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Improve of Footwear Comfort Sensation with Material Packages and Knitted Fabrics

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Abstract
The main goal of this paper was to analyse the hygienic properties of textile packages used for the construction of shoe uppers. Distance fabrics with varied hygienic properties were the basis of these packages. The discomfort indexes, which describe changes in footwear microclimate, were calculated according to the moisture absorbance capacity and temperature changes in the immediate surrounding of the foot skin surface. The experiment was done for a group of grain leather uppers, where the Grubbs test ($\alpha = 0.05$) gave positive information about the outliers, describing such parameters as the water vapour permeability and water vapour coefficient. The phase changes of the shoe microclimate were detected via temperature and relative humidity sensors during simulation of the shoes used via an elliptical trainer for a group of 7 men. Statistically significant differences between the packages upper – lining confirmed the possibility of monitoring the circulation of biophysical mediums inside a footwear volume. The appropriate choice of package materials could raise the comfort conditions for users. For certain material configurations the microclimate conditions described by the discomfort index were improved.

Key words: *footwear comfort, discomfort index, textile package.*

Introduction

The comfort of footwear use is a very complex problem, hence it is necessary to analyse this problem from several different points of view [1]. The comfort aspects are connected with right shape, size and material properties in combination with anthropometric features, which are individual for each user.

The most effective methods to determine the quality of a shoe microclimate seem to be simulation models – i.e. a human skin model [2], experiments with the use of effort simulators (i. e. treadmill [3], multifunctional tools like elliptical trainers [4 – 5], or virtual simulators [6]). This makes it possible to simulate real effort conditions with the inclusion of several aspects: biomechanical, connected with gait patterns, and biophysical, concentrated around the sweat secretion mechanism during the exercise duration.

A lot of simulators are based on foot – ground reaction forces [7-9]. Few investigations have focused on the interactions between the foot surface and the upper. This part of the foot is exposed to injuries during walking or running. The significant aspect is that footwear should support the foot muscles (in particular the extensors of toes and fingers, which lie along the dorsal plane), especially in the stance phase of gait [10].

The other model which can successfully describe the qualitative aspects of footwear comfort is the thermal foot model, which was invented in Finland. Originally this model consisted of 16 zones which simulated perspiration processes. It also gave a possibility to measure the heat flux in particular zones [11]. Now there are many thermal models of the human body fitted with individual characteristics like the temperature or perspiration rate [12].

On the other hand, a lot of literature sources show that thermal comfort conditions may be predicted with fabric (and their packages) properties, like thermal insulation or biophysical medium buffering indexes [13]. For example, in paper [14] the authors combined cotton and Angora rabbit fibres in order to produce knitted fabrics with better comfort properties. The authors of [15] established that the thermal properties of double – layered packages knitted from cotton or man – made bamboo yarns with polyamide, polypropylene or polyester were improved. The structure of fabrics is one of the most important determinants of some hygienic properties. For example, in papers [16-17] it was shown that the channel inlets of single fabrics can improve the air permeability, water vapour resistance and thermal resistance indicators for flat textile products. In order to optimise thermal conditions in a shoe volume, it is assumed that the material in the close foot skin neighbourhood should be water vapour permeable, and the further layer must be a good water vapour absorber. The effectivity of this configuration depends on the principal physical characteristics of textiles, like the porosity [18], geometry and position of loops, stitch density [19-21] or the thickness and mass per square metre of the fabric [22].

For the purposes of this paper, the authors conducted a study of textile and lining materials which are commonly used for footwear manufacture. To reduce the degrees of freedom, simulations were conducted in a limited group of footwear – with the use of only one insole material – natural flank leather and rubber for the sole.

The results of discomfort indexes are differentiated according to the upper and lining materials applied and their packages.

On that basis it was possible to pick the best packages, from the user's point of view, which were able to minimalise the discomfort sensation during the effort simulation.

Materials and method

Experimental tests were carried out with use of three types of high – quality upper leathers (***Table 1***). Samples of leather materials were collected from a specific part of leather due to the ISO standard [23]. All of upper leathers were grain types. The grain pattern of the leather is a part of the hide of an animal lying just below the hair. It is called full – grain leather (SW1), which is the strongest and most durable leather. Top – grain leather (SW2, SW4) is similar to that previously mentioned, but imperfections are taken

Table 1. Types of upper materials used in study.

Type of upper materials	Symbol	Thickness, mm	Softness, mm	Water vapour permeability, mg/cm²h (acc. to [25])	Water vapour coefficient, mg/cm² (acc. to [25])	Water absorption in dynamical conditions, mg/cm² (acc. to [25])
Calfskin full – grain leather	SW1	1.21 ± 0.06	4.12 ± 0.16	5.7 ± 0.5	52.9 ± 3.1	103.9 ± 1.0
Calfskin top – grain leather	SW2	1.38 ± 0.06	2.71 ± 0.20	10.1 ± 0.4	87.6 ± 2.5	6.9 ± 0.6
Grain leather type 'soft'	SW4	1.11 ± 0.08	2.97 ± 0.15	8.6 ± 0.9	75.3 ± 3.6	98.1 ± 2.8

away by sanding and buffing processes. The strength and durability of this leather are weaker than for full – grain. As linings leathers and textiles were used (***Tables 2*** and ***3***). In order to minimise the degrees of freedom, the same insole material was used, which was natural flank leather of 2 mm thickness. The model of shoe used represents the class of laced outdoor footwear (work or sport shoe) with an integral ankle support with an adjustable stoutness level [24]. Phase changes of the shoe microclimate were detected during simulation of the shoes used via an elliptical trainer for a group of 7 men at the age of 59.4 ± 1.9 who have a BMI equal to 24.9 ± 3.7. For each upper material, the basic hygienic parameters were measured [25]: water vapour permeability (WVP), water vapour coefficient (WVC) and indirectly – water vapour absorption (WVA). The relation between the water vapour permeability and water vapour absorption is given as ***Equation 1***:

$$W_{VC} = 8 \cdot W_{VP} + W_{VA} \qquad (1)$$

For the upper materials the water vapour absorption coefficient was also calculated. This aspect depends on the kind of retaining, type of fat liquor used and finishing, and has a great influence on thermal comfort, especially in wet conditions. From the user's point of view, important is also the softness of the leather, which corresponds to the leather structure. In paper [26] the authors showed that a strong relationship between softness and water vapour permeability exists.

Changes in the microclimate in the shoe volume interior were recorded during effort simulation using an elliptical trainer. The effort cycle was divided into three periods: rest (30 min), exertion (30 min) and relaxation (30 min). By using T/RH sensors, the effective changes in humidity and temperature were continuously recorded. The experiments were done in an air – conditioned room, where the temperature and relative humidity were equal to 21 ± 0.5 °C and 45 ± 2%, respectively. The T/RH sensors were located in two sectors where sweat secretion was the highest; first between the toe cap and forefoot in front of the arch and second – inside the filler [27, 28].

Table 2. Types of lining textile materials used in study.

Type of lining textile materials	Symbol	Water vapour permeability [mg/cm²h] (acc. to [25])	Water vapour coefficient, mg/cm² (acc. to [25])
3D knitted fabric with PA fibres	MP1	30.5 ± 4.2	245.0 ± 17.5
3D knitted 'a-jours' fabric with PA	MP2	45.8 ± 0.9	367.4 ± 6.1
Trevira	MP8	21.5 ± 1.7	173.3 ± 11.5
Knitted fabric PE (small loop)	MP39	37.7 ± 2.2	301.3 ± 3.2
Microfibre PE	MP41	21.3 ± 3.2	170.7 ± 7.1
Knitted fabric PE (bigger loop)	MP42	42.6 ± 5.2	341.7 ± 8.2

Table 3. Types of lining leather materials used in study.

Type of lining leather materials	Symbol	Water vapour permeability, mg/cm²h (acc. to [25])	Water vapour coefficient, mg/cm² (acc. to [25])
Cow split grinded leather	SP1	15.8 ± 0.8	136.0 ± 4.5
Cow leather	SP2	13.6 ± 1.1	128.3 ± 8.2
Pig grain leather	SP3	15.3 ± 0.6	113.6 ± 1.8

Table 4. Set of materials analysed.

Group I (materials compiled with MP41)	Group II (materials compiled with MP39)	Group III (leather lining materials)
MP8 + MP41	MP8 + MP39	SP1
MP42 + MP41	MP42 + MP39	SP2
MP2 + MP41	MP2 + MP39	SP3
MP1 + MP41	MP1 + MP39	

Results and discussion

Analysis of the impact of the combination of materials on the discomfort index values was carried out with the use of one – way statistical variance analysis – ANOVA. Independent variables used in this test were visualisation of the discomfort index means, obtained during physical effort and based on temperature and relative humidity values. The aggregation of experimental results in dependence on the type of material is shown in ***Table 4***.

On the basis of literature sources [29, 30], the range between 70 and 85% for relative humidity inside the footwear during physical effort was considered a partial discomfort zone, and over 85% – a total discomfort zone. Thus the following indicators are true:

$$T_{RH>70\%} = T_{70\%}/T, \qquad (2)$$

where, $T_{70\%}$ is the time when the relative humidity is higher than 70%, and T is the total effort duration.

Therefore the discomfort index for relative humidity higher than 70% is defined as ***Equation 3***:

$$DI_{RH>70\%} = \frac{(AVG_{RH>70\%} - 70\%)}{30\%} \qquad (3)$$

where, $AVG_{RH>70\%}$ is the approximate value of the relative humidity result for a set of values exceeding 70%.

Hence the generalised discomfort index is defined by the ***Equation 4***:

$$DI = T_{RH>70\%} \cdot DI_{RH>70\%} \qquad (4)$$

In order to implement the ANOVA procedure, the following assumptions, H_0 and H_1, were made:

H_0 – means of values of discomfort indexes are equal,
H_1 – some differences between values of discomfort indexes exist.

To determine which groups of materials differ from each other, a Tukey single – step multiple comparison was performed. The confidence interval was computed and fixed at 95%. The results obtained are listed in ***Tables 5-7***.

Comparison between SW1 and SW2

According to the ANOVA analysis of pairs of materials, it was shown that between the following material packages: MP8 + MP41 versus MP1 + MP41, MP42 + MP41 versus MP1 + MP41, and MP2 + MP41 versus MP1 + MP41, a statistically significant interference of the discomfort index exists. The test statistic (Test F) of the treatment means is equal to 6.59 and is larger than the critical value of the F distribution (105.48). Hence this fact implies a qualitative variation between discomfort indexes in this group of materials (upper and linings) (***Table 5***). Following confirmation of where the differences between groups occurred, the HSD for each pair of means was calculated.

In the case where material MP41 was substituted by MP39, statistically significant differences were also observed. The Test F – value was equal to 6.59 as compared to the F – value, which was equal to 67.05. With regard to the Tukey post-hoc analysis, it can be noticed that statistically significant interference occurred between the following material packages: MP8+MP39 vs MP1+MP39, MP42+MP39 vs MP1+MP39, MP2+MP39 vs MP1+MP39 (***Table 6***).

For lining leathers SP1, SP2, SP3 connected to SW1 and SW2 uppers, when statistic F is not within the range of the confidence interval (Test F – value (9.55) larger than the F – value (5.14)), there is no reason for rejection of the null hypothesis regarding the lack of diversification between comfort indexes.

Table 5. *Comparison of Tukey post-hoc analysis values for given materials mixed with SW1 and SW2 uppers.*

Treatment pair	Tukey HSD Q statistic	Tukey HSD p-value	Tukey HSD interference
MP8 + MP41 vs MP1 + MP41	19.50	0.001	significant (p < 0.01)
MP42 + MP41 vs MP1 + MP41	17.76		
MP2 + MP41 vs MP1 + MP41	22.99		
MP8 + MP39 vs MP1 + MP39	15.63		
MP42 + MP39 vs MP1 + MP39	13.89	0.002	
MP2 + MP39 vs MP1 + MP39	18.36	0.001	

Table 6. *Comparison of Tukey post-hoc analysis values for given materials mixed with SW2 and SW4 uppers.*

Treatment pair	Tukey HSD Q statistic	Tukey HSD p-value	Tukey HSD interference
MP8 + MP41 vs MP1 + MP41	8.98	0.011	significant (p < 0.05)
MP42 + MP41 vs MP1 + MP41	8.10	0.016	
MP2 + MP41 vs MP1 + MP41	10.57	0.006	significant (p < 0.01)
MP8 + MP39 vs MP1 + MP39	8.44	0.014	significant (p < 0.05)
MP42 + MP39 vs MP1 + MP39	7.42	0.021	
MP2 + MP39 vs MP1 + MP39	9.89	0.008	significant (p < 0.01)

Table 7. *Comparison of Tukey post-hoc analysis values for given materials mixed with SW2 and SW4 uppers.*

Treatment pair	Tukey HSD Q statistic	Tukey HSD p-value	Tukey HSD interference
MP8 + MP41 vs MP1 + MP41	15.90	0.001	significant (p < 0.01)
MP42 + MP41 vs MP1 + MP41	14.60	0.002	
MP2 + MP41 vs MP1 + MP41	18.82	0.001	
MP8 + MP39 vs MP1 + MP39	17.84	0.001	significant (p < 0.05)
MP42 + MP39 vs MP1 + MP39	15.90	0.001	
MP2 + MP39 vs MP1 + MP39	20.76	0.001	significant (p < 0.01)
SP1 vs SP2	17.68	0.002	
SP1 vs SP3	7.07	0.031	significant (p < 0.05)
SP2 vs SP3	10.61	0.010	significant (p < 0.01)

Comparison between SW2 and SW4

When a comparison was made within the SW2 and SW4 groups, significant differences occurred because of the presence of the following materials: MP8, MP1, MP2 and MP42 in packages composed of MP41 and MP39. The post-hoc significances are given as follows (***Table 6***).

For lining leathers connected to SW2 and SW4 uppers, when statistic F is not within the range of the confidence interval and Test F (9.55) is larger than F (3.23), there is no reason for rejection of the null hypothesis regarding the lack of diversification between comfort indexes. This is the same situation as when SW1 and SW2 were used.

Comparison between SW1 and SW4

As in the previous cases, we can observe the influence of MP8, MP1, MP42 and MP2 on the diversity level of the comfort index for both MP39 (Test F is equal to 6.59, F – 86.53) and MP41 (Test F is equal to 6.59, F – 70.67). In contrast to the previous pairs analysed (SW1 versus SW2 and SW2 versus SW4), for this case significant differences were observed for all possible combinations of leather linings i. e. SP1, SP2, SP3 (Test F – 9.55, F – 79.17) (***Table 7***).

Statistical analysis of groups of lining – upper sets provided information that the discomfort index is different because of the materials applied in the combinations with uppers.

Thus the material combinations are very important in inducing optimal temperature and humidity conditions for users during physical effort. When the uppers SW1 and SW2 are applied, statistically significant differences were obtained between MP8 – MP2, MP1 – MP42 and MP1 – MP2 in combination with MP41 ($p_{value} = 0.001$). Maximum values of discomfort indexes (between 0.15 – 0.19) were recorded for MP42 connected with

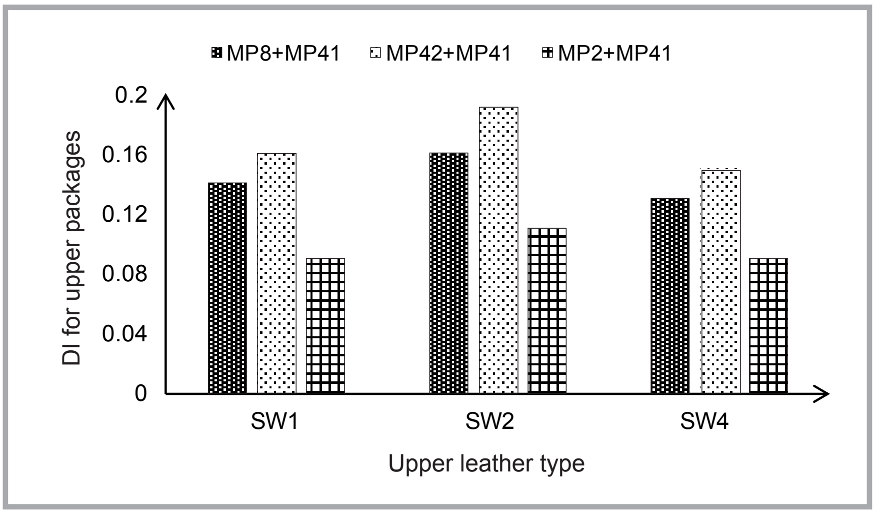

Figure 1. Discomfort index ratio for sets of materials MP8, MP2, MP42 mixed with MP41 due to uppers SW1, SW2 and SW4.

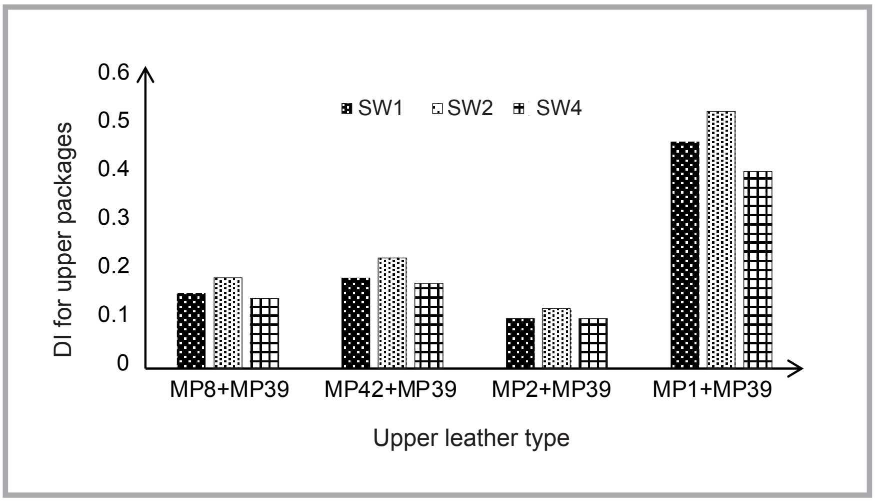

Figure 2. Discomfort index ratio for sets of materials MP8, MP2 and MP42, mixed with MP39 due to uppers SW1, SW2 and SW4.

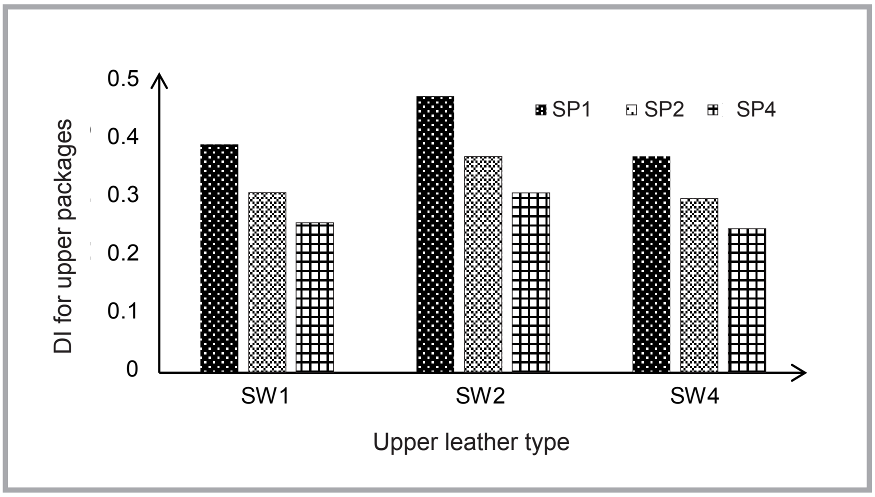

Figure 3. Discomfort index ratio for sets of materials SP2, SP3 and SP1 due to uppers SW1, SW2 and SW4.

MP41 (***Figure 1***) and for MP1 mixed with MP39 (from 0.39 for SW4 to 0.51 for SW2) (***Figure 2***).

When material MP41 was substituted by MP39, we observed analogous results. From the user's point of view, following combinations are favourable: MP2 – MP39 – SW1 and MP2 – MP39 – SW4, with the discomfort index fluctuating around 0.10.

This trend was also observed for the following combinations: SW1 versus SW4 and SW2 versus SW4. The conducted analysis gave the possibility to highlight the uppers and linings, which are able to minimalise the discomfort sensation. The best materials are given as follows: MP2 – MP41 – SW1 and MP2 – MP39 – SW1 (given above) and for analogous compositions with the SW4 upper: MP2 – MP41 – SW4 (DI = 0.09) and MP2 – MP39 – SW4 (DI fluctuating around 0.10). It is worth noting that only the MP41 and MP39 materials were selected because for the other materials, where changes in the discomfort indexes were recorded after longer time of use – for 30 minutes exertion, the changes were not significantly invisible.

An interesting observation is that for leather linings statistically significant differences occurred only for uppers SW1 and SW4 (***Figure 3***).

According to the minimalised discomfort index, we can state the best materials: SP1 (DI = 0.24), SP2 (DI = 0.36) and SP3 (DI = 0.29). Hence, in general, when we would like to use leather linings, the best will be SP1.

Summary

Analysis of the relationship between combinations of lining and upper materials and discomfort indexes values obtained on the basis of effort simulations confirmed that differences exist and are statistically significant. Optimal choice of footwear materials can give positive results in minimalising discomfort conditions inside the footwear volume. It is a very important aspect, especially for miscellaneous special footwear manufacturers, like footwear for workers [31, 32], athletes [33] and children [34]. In these cases, the risk of sweating the footwear materials is higher than elsewhere.

The most important is for the lining to to be kept away from the foot skin and accumulated sweat and water, and of second importance is its strong absorbance. Thus this way of making material mixtures is a very important factor in the supporting of biophysical medium exchange between the interior and exterior of shoes, making it possible to reduce the discomfort index during physical activity. For this purpose the most suitable are knitted fabrics (i.e. MP2), because they have a spatial warp structure, and the accumulation of moisture is possible inside the empty spaces. This feature is very good support for sweat distribution, especially for an alkaline environment, which is characteristic for physical activities [35]. There are multiple papers which confirm the validity of applying multi – layered compositions in order to improve the functionality of clothing or footwear. In [36] the authors showed that for materials composed of two textiles: natural and synthetic, an improvement in the discharge of sweat and vapour from the skin surface was observed.

A theoretical model of moisture transport is a very difficult issue, due to the fact that sweat exists in two forms: liquid or saturated steam. The second aspect is that sweat secretion is not a continuous process, the velocity of which depends on individual features of the organism [37].

The research conducted in this paper gives advice on the design of a footwear material system in respect of the hygienic properties of materials, which can be reflected in the improvement of comfort sensation in a wide spectrum of aspects. This area is also important for manufacturers because it can be a part of innovative solutions in the footwear sector. For example, the use of innovative materials or material packages can improve functionality and environmental – safety. Controlling thermal and humidity properties can improve some characteristics of the final product [38], for example, better hygienic properties can reduce the probability of pathogenic microbes, fungi diseases or odours arising [39]. The concept presented in this paper will be valid for various types of footwear solutions, especially for elderly people and children [34] as well as in the sport, military and protective fields [40].

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  - development of new research and analytical methods;
- **research services** (measurements and analytical tests) in the field of environmental protection, especially monitoring the emission of pollutants;
- **seminar and training activity** concerning methods of instrumental analysis, especially the analysis of water and wastewater, chemicals used in paper production, and environmental protection in the paper-making industry.

Since 2004 Laboratory has had the accreditation of the Polish Centre for Accreditation No. AB 551, confirming that the Laboratory meets the requirements of Standard PN-EN ISO/IEC 17025:2005.

AB 388

Investigations in the field of environmental protection technology:

- Research and development of waste water treatment technology, the treatment technology and abatement of gaseous emissions, and the utilisation and reuse of solid waste,
- Monitoring the technological progress of environmentally friendly technology in paper-making and the best available techniques (BAT),
- Working out and adapting analytical methods for testing the content of pollutants and trace concentrations of toxic compounds in waste water, gaseous emissions, solid waste and products of the paper-making industry,
- Monitoring ecological legislation at a domestic and world level, particularly in the European Union.

A list of the analyses most frequently carried out:

- Global water & waste water pollution factors: COD, BOD, TOC, suspended solid (TSS), tot-N, tot-P
- Halogenoorganic compounds (AOX, TOX, TX, EOX, POX)
- Organic sulphur compounds (AOS, TS)
- Resin and chlororesin acids
- Saturated and unsaturated fatty acids
- Phenol and phenolic compounds (guaiacols, catechols, vanillin, veratrols)
- Tetrachlorophenol, Pentachlorophenol (PCP)
- Hexachlorocyclohexane (lindane)
- Aromatic and polyaromatic hydrocarbons
- Benzene, Hexachlorobenzene
- Phthalates
- Carbohydrates
- Glycols
- Polychloro-Biphenyls (PCB)
- Glyoxal
- Tin organic compounds

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