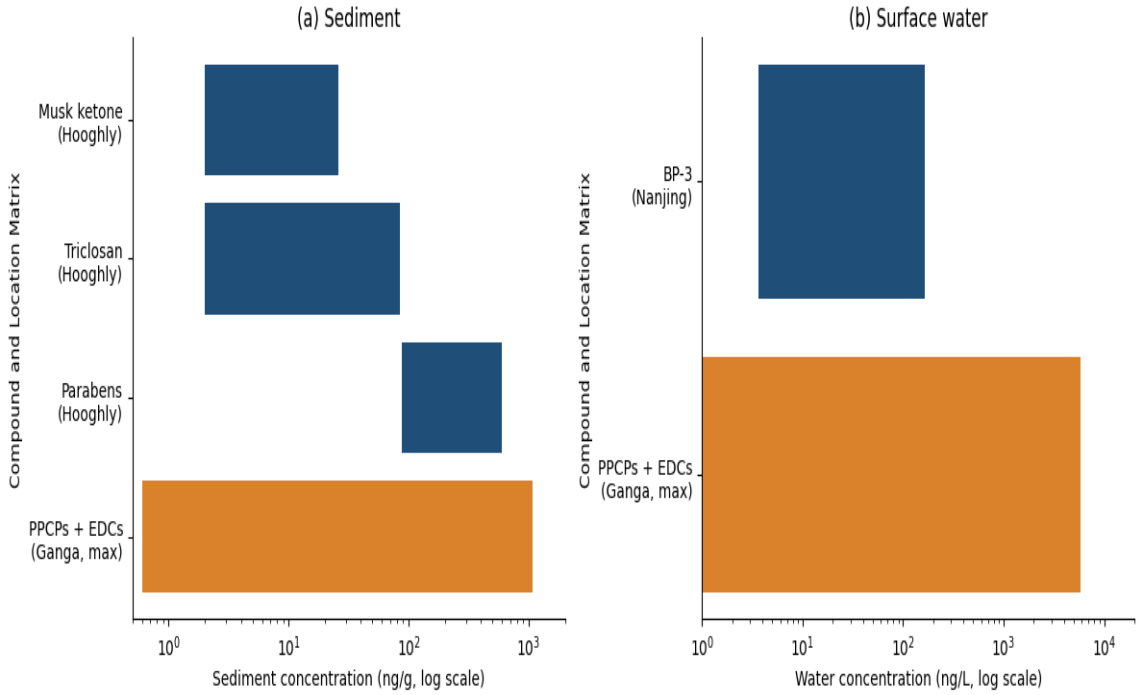


Figure 2: Ranges of Reported Residue Concentrations in (a) Sediment and (b) Surface Water

Figure 2 present minimum to maximum ranges on a logarithmic plot. Figure (a) depicts the concentration of sedimentary musk ketone, triclosan and parabens, which are part of the combined PPCP and endocrine-disrupting group, from the Hooghly River compared with the maximum concentration of the combined PPCP and endocrine-disrupting group from the Ganga River. In Nanjing surface water, the concentration of benzophenone-3 is compared with Ganga water maximum as given in figure (b). The Ganga maxima are the highest sediment value and the parabens are at a distinctly higher sediment range than the triclosan and musk ketone. Ranges marked with hatched bars are those for which the lower limit was not found.

4.2 Experimental Toxicity and Developmental Evidence

Daphnia magna was the most sensitive of the three organisms tested and BP-3 was always more toxic than BP-4. Molecular evidence of insects in the consolidated set is limited to five endocrine and stress genes in C. riparius that were altered after 24 h in the presence of triclosan at 10–1,000 µg/L. The reviewed study reports growth, mortality, development time or emergence data for insects exposed to realistic concentrations of PCP.

Table 2: Acute Toxicity and Predicted No-Effect Concentrations of BP-3 and BP-4

Organism (endpoint)	**BP-3 (mg/L)**	**BP-4 (mg/L)**
Chlorella Vulgaris (96-h EC50)	2.98	201.00
Daphnia Magna (48-h LC50)	1.09	47.47
Brachydanio Rerio (96-h LC50)	3.89	633.00
Predicted No-Effect Concentration	0.0018	0.47

Table 2 shows the Acute values for two benzophenone UV filters are compared between a green alga, crustacean and fish. Depending on the species, toxicity of BP-3 was 44 to 163 times higher than BP-4, with the most sensitive being Daphnia magna. The no-effect concentration for BP-3 is predicted using the assessment-factor method to be 1.8 µg/L while the no-effect concentration for BP-4 is predicted to be

470 µg/L. The surface-water concentrations of BP-3 in Nanjing (3.63-164 ng/L) are below the predicted no-effect level, suggesting a low acute risk at these locations.

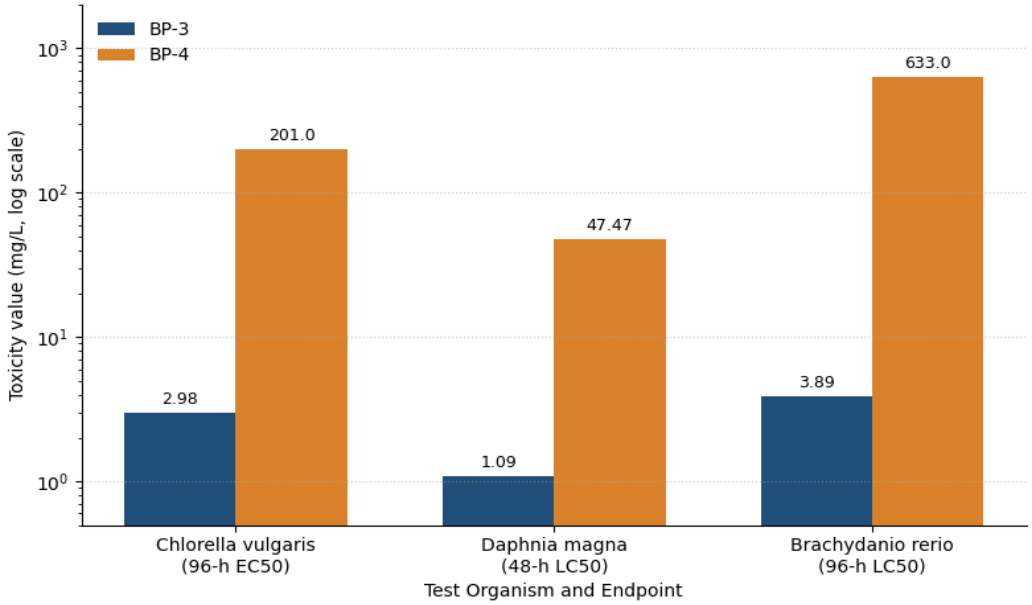


Figure 3. Acute toxicity of BP-3 and BP-4 to Three Freshwater Organisms

Figure 3 display effect concentrations on a logarithmic axis for *Chlorella vulgaris* (96-h EC50), *Daphnia magna* (48-h LC50), and *Brachydanio rerio* (96-h LC50). The values of the BP-3 are 1.09 to 3.89 mg/L while the BP-4 values are 47.47 to 633 mg/L, which is good, it shows that the sulfonated filter is not toxic as much as the BP-3. Invertebrates (Daphnia magna) have the lowest values for both compounds, suggesting that the invertebrates may be more sensitive than the algae or fish. There are still few insect-specific effect concentrations available, restricting benthic risk assessment.

4.3 Insect Communities and Statistical Associations

No effect size reported because the pairs do not have an abundance of insects or EPT richness or Shannon diversity. The statistical analysis answers related questions such as seasonal variations in most wastewater PPCP concentrations ($p < 0.05$, except for bisphenol A, diethyl phthalate and carbamazepine) and statistically significant correlation between PPCP concentrations of bisphenol A and phthalate esters in Hooghly sediment ($r^2 = 0.5$, $p < 0.01$), suggesting common sources. The design will be used to generate the missing paired data.

V. Discussion

5.1 Possible Mechanisms

The most well-documented pathway is endocrine interference: changes in expression of the ecdysone receptor, ultraspiracle and E74 suggest a role in moulting and metamorphosis control. Raised hsp70 is indicative of oxidative or cellular stress. Additional routes of exposure include sediment associated exposure to hydrophobic compounds and loss of microbial food resources due to antimicrobial activity, and additive effects in mixtures of preservatives, UV filters and antimicrobials.

5.2 Comparison with Earlier Work and Confounding Factors

Measured water concentrations of 10-1000 µg/L are orders of magnitude higher than concentrations in the environment (BP-3: 3.63-164 ng/L; summed Ganga PPCPs: 0-5,850 ng/L), thus environmental relevance requires chronic low dose testing. The BP-3 concentrations are below the thresholds predicted to

have no effect but long-term exposures to concentrations of parabens and triclosan in sediment are possible. Low EPT richness below an outfall can also be indicative of low dissolved oxygen, habitat alteration, nutrients, metals, and pesticides, therefore these are also included in the regression design.

5.3 Ecological Implications

The resulting decrease in emergence or delay in development would affect the availability of prey for fish and terrestrial insectivores like spider, birds and bats as well as changing decomposition by changing the feeding groups. Insect indicators continue to be useful in wastewater impacted reaches but need to be used in conjunction with the residue measure to differentiate chemical effects from overall organic enrichment.

VI. Conclusion

Personal care product residues have been found in wastewater, surface water and sediment around the world and for example Indian rivers like the Hooghly and Ganga have been found to contain measurable quantities of triclosan, paraben and musk. Experimental research demonstrates species-specific toxicity of UV filters, and molecular disruption of ecdysone-related genes in Chironomus riparius at 10-1000 µg/L triclosan. These results suggest potential impacts on insect development, but there is no evidence of impacts on insect community diversity or emergence at environmentally realistic concentrations. The overall evidence is therefore consistent with exposure but not yet effect, and hypotheses related to diversity, EPT decline and site differences remain. Some limitations are: the use of single-compound and short-term tests, laboratory concentrations that are higher than field concentrations, limited data on insects, lack of information on mixture effects, and lack of paired chemical and community data. Research priorities include chronic multi-generational exposures (ng/L to µg/L), mixture experiments, sediment-dwelling taxa, and combined molecular and whole-organism endpoints, as well as seasonal sampling. Monitoring should be conducted using chemical analysis of water and sediment, benthic indices such as EPT richness and Shannon diversity and other supporting physicochemical monitoring to differentiate between the effects of PCP and other stressors. Strategies for practical control measures include improvements in wastewater treatment by using activated carbon or oxidation, safer formulations of products, decreased applications of antimicrobials, proper disposal methods for unused products, monitoring of discharge, and more robust regulations of emerging contaminants. Coordinated monitoring and experimental work will provide a better understanding of whether personal care residues pose a threat to insect based freshwater food webs and the ecological indicator value of insects. Future research opportunities involve chronic multigenerational exposures at ng/L to µg/L levels, mixture experiments, and investigations of sediment-inhabiting taxa. Seasonal sampling and combined molecular and whole organism endpoints and paired chemical and biological monitoring are some more priorities. New research needs include chronic exposures on mixture studies to ng/L to µg/L exposures, and studies of sediment-dwelling taxa.

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