

Article

Characterization of Pyrolysis Oils Using a Combination of GC×GC/TOFMS and GC/HRMS Analysis: The Impact of Data Processing Parameters

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Abstract

Human population growth and increasing transportation demands have led to rising global tire consumption and associated waste. In response, various material and energy recovery strategies, such as pyrolysis, have been developed to produce high-value-added products such as pyrolysis oils, which can be reused as materials or fuels. However, these oils often contain heteroatom-containing compounds (e.g., nitrogen, oxygen, sulfur) that can hinder their valorization and must therefore be identified and removed. To characterize heteroatomic compounds present in distillation fractions of pyrolysis oils, GC×GC/TOFMS and GC/HRMS were employed. For non-target analysis, data processing parameters were optimized using a Central Composite Design (CCD). The most influential parameters for GC×GC/TOFMS were the minimum number of mass-to-charge ratio (m/z) signals kept in the deconvoluted spectra (minimum stick count) and peak signal-to-noise ratio (S/N), while for GC/HRMS, optimization focused on the m/z S/N threshold, peak S/N, and total ion current (TIC). Under optimal conditions, 129 and 92 heteroatomic compounds were identified via GC×GC/TOFMS and GC/HRMS, respectively, within a single distillation fraction, with 57 compounds identified using both techniques. Notably, GC×GC/TOFMS exclusively identified 72 compounds, while there were only 5 unique to GC/HRMS. These results highlight the effectiveness of GC×GC/TOFMS in characterizing heteroatomic compounds in complex mixtures, while also underlining the complementary value of GC/HRMS.

Keywords: central composite design; tire recycling; data processing; pyrolysis



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1. Introduction

Currently, different types of pollution, having a negative impact on the environment, are generated by transport (whether public or private). They do not only consist of air pollution (the emission of CO₂ or SO₂ by using fuels for instance), but also of industrial waste, especially tire waste. With the growth of the human population, and consequently the growth of transport use, the demand for tires has increased around the world. In fact, the production rate of all types of tires is continuing to grow as their demand in developed countries is rapidly increasing. In 2023, the global consumption of tires and tire products

was 17 billion tons, an increase of 1% from 2022 [1]. According to the literature, the annual rates of tire accumulation are considerable: around 1.5 billion waste tires are produced per year after their end of life, which will increase to 5 billion by the end of 2030 [2,3]. Different methods to manage tire waste have been considered in the past few decades, with the most common being landfilling, direct reutilization, retreading, and material and energy recovery [2,4]. With restrictions on waste tire disposal in landfills, 95% of wasted tires were collected and treated for material recycling and energy recovery in Europe in 2019 [5].

Pyrolysis constitutes an alternative tire waste treatment method that can obtain high-value-added products [6,7]: solid residues (such as recovered carbon black and metals), gases (such as methane and hydrogen, which can be recycled as a syngas) and the product of interest in this study, pyrolysis oils, which may be reused as a source of materials and fuel [7–9]. Pyrolysis oils are a complex matrix containing high amounts of aliphatic, aromatic and heterocyclic compounds (usually more than thousands of compounds, some of which have similar boiling points) [7,8,10]. For this reason, the distillation of pyrolysis oils is commonly performed to simplify the matrix and to obtain different fractions for targeted valorization processes.

Several analytical methods have been considered to characterize the chemical composition of these samples. Gas chromatography coupled with low-resolution mass spectrometry (GC/MS) [6,11,12] and liquid chromatography coupled with low-resolution mass spectrometry (LC/MS) were applied to understand the composition of the distillation fractions of pyrolysis oils and evaluate their applications [13,14]. However, the analysis of these samples with these conventional methods is complicated. In order to obtain a detailed characterization of the pyrolysis oils of waste tires, high-resolution MS and/or high chromatographic resolution is necessary. Zhang et al. (2023) have analyzed light fractions of waste tire pyrolysis oil (WTPO) using GC/MS and a GC/nitrogen chemiluminescence detector (NCD) in order to characterize the nitrogen compounds present in WTPO [15]. Due to the high complexity of heavy distillation fractions, Fourier-Transform Ion Cyclotron Resonance Mass Spectrometry (FT-ICR MS) was employed to detect nitrogen compounds instead of GC/MS [15]. Li et al. (2023) demonstrated the advantages of Comprehensive two-Dimensional Gas Chromatography combined with Time of Flight Mass Spectrometry (GC×GC/TOFMS) over GC/MS for analyzing heavy lubricant oil due to its high separation capacity [16]. Furthermore, the authors compared the characterization results of GC×GC/TOFMS and Atmospheric Pressure Chemical Ionization (APCI)-Orbitrap MS in the same study [16].

More specifically, the detailed characterization of the volatile fraction of pyrolysis oils (plastic waste [17] and crude tire [18]) has previously been conducted using GC×GC/TOFMS and Gas Chromatography combined with High-Resolution Mass Spectrometry (GC/HRMS) [19]. GC×GC increases peak capacity by utilizing the ideal orthogonality of two columns; for instance, a non-polar column in the first dimension to separate compounds according to their volatility and a polar column in the second dimension to separate them according to polarity [20,21]. Reversed configuration was also considered to complete the normal configuration. The choice of column configuration should be made with care: Mahé et al. (2011) compared four normal configurations with four reverse configurations to determine which combination was the most well adapted for heavy petroleum cuts [22]. Therefore, compounds that coeluted in one-dimensional gas chromatography (GC-1D) can often be resolved in GC×GC, making it particularly useful for complex mixtures. Moreover, due to the cryogenic modulation process, compounds are collected and focused into narrower and more concentrated modulated peaks that are reinjected in the second column, hence increasing the sensitivity of the analysis compared with

GC-1D [23]. Therefore, trace compounds can be more easily detected. HRMS allows the determination of the m/z of ions with high resolving power and mass accuracy: ions with very close m/z values can be distinguished, making it efficient for the identification of unknown compounds, isotopic patterns and elemental compositions [24,25]. HRMS is usually coupled with GC for the targeted and untargeted analysis of volatile and semi-volatile compounds, including those containing heteroatoms such as nitrogen, oxygen and sulfur [26,27]. According to previous studies, heteroatomic compounds present in pyrolysis oils hinder their valorization. For example, sulfur and nitrogen compounds are sources of toxic and corrosive gas such as SO_x and NO_x [7,11,15,28,29].

In this study, GC $\times$ GC/TOFMS and GC/HRMS analytical protocols were used for the untargeted analysis of pyrolysis oils from car waste tires, with a particular focus on the characterization of heteroatom-containing compounds. Two distillation fractions of pyrolysis oil were characterized by this analytical strategy. After chromatographic acquisition, the data processing software, ChromaTOF for GC $\times$ GC/TOFMS and TraceFinder for GC/HRMS, were used to deconvolute coeluted peaks. Here, different software parameters were studied and optimized in an innovative manner as they can have a critical impact on the detection of trace-level compounds. Until now, the determination of these parameters has rarely been discussed in detail in the literature, with several articles roughly reporting the applied values [21,30]. Therefore, in the present study, the key parameters for each data processing software were identified by a CCD that could assess the influence and interactions of software parameters and model the responses in view of optimization [31–33]. The number of detected peaks and true positives were considered as responses. The optimization criteria were to minimize the number of detected peaks and maximize the true positives for identification. Using the identified optimal settings, compound identification of selected fractions was performed with each software. The resulting peak attributions were then compared to evaluate which approach, GC $\times$ GC/TOFMS or GC/HRMS, was more suitable for the untargeted analysis of heteroatom-containing compounds in the pyrolysis oils.

2. Materials and Methods

2.1. Sample Preparation

Tire pyrolysis oil was purchased from Enviro Systems (Gothenburg, Sweden). This oil was subjected to distillation, yielding eight fractions with boiling points ranging from 95 °C to 549 °C. Fractions 369 °C to 509 °C and 509 °C to 549 °C could not be easily analyzed by GC $\times$ GC/TOFMS: the nitrogen cryogenic modulator can trap the heaviest molecules and these two heavy fractions risked being partially eluted. The six remaining fractions were considered for this study. Among them, two light fractions named fraction A (95–142 °C) and B (142–169 °C) were chosen. Fraction A and B could be considered representative of pyrolysis oil fractions in terms of their complexity and were analyzed using GC $\times$ GC/TOFMS and GC/HRMS. The distillation fractions were diluted tenfold with dichloromethane before use. A C_8 – C_{40} alkane mixture (Sigma-Aldrich, Saint-Quentin-Fallavier, France) was used to determine the linear retention indices of the identified compounds. As the original concentration of the standard (1000 ppm) was too high, it was diluted 20-fold in dichloromethane before use.

2.2. GC $\times$ GC/TOFMS Analysis

Once prepared, the distillation fractions of the pyrolysis oils were analyzed using a GC $\times$ GC/TOFMS system (Pegasus BT4D, LECO, Villepinte, France). The Pegasus BT4D combines a TOFMS detector and an Agilent 7890 GC device equipped with a cryogenic modulator and a secondary oven. A normal configuration was chosen. A non-polar

column, Rxi-5ms column (5% diphenyl/95% dimethylpolysiloxane; 30 m $\times$ 0.25 mm $\times$ 0.25 μ m; Restek, Lisses, France) was used in the first dimension (1D). In the second dimension (2D), a medium polar DB-1701 (14% cyanopropyl-phenyl-methylpolysiloxane; 52 cm $\times$ 0.18 mm $\times$ 0.18 μ m; Agilent, Les Ulis, France) was installed in the secondary oven. This column configuration allowed us to separate the compounds according to their volatility. Heteroatomic compounds, the compounds of interest, were located at the top of the 2D chromatogram. Other column configurations could also have been considered, especially the reverse configuration, but this was beyond the scope of the present study. Helium was used as the carrier gas at a constant flow rate of 1 mL/min. The Split/Splitless liquid (SSL) injector was maintained at 300 °C with a split ratio of 100:1. The oven temperature program began at 35 °C (held for 2 min) and increased at 3 °C/min to 250 °C (held for 5 min). The secondary oven followed the same temperature program with a 5 °C offset. Modulation was performed using a QuadJetTM nitrogen cryogenic modulator, operating with a 4 s modulation period composed of two 2 s stages: 1.2 s hot jet and 0.8 s cold jet. After compound separation, analytes were transferred to the TOFMS via a deactivated silica transfer line (31 cm $\times$ 0.18 mm) heated to 250 °C. Mass spectra were recorded over a mass range of 45–500 m/z with an acquisition rate of 200 spectra/s. To calculate the retention indices, a solution of C₈–C₄₀ alkanes (50 ppm) was injected under the same analytical conditions [34].

2.3. GC/HRMS Analysis

For the GC/HRMS analysis of the distillation fractions, a Q-Exactive GC Orbitrap system coupled with a Trace 1310 GC (Thermo Fisher Scientific, Waltham, MA, USA) was employed. A non-polar HP-5ms column (5% diphenyl/95% dimethylpolysiloxane; 30 m $\times$ 0.25 mm $\times$ 0.25 μ m; Agilent) was installed. This column was nearly the same one as the column used in the first dimension of GC $\times$ GC/TOFMS in order to provide a similar separation. Helium was used as the carrier gas at a constant flow rate of 1 mL/min. The SSL injector was maintained at 300 °C with a split ratio of 20:1. The oven temperature program started at 40 °C (held for 3 min), increased at a rate of 5 °C/min to 300 °C (held for 5 min). These temperature program settings are quite standard and are routinely used in this technique to allow a reasonable analysis time. After chromatographic separation, analytes were transferred to the HRMS through the non-polar column, of which the last centimeter also served as a heated transfer line maintained at 300 °C. Mass spectra were acquired over a mass range of 50–500 m/z with a mass resolution set at 60,000 (corresponding to an acquisition rate of 7 spectra/s). A solution of C₈–C₄₀ alkanes (50 ppm) was injected under the same analytical conditions as the real samples, enabling the calculation of retention indices for compound identification.

2.4. Data Processing Software

Once the distillation fractions of the pyrolysis oils were analyzed by GC $\times$ GC/TOFMS and GC/HRMS, the resulting chromatograms were processed using dedicated software. Due to the complex nature of pyrolysis oil matrices, many peaks in both one-dimensional and two-dimensional chromatograms were coeluted. Therefore, deconvolution was essential for accurate peak identification. ChromaTOF (v5.55.41, Leco Corporation, St. Joseph, MI, USA) was used for processing the GC $\times$ GC chromatograms, while TraceFinder (v4.1) equipped with the deconvolution plugin (v1.7, ThermoFisher Scientific instruments, Waltham, MA, USA) was used for the GC/Orbitrap data. After deconvolution and data processing, untargeted analysis was performed by comparing the obtained mass spectra with entries in the National Institute of Standards and Technology (NIST) mass spectral library (NIST 20). Both software platforms provided preliminary lists of identified compounds,

which were subsequently verified manually using retention indices to ensure accuracy of the identification.

2.5. Level of Identification Confidence

In this study, the detection of heteroatom-containing compounds arises from proposed identifications automatically generated through the data processing method. However, their identities must be manually verified using their calculated retention index in both GC×GC/TOFMS and GC/HRMS and/or their position in the 2D chromatogram in the case of GC×GC/TOFMS. A detected compound was considered as a true positive if its mass spectrum and retention index (semi-standard non-polar column) match those of the proposed compound identified by the software. During GC×GC/TOFMS analysis, the second dimension of the 2D chromatograms provides additional information on the polarity of detected compounds, enabling the rejection of several false positives, defined as detected compounds which were in reality not present in the distillation fraction. In contrast, GC/HRMS offers structural information through the exact molecular masses of fragment ions.

To improve the confidence level of the identification, further investigations should be conducted using chemical standards of the identified heteroatomic compounds. This approach was not undertaken in the present study, as it falls beyond the scope of this paper.

2.6. Selection of Experimental Design

A CCD was applied to optimize the key parameters of each data processing software. The CCD enabled the quadratic modeling of the experimental responses as functions of the k parameters shown in Equation (1):

$$y = \beta_0 + \sum_{i=1}^k \beta_i x_i + \sum_{i=1}^k \beta_{ii} x_i^2 + \sum_{i=1}^k \sum_{j=i+1}^k \beta_{ij} x_i x_j + \varepsilon \quad (1)$$

The CCD design included three types of points: 2^k factorial points, $2k$ axial or star points at a distance α from the center (to estimate curvature), and center points (to estimate experimental error). In our case, α was set to 1 for the sake of simplicity. The responses considered in the CCD were the number of detected heteroatomic compounds and the number of true positives (heteroatomic compounds identified by mass spectrum and retention index comparisons, Section 2.5). The overall objective was to minimize the number of detected peaks (to reduce the number of peaks requiring manual verification) while maximizing the number of true positives (to ensure reliable identification). JMP 18.2.0 was used to build experimental designs and perform statistical analyses.

For GC×GC/TOFMS data, a CCD with 2 factors was established: the minimum signal-to-noise ratio threshold (MSN) and the minimum stick count (MSC). These two parameters were selected based on a preliminary study investigating the influence of all the parameters: MSN and MSC.

- MSN specifies the lowest signal-to-noise ratio required for a signal to be recognized as a true peak. If the MSN is too high, trace compounds cannot be detected. Therefore, an appropriate S/N threshold value should be carefully selected. Boudard et al. (2024) chose 1000 as a minimum S/N threshold for body odor samples [21] while Stephanuto et al. (2017) used an S/N threshold of 100 for profiling volatile aromas of beer upon Thermal desorption(TD)-GC×GC/TOFMS analysis [35]. In the context of TD injection, ambient air contributes significantly to background noise, which justifies the use of a relatively high minimum S/N to balance between the number of detected peaks and the reliability of true positive identifications. However, in the case of liquid injections, the background noise is significantly lower than in TD injection. Consequently, a

lower minimum S/N threshold is more suitable to enable the untargeted detection of heteroatom-containing compounds at the trace level. Bean et al. (2015) used an S/N of 10 to analyze metabolites for biomarker discovery [36], which is comparable to the value used in our study for liquid injection.

- MSC refers to the minimum number of ions in a mass spectrum that must be present for a detected peak to be considered as a valid compound, thereby reducing the risk of false positives due to artefacts. Thus, increasing the MSC leads to a decrease in the number of detected peaks, due to the stricter criteria imposed for peak formation. Bean et al. (2015) used an MSC of 2 for data processing (called apexing masses) [36].

Consequently, MSN and MSC appear to have the most significant impact. Within the frame of the experimental design, 9 experiments were performed to examine the influence of these two parameters on the two responses mentioned above. Table 1 indicates the experiments and factor levels used for GC×GC/TOFMS.

Table 1. Experimental table of experiments for the GG × GC/TOFMS parameters and factor levels.

Experiment	MSC	MSN
1	0	0
2	−1	1
3	1	−1
4	1	1
5	−1	0
6	0	1
7	0	−1
8	−1	−1
9	1	0
Factor level	MSC	MSN
−1	3	5
0	5	55
1	7	105

For GC/HRMS, a CCD with 3 factors was established: the signal-to-noise ratio threshold for mass-to-charge ratio m/z (m/z S/N), the peak S/N threshold (peak S/N) and the TIC. These three parameters were selected based on a preliminary study investigating the influence of all data processing parameters on TraceFinder.

- The m/z S/N threshold corresponds to the minimum ratio between an ion's signal height and the baseline noise for the ion to be included in the mass spectrum. Increasing the m/z S/N threshold led to a decrease in the number of detected peaks, due to stricter filtering of low-intensity ions.
- The peak S/N threshold specifies the minimum ratio between the peak height and the baseline noise for a signal to be classified as a valid chromatographic peak.
- The TIC intensity threshold sets the minimum total ion current (TIC) intensity required for a peak to be retained.

The effect of these three factors was studied in 15 experiments. Table 2 shows the experiments and factor levels used for GC/HRMS.

Table 2. Experimental table for the GC/HRMS parameters and factor levels.

Number of Experiments	<i>m/z</i> S/N	TIC	S/N
1	−1	1	−1
2	1	−1	−1
3	0	0	1
4	0	1	0
5	0	0	0
6	−1	0	0
7	0	−1	0
8	0	0	−1
9	1	−1	1
10	1	0	0
11	−1	1	1
12	−1	−1	−1
13	1	1	1
14	−1	−1	1
15	1	1	−1
Factor level	<i>m/z</i> S/N	TIC	S/N
−1	3	10^4	3
0	51.5	5.0005×10^7	6.5
1	100	10^8	10

To achieve both a minimum number of detected peaks and a maximum number of identified true positives, a desirability approach was applied using Derringer functions to transform each response of interest into a scale from 0 (fully undesirable) to 1 (fully desirable) [37,38]. Optimal parameter values were determined when desirability became maximum. The optimized values were applied to compare the results obtained from GC×GC/TOFMS and GC/HRMS, in order to assess and contrast the analytical performance of both methods on two chosen fractions. It must be noted that in the present case, each assay corresponded to the application of a reprocessing algorithm with different settings but on the same raw data. Replicates would therefore lead to the same mathematical value for the responses and would be of no interest.

3. Results and Discussion

3.1. GC×GC/TOFMS and GC/HRMS Chromatograms of Fraction A

Figure 1 presents the chromatograms obtained by GC × GC/TOFMS (a) and GC/HRMS (b). The organization of the chemical families was observed in the 2D chromatogram: alkane/alkene compounds, monoaromatic compounds and heteroatom-containing compounds. Examples of heteroatomic compounds are circled in red in Figure 1a. Three main classes of heteroatom-containing compounds were identified: oxygen-, nitrogen-, and sulfur-containing species. Heteroatomic compounds were usually located above hydrocarbon compounds as a result of their higher polarity, which facilitated their identification. However, with GC/HRMS, heteroatomic compounds were usually co-eluted with hydrocarbon compounds and were thus difficult to identify. Only major compounds, such as for example toluene, p-xylene and o-xylene, could still be easily visualized and identified as shown in Figure 1b.

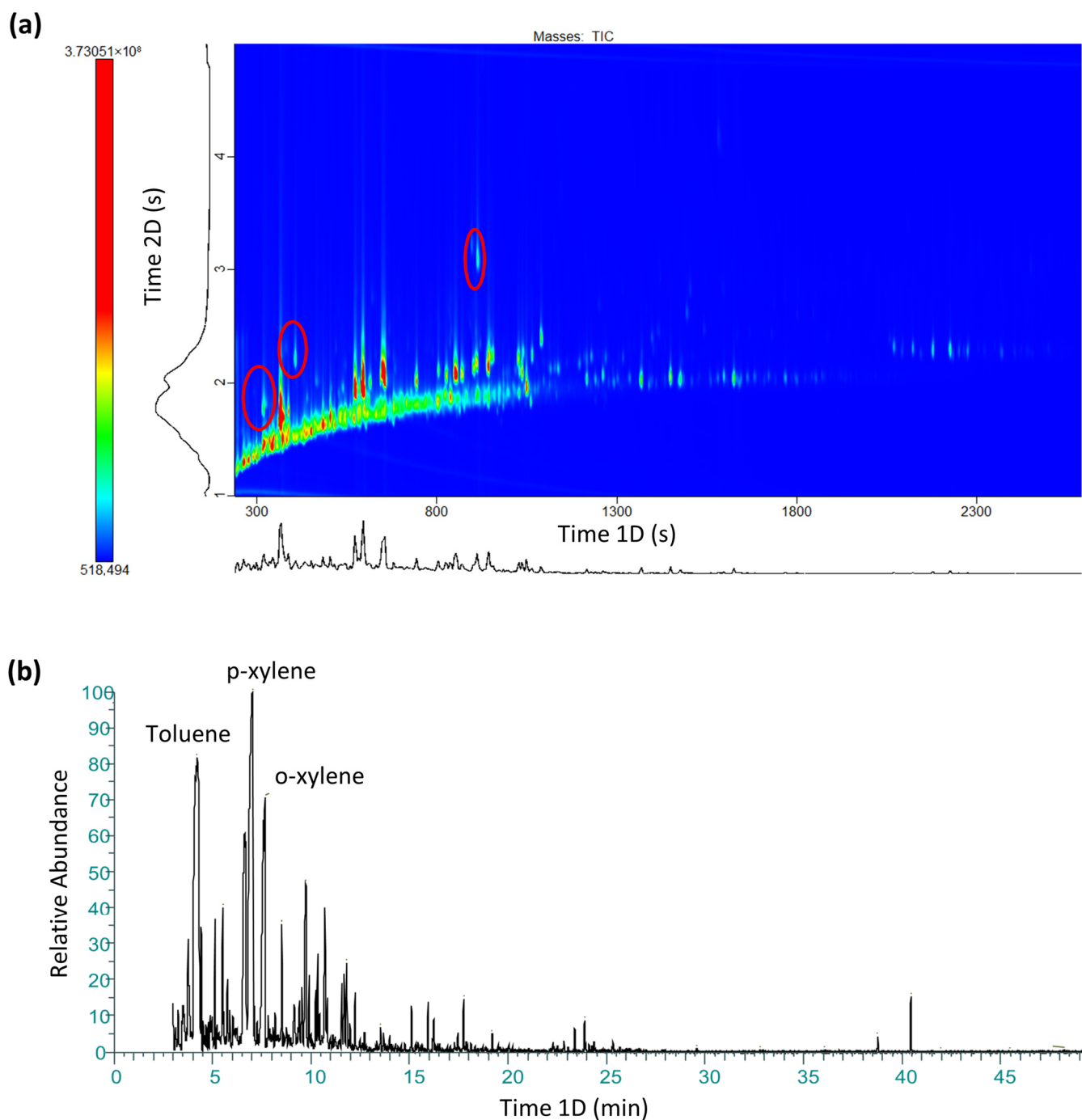


Figure 1. Chromatograms of pyrolysis oil fraction A (95–142 °C) obtained by (a) GC×GC/TOFMS and (b) GC/HRMS. Three heteroatomic compounds are circled in red in (a): from left to right, red circles identify, respectively, 4-Methyl-2-pentanone, cyclopentanone and benzonitrile. Some major compounds in GC/HRMS chromatogram are presented in (b): Toluene, p-xylene and o-xylene.

3.2. CCD for GC×GC/TOFMS

3.2.1. Correlation of the Two Responses

To investigate the correlation between the number of detected heteroatomic compounds and the number of true positives, a correlation plot was performed based on the results of CCD. Figure 2 presents the results with ellipse density contours highlighted at a confidence level of 0.95. The more circular the shape of the ellipse, the weaker the correlation between the two responses. In this case, the number of detected heteroatomic compounds and the number of true positives appeared to be weakly correlated, which cor-

responds to a correlation coefficient of 0.54 (which is not significantly different from 0 with a risk of first kind set at 5%). This indicates that they deserve to be studied independently.

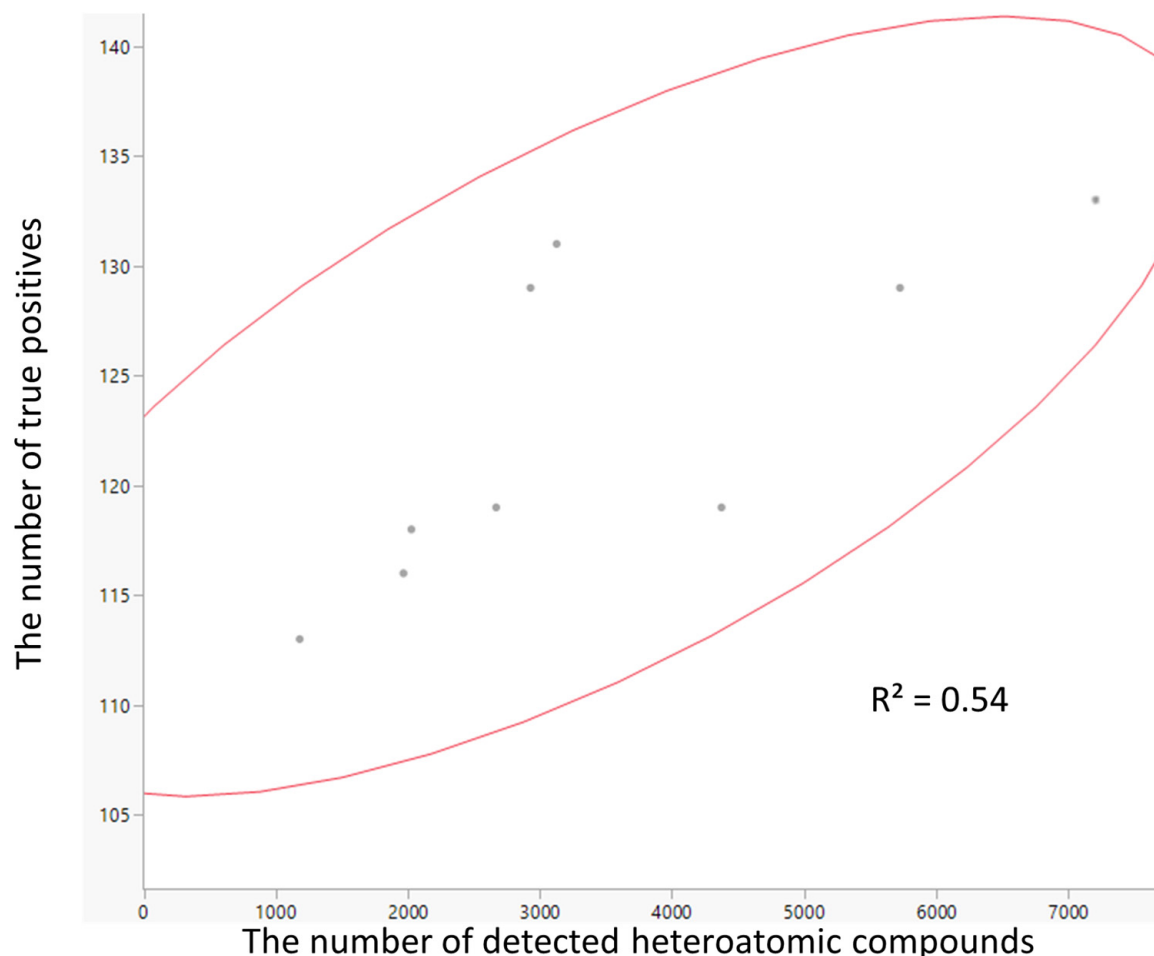


Figure 2. The correlation of the number of detected heteroatomic compounds and the number of true positives based on the results of CCD of GC×GC on pyrolysis oil fraction A (95–142 °C) using the multivariate correlation of JMP. Ellipse density at confidence level of 0.95 was highlighted in red.

3.2.2. Significance of Coefficients for Each Response

By using a CCD, it becomes possible to assess the extent to how each factor influences the two responses in terms of their linear contribution, interaction and curvature. Figure 3 illustrates the significance of these two factors and their interaction on two responses: the number of detected heteroatom-containing peaks and the number of true positives in fraction A. In this case, [MSN] and [MSC] had a significant negative effect and the quadratic term $[MSN]^2$ and $[MSC] \times [MSN]$ a significant positive effect on the number of detected heteroatomic compounds. In addition, [MSC], [MSN], $[MSN]^2$ and $[MSC]^2$ had a significant negative effect on the number of true positives, whereas the interaction term $[MSC] \times [MSN]$ had a positive effect. When applying the same CCD approach on fraction B, the results obtained were similar to those described for fraction A.

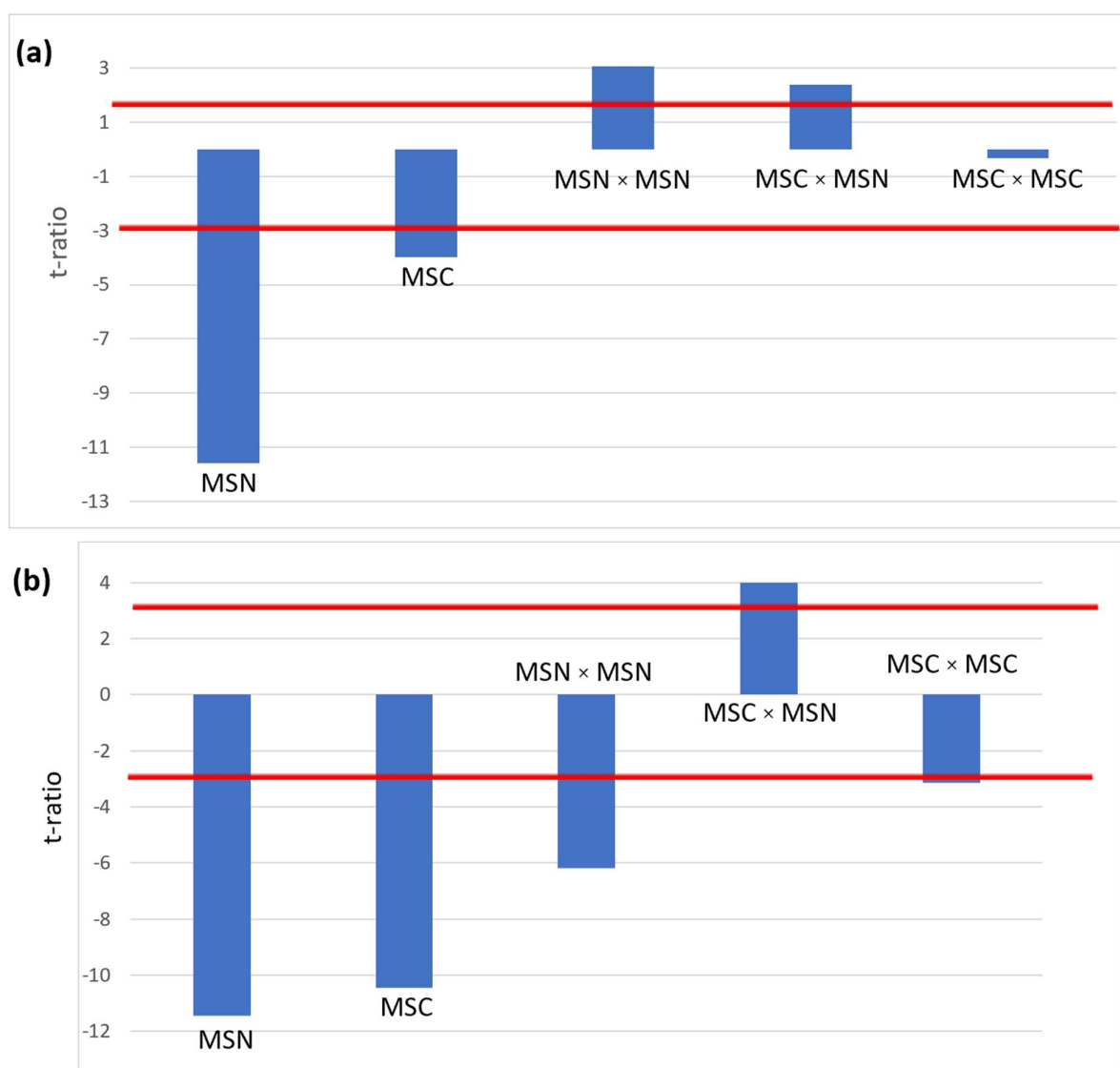


Figure 3. GC×GC/TOFMS CCD results: standardized values of the coefficients of the model for (a) the number of detected peaks and (b) the number of true positives. The effects of MSN, MSC, their interaction, and their quadratic terms on both responses were evaluated by the t-ratio using the scaled estimates. The red lines represent the 5% significance threshold. When a coefficient exceeds the red line, the corresponding coefficient is considered statistically significant.

3.2.3. Optimization with Desirability for Fraction A

To achieve the best compromise between minimizing the number of detected heteroatom-containing compounds and maximizing the number of true positives, a desirability approach using Derringer functions was employed. Desirability was defined to range linearly from 0 (least desirable outcome) to 1 (most desirable), with a value of 1 corresponding to a minimum number of detected heteroatomic peaks and a maximum number of true positives. Figure 4 shows the optimal point that satisfies both objectives simultaneously. The maximum overall desirability was reached at an MSC of 3.936 and an MSN of 60. Given that the MSC and MSN values must be integers in practice, the MSC value was rounded up to 4 and the MSN value to 60 to identify the heteroatomic compounds. These parameters values were also used as the basis for comparison with results obtained from GC/HRMS.

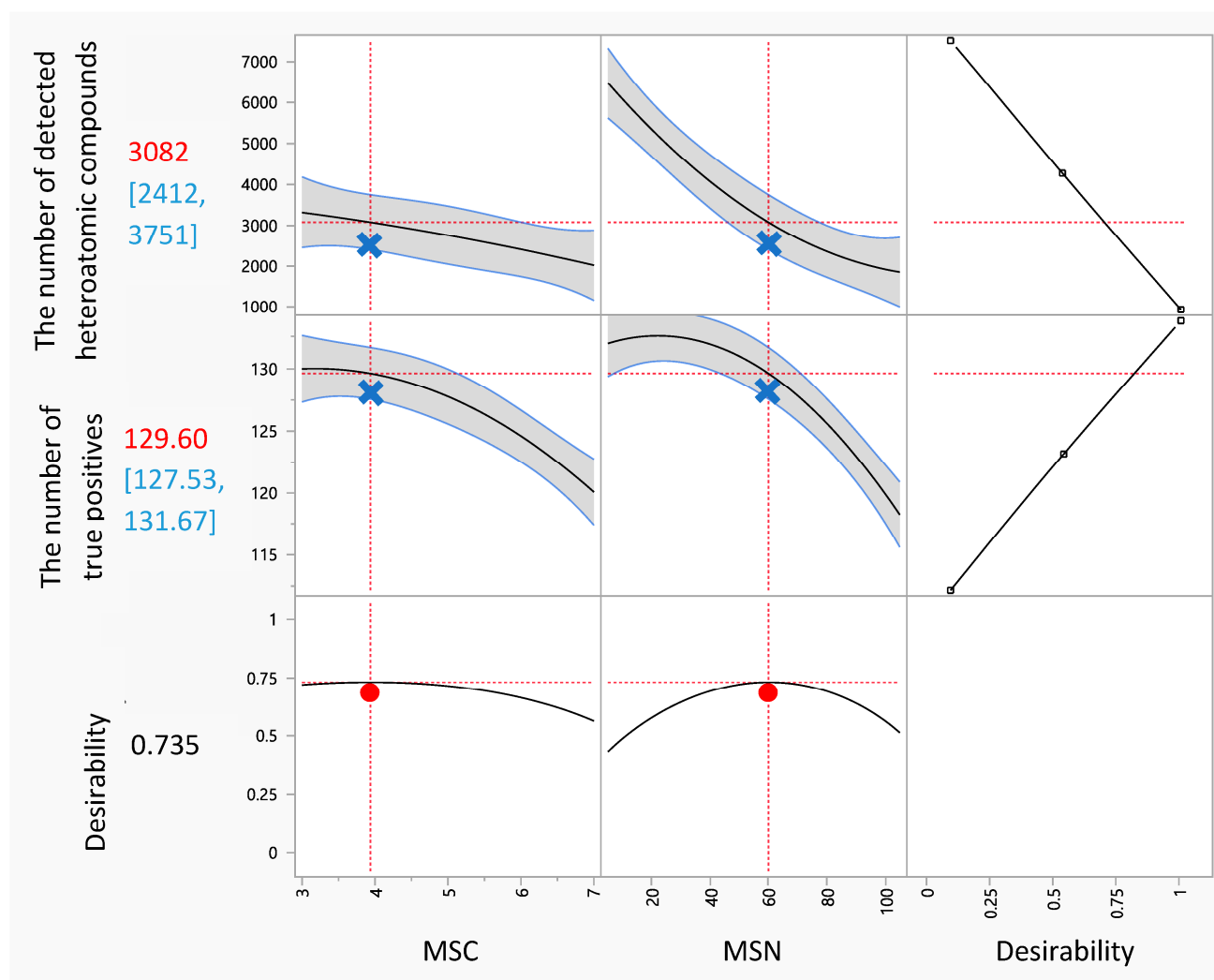


Figure 4. Variation in the predicted number of detected heteroatomic compounds and the predicted number of true positives as a function of MSN and MSC by modeled responses, using prediction profiler of JMP based on the results of CCD of GC×GC. The last row indicates the desirability as a function of MSC and MSN, with optimum values in red (MSC = 3.936, MSN = 60), and the corresponding 95% confidence interval. The last column represents the individual desirability values for each response. The red points represent the optimal parameter settings that yielded the maximum desirability. The four blue crosses represent the values of experimental responses at the optimum values of MSC and MSN: experimental values were all included in the 95% confidence interval.

3.2.4. CCD Relevance and Experimental Validation for Fraction A

To illustrate the relevance of using a CCD—and thus a quadratic model—response surfaces were generated for each response. Figure 5 displays the response surfaces for the number of detected heteroatom-containing compounds (Figure 5a) and for the number of true positives (Figure 5b). In both cases, the surfaces deviated significantly from a flat plane and exhibited curvature characteristic of quadratic variation, indicating that the response behavior was not linear. This result demonstrates the relevance of using CCD as an experimental design strategy. In addition, the R square value for the number of detected heteroatomic compounds was 0.9763, and for the number of true positives was 0.9851, which showed the high performance of predicted model. Residual plots are provided in Figure S2: the residuals are randomly distributed around the line $y = 0$.

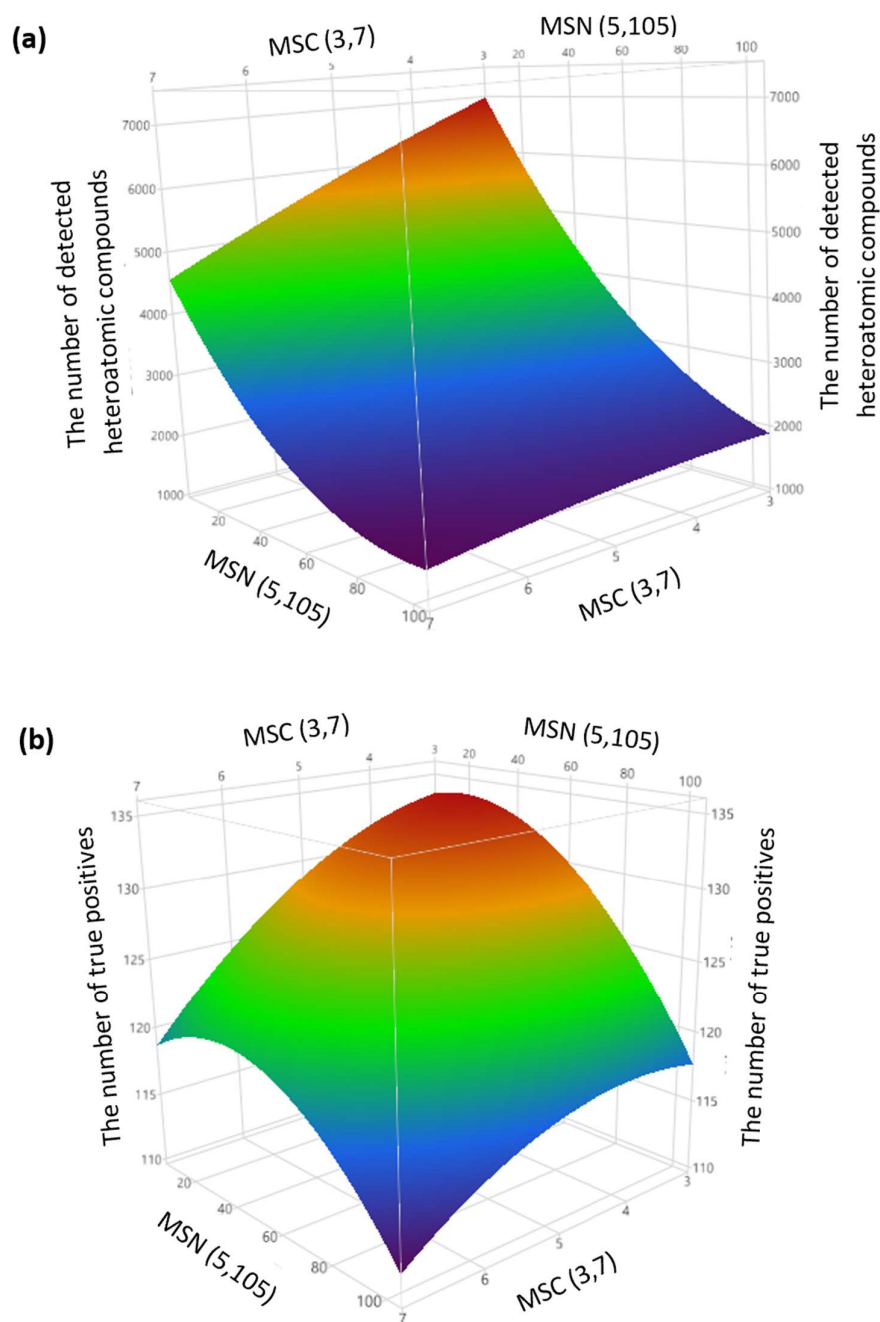


Figure 5. Response surface plots of (a) the number of heteroatomic compounds detected as a function of MSC and MSN and (b) the number of true positives as a function of MSC and MSN using the surface profiler in JMP based on the results of CCD of GC×GC. The color scale ranges from purple to red, where purple indicates the minimum response and red the maximum.

The optimized parameter values predicted by the model were then validated experimentally. As shown in Figure 4, the predicted number of detected heteroatomic compounds was 3082 and of true positives was 129.6 at an MSC of 3.936 (rounded up to 4 for the subsequent study) and an MSN of 60, with 95% confidence intervals of [2412.6, 3751.6] and [127.5, 131.6], respectively. When applying these settings, 2848 heteroatom-containing compounds were detected, and 129 true positives corresponding to heteroatom-containing compounds were identified. Figure 4 highlights this result, with the blue crosses corresponding to the experimental validation at the optimum set of values for MSC and MSN. This result closely matched the predicted value, thereby validating the chosen optimization strategy and optimum.

3.3. CCD for GC/HRMS Data of Fraction A

The same strategy was applied to data obtained by GC/HRMS in order to optimize software parameters. Detailed results are shown in Supplementary Material. Figure S1 illustrates the significance of these three factors and their interaction on two responses. However, several results presented a behavior different from those previously observed for GC×GC/TOFMS data. As in Section 3.2.1, a multivariate analysis was conducted, and the results are represented by a scatterplot matrix. Figure 6 shows the correlation plot of the two responses based on the results of CCD of GC/HRMS, with the highlighted ellipse density at a confidence level of 0.95. Compared to Figure 2, the two responses seem to correlate more in the case of GC/HRMS, as the shape of the ellipse was flattened. Therefore, the behavior of these two responses should be rather similar in this case.

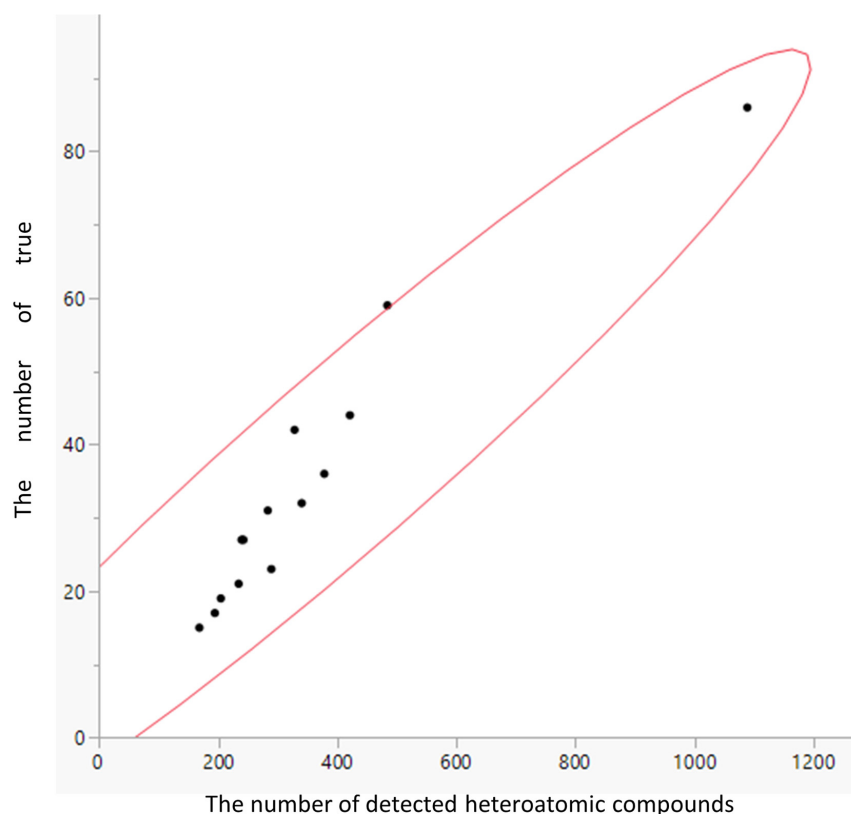


Figure 6. The correlation of the number of detected heteroatomic compounds and the number of true positives based on the results of CCD of GC/HRMS on pyrolysis oil fraction A (95–142 °C) using the multivariate correlation of JMP. Ellipse density at confidence level of 0.95 is highlighted in red. The black dots represent the experimental data points selected in JMP.

As a consequence, the two responses decreased in a correlated manner as a function of the parameters. According to the desirability curve (Figure 7), it was not possible to identify a set of conditions that would simultaneously maximize the number of true positives and minimize the number of detected heteroatomic compounds. As a result, the most optimal compromise was found at the following parameter settings: m/z S/N = 3, TIC intensity threshold = 104, and peak S/N = 3, which provided the maximum true positives (predicted value of 89 with a confidence interval of [79.5, 98.8]) and the maximum detected heteroatomic compounds to inspect manually (predicted value of 1230 with a 95% confidence interval of [989.2, 1470.9]). Experimentally, the set of values (m/z S/N = 3, TIC = 104, S/N = 3) provided 1306 detected heteroatomic compounds and 92 true positives. Figure 6

highlights this result with six blue crosses at the optimum set of values for MSC and MSN. Both values were in the 95% confidence interval, which validated the chosen model.

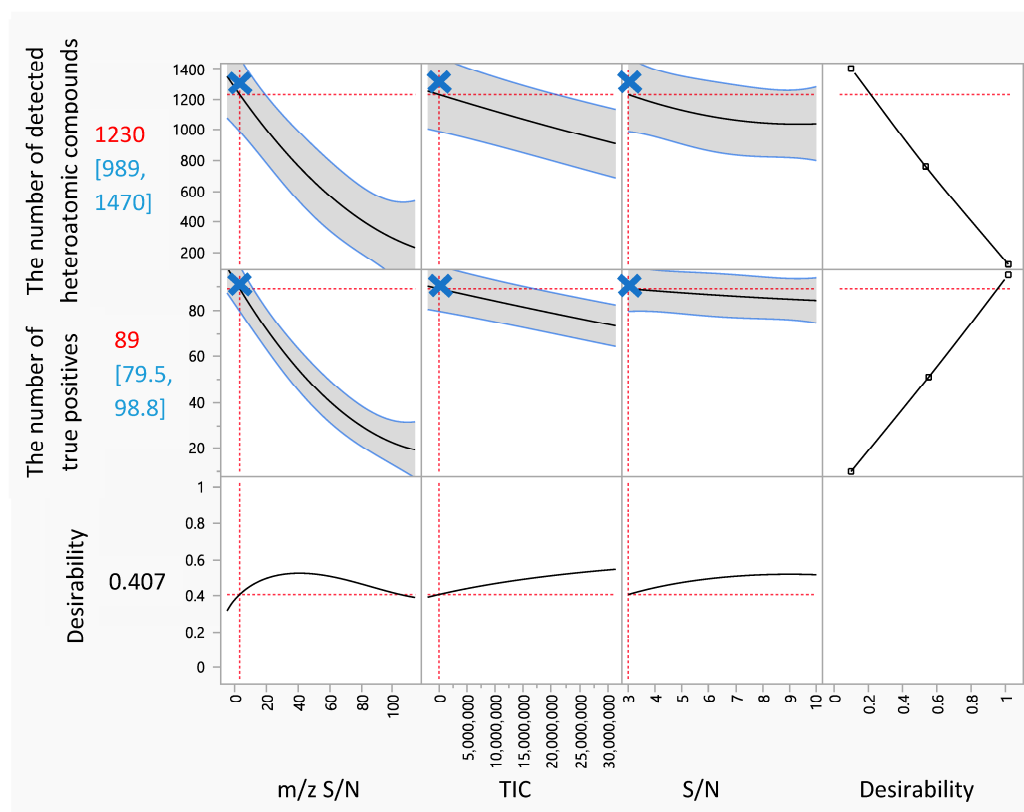


Figure 7. Variation in the number of detected heteroatomic compounds and the number of true positives as a function of m/z S/N, TIC and S/N predicted by modeled responses, using the prediction profiler of JMP based on the results of CCD of GC/HRMS. The last row indicates the desirability as a function of m/z S/N, TIC intensity and S/N represented at optimum values (m/z S/N = 3, TIC = 10^4 and S/N = 3) and the corresponding 95% confidence level. The last column represents the individual desirability values for each response. The six blue crosses represent the values of experimental responses at the optimum values (m/z S/N = 3, TIC = 10^4 and S/N = 3): experimental values were all included in the 95% confidence interval.

3.4. Confirmation of These Optimal Values Through Another Sample: Fraction B (142–169 °C)

Using the optimized parameter set of MSC = 4 and MSN = 60, 2928 heteroatomic compounds were detected in fraction B (142–169 °C) upon GC×GC/TOFMS analysis, of which 159 were true positives—covering 99.3% of all true positives. In contrast, the MSC = 3 and MSN = 5 setting ((−1, −1) point in CCD) led to the detection of 7020 compounds to recover all 160 true positives. The only compound not detected with (MSC = 4, MSN = 60) was a low-intensity trace compound. This highlights the power of the CCD experimental design, as well as the relevance of the (MSC = 4, MSN = 60) setting, which achieved near-complete identification while reducing the number of detected heteroatom-containing compounds by more than half (58.3%). Table S1 shows the identification of the 160 true positives detected.

For GC/HRMS, the set of values (m/z S/N = 3, TIC = 10^4 , S/N = 3) provided 1390 detected heteroatomic compounds and 154 true positives. With this set, the maximum true positives and the maximum detected heteroatomic compounds were obtained. Consequently, no experimental validation was necessary, as this set of values was a point in the CCD.

3.5. Comparison of GC×GC/TOFMS and GC/HRMS Results

Using the optimized parameter sets defined in Sections 3.2.3 and 3.3, a comparison of compounds identified between GC×GC/TOFMS and GC/HRMS was carried out on fraction A. The results for fraction B were similar to those of fraction A. As previously mentioned, 129 and 92 heteroatom-containing compounds were identified using GC×GC/TOFMS and GC/HRMS, respectively, under optimum conditions. The lists of compounds identified using both methods were compared: a total of 57 compounds were commonly identified using both techniques. Table S2 highlights these 57 compounds. When comparing the results obtained for GC×GC/TOFMS and GC/HRMS data processing, false positives and false negatives could be defined. In fact, the false positives corresponded to compounds identified and proposed by the software, but which did not actually exist. These false positives mainly appeared in GC/HRMS, as the proposed heteroatomic compounds were based solely on the measured mass spectrum rather than being controlled by the retention index value and, consequently, the presence of these compounds was not confirmed in the 2D chromatogram. For instance, the oxygenated heteroatomic compound, furan 2-ethyl-5-methyl, was detected twice by GC/HRMS, but only once in the 2D chromatogram of fraction A (with an associated retention time that is in accordance with its retention index). False negatives are compounds that were present but not identified. They are typically overlooked either due to the parameter values applied during data processing, or simply because of limited separation capacity caused by the complexity of the samples and the chromatographic configurations. False positives and false negatives were not considered as responses in the CCD, as their identification necessitated the comparison between GC×GC and GC/HRMS results.

No false positives were observed with GC×GC/TOFMS, while 26 false positives were detected with GC/HRMS. This observation suggested that the enhanced chromatographic separation provided by GC×GC/TOFMS was more effective in eliminating false identifications. However, false negatives were observed in both cases: 5 compounds were missed by GC×GC/TOFMS and 72 by GC/HRMS. Tables S3 and S4 show these compounds. The large number of false negatives in GC/HRMS can be attributed to the absence of a second dimension of separation by polarity, which limits the resolution of coeluted species. Conversely, the 5 compounds detected by GC/HRMS but not by GC×GC/TOFMS exhibited very low intensity. These compounds were not initially detected by the GC×GC/TOFMS software but after the manual inspection of the 2D chromatogram, they were detected and identified.

These results demonstrate that the two analytical methods are complementary, allowing cross-verification of compound identifications. In particular, the results obtained with GC×GC/TOFMS could be considered to confirm the presence or absence of specific compounds detected in GC/HRMS.

For example, hexanal, 3-methyl- was detected in fraction A by GC/HRMS. Surprisingly, this compound was not observed in the upper region of the GC×GC chromatogram, a zone where polar compounds are usually eluted in the second dimension under our conditions of GC×GC analysis. This suggests that this chemical species was probably a false positive when detected by GC/HRMS and processed with the software Trace Finder. On the other hand, GC/HRMS detected quinoline 2,4-dimethyl, a compound that is present in very small amounts and is polar, but ChromaTOF's data processing did not detect it after GC×GC/TOFMS analysis. Following a manual inspection of processed data, the presence of quinoline 2,4-dimethyl was indeed confirmed in the 2D chromatogram. These two examples highlight how GC×GC/TOFMS can help eliminate false positives detected during the GC/HRMS analysis and how the combined use of both analytical approaches enhanced the performance of heteroatomic compound identification in pyrolysis oil fractions.

4. Conclusions and Perspectives

The GC×GC/TOFMS and GC/HRMS data processing methods have been developed to analyze distillation fractions of pyrolysis oil from waste tires. In particular, heteroatom-containing compounds were investigated by combining these protocols. Optimization of parameters was first carried out with an experimental design (CCD), yielding a value set for both MSC and MSN parameters of 4 and 60, respectively, to obtain the maximum true positives and the minimum detected heteroatomic peaks during GC×GC/TOFMS data processing. In the case of GC/HRMS data, m/z S/N, TIC intensity, and S/N were optimized, with values of 3, 10^4 , and 3, respectively, chosen for m/z S/N, TIC intensity, and S/N in the case of GC/HRMS. The curvature of the response surfaces justified the use of the CCD experimental design.

GC×GC/TOFMS proved to be more effective for the detailed identification of heteroatom-containing compounds in light distillation fractions, owing to the second dimension separation based on polarity. In total, 129 heteroatomic compounds were identified in distillation fraction A and 160 in fraction B using GC×GC/TOFMS. However, the results could still be complemented by GC/HRMS, which enabled the additional detection of five trace compounds in fraction A based on the high mass accuracy (within 5 ppm) provided by the Orbitrap analyzer. The optimized parameter set was validated on another distillation fraction (boiling range: 142–169 °C), where 159 true positives were recovered out of 160 confirmed heteroatomic compounds (confirmed with the similarity of the mass spectrum and retention index), with only 2968 detected compounds—compared to 7020 detected compounds using the initial parameter set (MSC = 3, MSN = 5, level (−1, −1) in CCD).

In this study, only two light distillation fractions of pyrolysis oil from waste tires were considered. GC×GC/TOFMS allows for a detailed characterization of heteroatom-containing compounds on these two fractions. For further study, other types of distillation fractions from different types of waste tires should be considered to confirm the optimal values obtained from the CCD. However, the results obtained with these two fractions show that applying a CCD to rationalize key parameters is appropriate for optimizing the experimental parameters associated with specific analytical techniques, enabling full utilization of their potential. Furthermore, it would be interesting to consider GC×GC/HRMS for the analysis of distillation fractions of pyrolysis oils, given that the LECO HRMS is 10 to 100 times less sensitive than the LECO BT-4D TOFMS.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/separations12090239/s1>. Figure S1. GC/HRMS CCD results: standardized values of the coefficients of the model for the number of detected peaks (a) and the number of true positives (b); Figure S2. Residual plots of the number of detected heteroatomic compounds (a) and the number of true positives (b) in the case of GC×GC/TOFMS; Table S1. Identification of 160 true positives in fraction B by GC×GC/TOFMS; Table S2. 57 common heteroatomic compounds detected by GC×GC/TOFMS and GC/HRMS; Table S3. 5 compounds detected by GC/HRMS but not by GC×GC/TOFMS; Table S4. 72 compounds detected by GC×GC/TOFMS but not by GC/HRMS.

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