Quality by design based silymarin nanoemulsion for enhancement of oral bioavailability

The purpose of this research paper is to develop silymarin loaded nanoemulsions with good oral bioavailability. Design of experiments (DoE) methodology is implemented for the optimization of the silymarin loaded nanoemulsions.

The factors (independent variables) examined are: A = surfactant/cosurfactant mixture concentration (%), B = homogenization pressure (bar) and C = number of homogenization cycles. All the factors are continuous. The responses (dependent variables) examined are: R_1 = globule size (nm), R_2 = polydispersity index, R_3 = transmittance percentage (%) and R_4 = drug release (%). The applied DoE method is Box Behnken design.

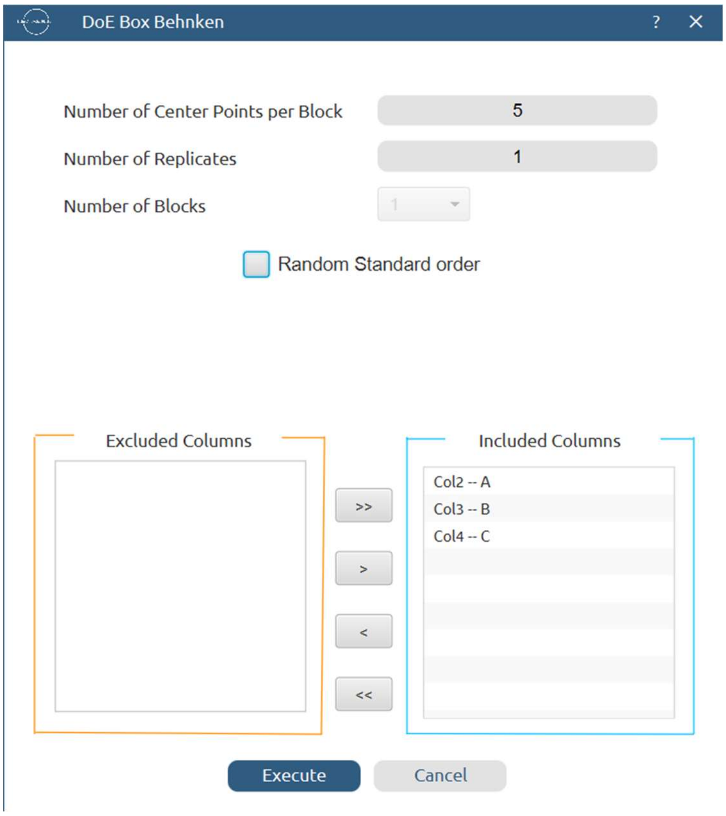
Isalos version used: 2.0.6

Scientific article: https://www.sciencedirect.com/science/article/abs/pii/S0928098716305607

Step 1: Box Behnken Design

In the first tab named "Action" define the factors in the column headers and fill each column with the low and high levels of the corresponding factors. This tab can be renamed "Box Behnken". Afterwards, apply the Box Behnken method: *DOE → Response Surface → Box Behnken*

	Col1	Col2 (I)	Col3 (I)	Col4 (I)
User Header	User Row ID	A	B	C
1		30	1000	5
2		40	2500	15

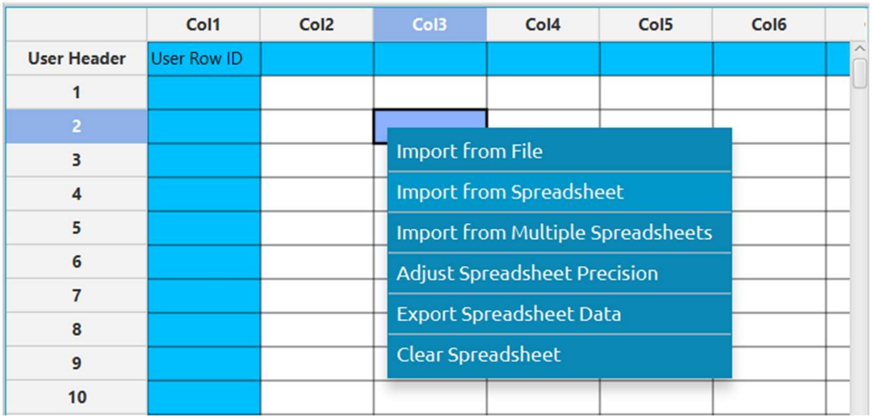


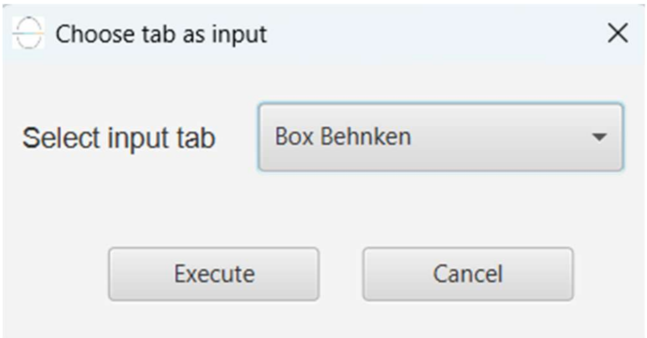
Results (right spreadsheet):

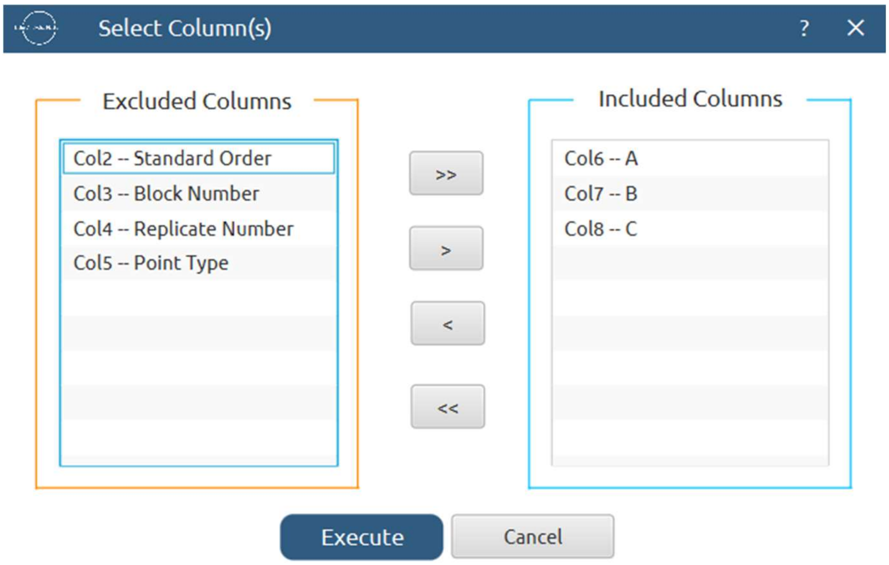
	Col1	Col2 (I)	Col3 (S)	Col4 (S)	Col5 (S)	Col6 (D)	Col7 (D)	Col8 (D)
User Header	User Row ID	Standard Order	Block Number	Replicate Number	Point Type	A	B	C
1		1	Block: 1	Replicate: 1	Design Point	30.0	1000.0	10.0
2		2	Block: 1	Replicate: 1	Design Point	40.0	1000.0	10.0
3		3	Block: 1	Replicate: 1	Design Point	30.0	2500.0	10.0
4		4	Block: 1	Replicate: 1	Design Point	40.0	2500.0	10.0
5		5	Block: 1	Replicate: 1	Design Point	30.0	1750.0	5.0
6		6	Block: 1	Replicate: 1	Design Point	40.0	1750.0	5.0
7		7	Block: 1	Replicate: 1	Design Point	30.0	1750.0	15.0
8		8	Block: 1	Replicate: 1	Design Point	40.0	1750.0	15.0
9		9	Block: 1	Replicate: 1	Design Point	35.0	1000.0	5.0
10		10	Block: 1	Replicate: 1	Design Point	35.0	2500.0	5.0
11		11	Block: 1	Replicate: 1	Design Point	35.0	1000.0	15.0
12		12	Block: 1	Replicate: 1	Design Point	35.0	2500.0	15.0
13		13	Block: 1	----	Center Point	35.0	1750.0	10.0
14		14	Block: 1	----	Center Point	35.0	1750.0	10.0
15		15	Block: 1	----	Center Point	35.0	1750.0	10.0
16		16	Block: 1	----	Center Point	35.0	1750.0	10.0
17		17	Block: 1	----	Center Point	35.0	1750.0	10.0

Step 2: Factor isolation

Create a new tab named "Factors" and import the results from the "Box Behnken" spreadsheet by right clicking on the left spreadsheet. Then, select only the factor columns to be transferred to the right spreadsheet: *Data Transformation → Data Manipulation → Select Column(s)*







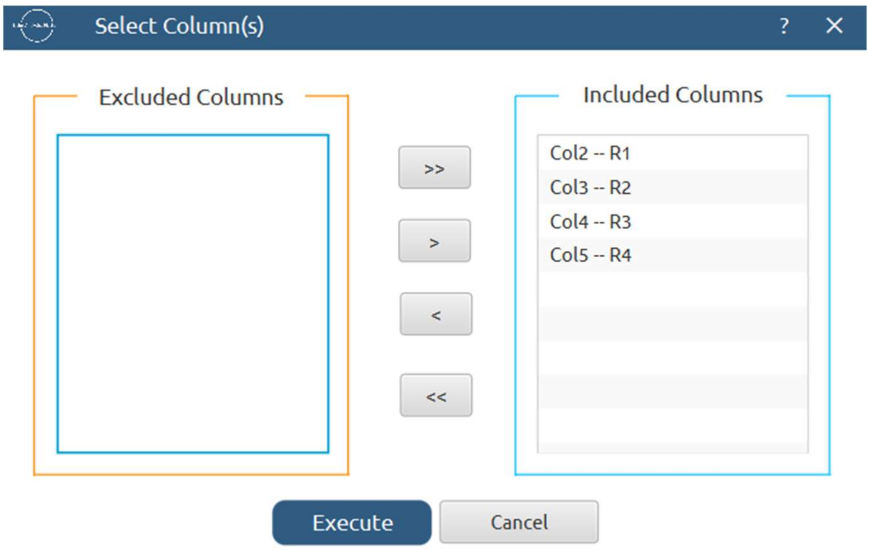
Results:

	Col1	Col2 (D)	Col3 (D)	Col4 (D)
User Header	User Row ID	A	B	C
1		30.0	1000.0	10.0
2		40.0	1000.0	10.0
3		30.0	2500.0	10.0
4		40.0	2500.0	10.0
5		30.0	1750.0	5.0
6		40.0	1750.0	5.0
7		30.0	1750.0	15.0
8		40.0	1750.0	15.0
9		35.0	1000.0	5.0
10		35.0	2500.0	5.0
11		35.0	1000.0	15.0
12		35.0	2500.0	15.0
13		35.0	1750.0	10.0
14		35.0	1750.0	10.0
15		35.0	1750.0	10.0
16		35.0	1750.0	10.0
17		35.0	1750.0	10.0

Step 3: Definition of response variables

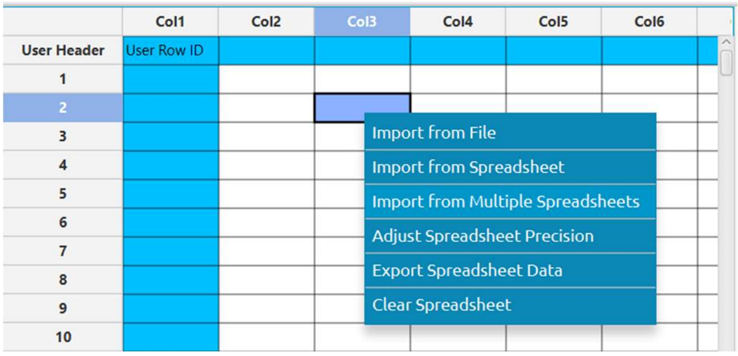
Create a new tab named “Responses” and define the responses in the column headers. Fill each column with the values of the corresponding responses that were observed and make sure the values follow the order of the experiments as given by the Box Behnken design. Then, select all columns to be transferred to the right spreadsheet: *Data Transformation → Data Manipulation → Select Column(s)*

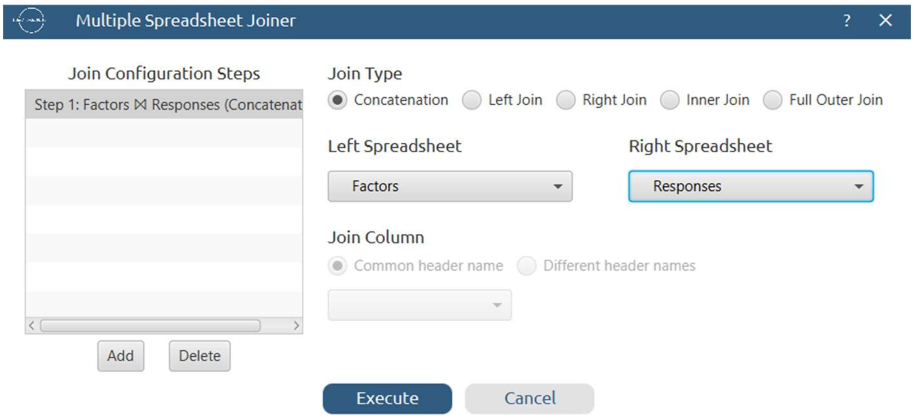
	Col1	Col2 (D)	Col3 (D)	Col4 (D)	Col5 (D)
User Header	User Row ID	R1	R2	R3	R4
1		317.3	0.87	81.5	65.2
2		125	0.46	97.2	84
3		256.7	0.64	88.5	76.3
4		50.02	0.45	100	90
5		286.2	0.75	85	66.7
6		92	0.46	98	85.3
7		273	0.65	87	68.1
8		70.82	0.5	99.5	88.6
9		230	0.45	90	70
10		145	0.46	97	82.6
11		208.4	0.45	92.5	79.8
12		112	0.46	97.8	85.4
13		180	0.49	99.4	78.5
14		188	0.43	95	78
15		171	0.43	96.2	80.4
16		168	0.43	96.5	77.1
17		175	0.43	96	76.8

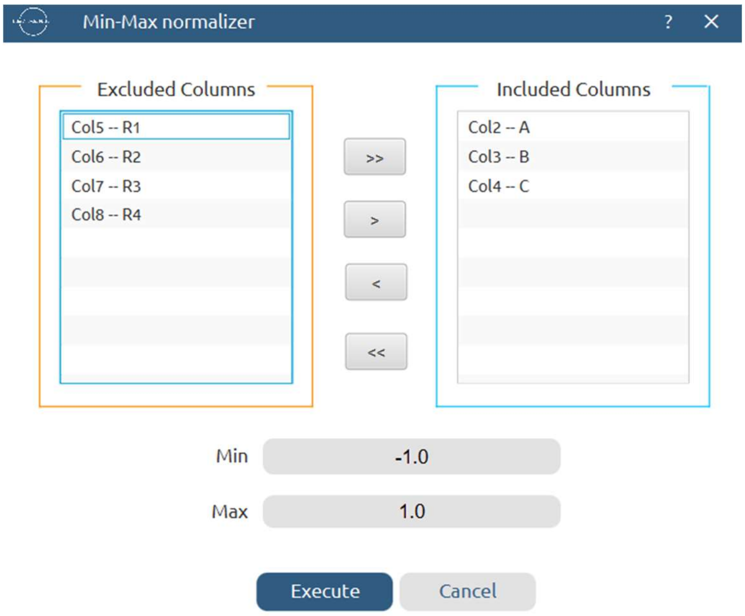


Step 4: Normalization

Create a new tab named "Normalized data" and import the results from the "Factors" and "Responses" spreadsheets. Afterwards, normalize the factor columns to take values in the range [-1, 1]: *Data Transformation → Normalizers → Min-Max*







Results:

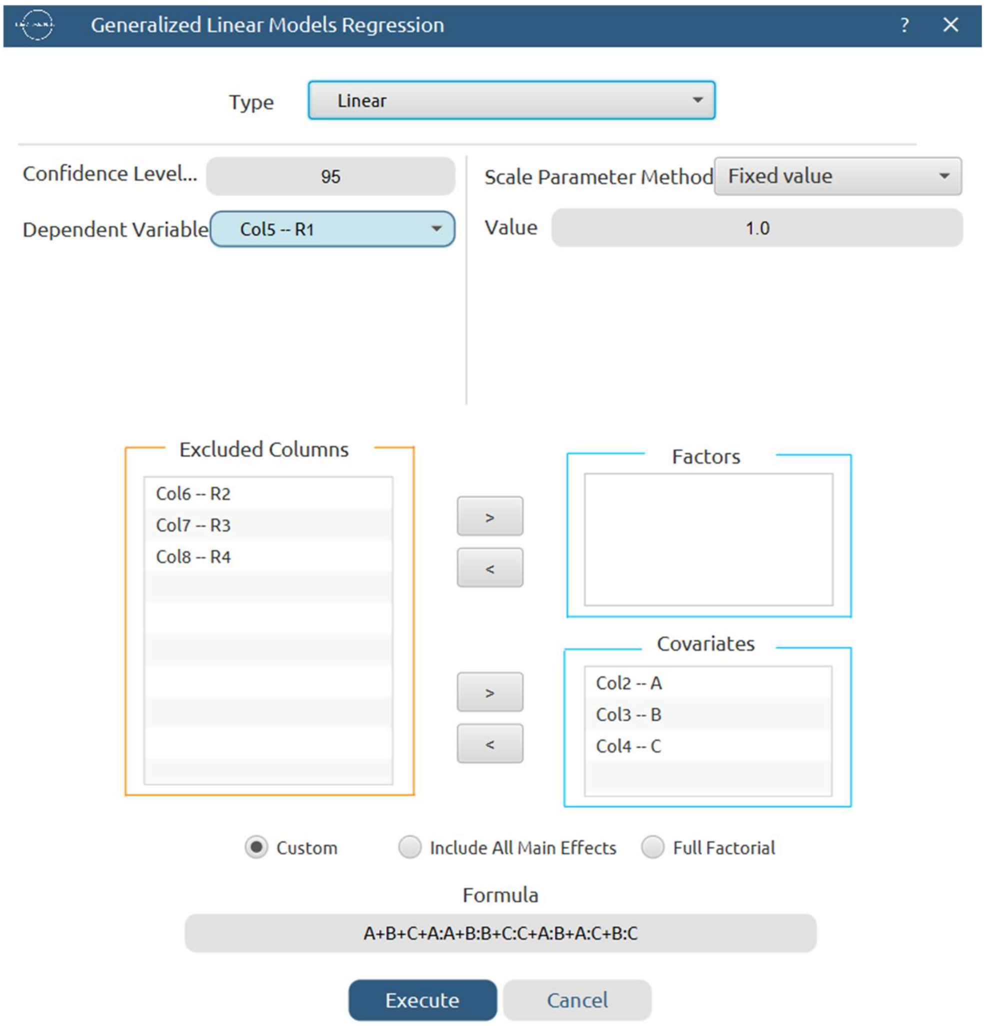
	Col1	Col2 (D)	Col3 (D)	Col4 (D)	Col5 (D)	Col6 (D)	Col7 (D)	Col8 (D)
User Header	User Row ID	A	B	C	R1	R2	R3	R4
1		-1.0	-1.0	0.0	317.3	0.87	81.5	65.2
2		1.0	-1.0	0.0	125.0	0.46	97.2	84.0
3		-1.0	1.0	0.0	256.7	0.64	88.5	76.3
4		1.0	1.0	0.0	50.02	0.45	100.0	90.0
5		-1.0	0.0	-1.0	286.2	0.75	85.0	66.7
6		1.0	0.0	-1.0	92.0	0.46	98.0	85.3
7		-1.0	0.0	1.0	273.0	0.65	87.0	68.1
8		1.0	0.0	1.0	70.82	0.5	99.5	88.6
9		0.0	-1.0	-1.0	230.0	0.45	90.0	70.0
10		0.0	1.0	-1.0	145.0	0.46	97.0	82.6
11		0.0	-1.0	1.0	208.4	0.45	92.5	79.8
12		0.0	1.0	1.0	112.0	0.46	97.8	85.4
13		0.0	0.0	0.0	180.0	0.49	99.4	78.5
14		0.0	0.0	0.0	188.0	0.43	95.0	78.0
15		0.0	0.0	0.0	171.0	0.43	96.2	80.4
16		0.0	0.0	0.0	168.0	0.43	96.5	77.1
17		0.0	0.0	0.0	175.0	0.43	96.0	76.8

Step 5: Regression

The goal here is to produce a regression equation that includes main effects, two-factor interactions and quadratic effects for R_1:

$$R = b_0 + b_1 A + b_2 B + b_3 C + b_4 AB + b_5 AC + b_6 BC + b_7 A^2 + b_8 B^2 + b_9 C^2$$

Create a new tab named "Regression – R1" and import the results from the spreadsheet "Normalized data". Afterwards, fit a generalized linear model to the data: *Analytics → Regression → Statistical fitting → Generalized Linear Models*



Results:

R1	Prediction
317.3	322.7025000
125.0	131.0525000
256.7	250.6475000
50.02	44.6175000
286.2	289.0525000
92.0	94.2025000
273.0	270.7975000
70.82	67.9675
230.0	221.7450000
145.0	148.2000000
208.4	205.2000000
112.0	120.2550000
180.0	176.4000000
188.0	176.4000000
171.0	176.4000000
168.0	176.4000000
175.0	176.4000000

Goodness of Fit	
	Value
Deviance	563.5851000
Scaled Deviance	563.5851000
Pearson Chi-Square	563.5851000
Scaled Pearson Chi-Square	563.5851000
Log Likelihood	-297.4145051
Akaike's Information Criterion (AIC)	614.8290101
Finite Sample Corrected AIC (AICC)	651.4956768
Bayesian Information Criterion (BIC)	623.1611436
Consistent AIC (CAIC)	633.1611436

Parameter Estimates							
Variable	Coefficient	Std. Error	Lower CI	Upper CI	Test Statistic	df	p-value
intercept	176.4000000	0.4472136	175.5234775	177.2765225	155584.8000000	1	0.0
A	-99.4200000	0.3535534	-100.1129519	-98.7270481	79074.6912000	1	0.0
B	-39.6225000	0.3535534	-40.3154519	-38.9295481	12559.5400500	1	0.0
C	-11.1225000	0.3535534	-11.8154519	-10.4295481	989.6800500	1	0.0
A*A	8.7550000	0.4873397	7.7998317	9.7101683	322.7369474	1	0.0
A*B	-3.5950000	0.5	-4.5749820	-2.6150180	51.6961000	1	0E-7
B*B	2.1000000	0.4873397	1.1448317	3.0551683	18.5684211	1	0.0000164
A*C	-1.9950000	0.5	-2.9749820	-1.0150180	15.9201000	1	0.0000661
B*C	-2.8500000	0.5	-3.8299820	-1.8700180	32.4900000	1	0E-7
C*C	-4.6500000	0.4873397	-5.6051683	-3.6948317	91.0421053	1	0.0

Repeat this step for the rest of the response variables. Results, R_2:

R2	Prediction
0.87	0.8175000
0.46	0.4475000
0.64	0.6525000
0.45	0.5025000
0.75	0.7625000
0.46	0.4325000
0.65	0.6775000
0.5	0.4875000
0.45	0.4900000
0.46	0.435
0.45	0.4750000
0.46	0.42
0.49	0.4420000
0.43	0.4420000
0.43	0.4420000
0.43	0.4420000
0.43	0.4420000

Goodness of Fit	
	Value
Deviance	0.0149800
Scaled Deviance	0.0149800
Pearson Chi-Square	0.0149800
Scaled Pearson Chi-Square	0.0149800
Log Likelihood	-15.6294451
Akaike's Information Criterion (AIC)	51.2588901
Finite Sample Corrected AIC (AICC)	87.9255568
Bayesian Information Criterion (BIC)	59.5910236
Consistent AIC (CAIC)	69.5910236

Parameter Estimates							
Variable	Coefficient	Std. Error	Lower CI	Upper CI	Test Statistic	df	p-value
intercept	0.4420000	0.4472136	-0.4345225	1.3185225	0.9768200	1	0.3229852
A	-0.1300000	0.3535534	-0.8229519	0.5629519	0.1352000	1	0.7131003
B	-0.0275000	0.3535534	-0.7204519	0.6654519	0.0060500	1	0.9380017
C	-0.0075000	0.3535534	-0.7004519	0.6854519	0.0004500	1	0.9830756
A*A	0.1490000	0.4873397	-0.8061683	1.1041683	0.0934779	1	0.7598014
A*B	0.0550000	0.5	-0.9249820	1.0349820	0.0121000	1	0.9124094
B*B	0.0140000	0.4873397	-0.9411683	0.9691683	0.0008253	1	0.9770820
A*C	0.0350000	0.5	-0.9449820	1.0149820	0.0049000	1	0.9441937
B*C	0E-7	0.5	-0.9799820	0.9799820	0E-7	1	1.0
C*C	-0.0010000	0.4873397	-0.9561683	0.9541683	0.0000042	1	0.9983628

Results, R_3:

R3	Prediction
81.5	81.4000000
97.2	96.675
88.5	89.0250000
100.0	100.1000000
85.0	84.8125000
98.0	98.2375000
87.0	86.7625000
99.5	99.6875000
90.0	90.2875
97.0	96.6625000
92.5	92.8375000
97.8	97.5125000
99.4	96.62
95.0	96.62
96.2	96.62
96.5	96.62
96.0	96.62

Goodness of Fit	
	Value
Deviance	12.0755000
Scaled Deviance	12.0755000
Pearson Chi-Square	12.0755000
Scaled Pearson Chi-Square	12.0755000
Log Likelihood	-21.6597051
Akaike's Information Criterion (AIC)	63.3194101
Finite Sample Corrected AIC (AICC)	99.9860768
Bayesian Information Criterion (BIC)	71.6515436
Consistent AIC (CAIC)	81.6515436

Parameter Estimates							
Variable	Coefficient	Std. Error	Lower CI	Upper CI	Test Statistic	df	p-value
intercept	96.62	0.4472136	95.7434775	97.4965225	46677.1220000	1	0.0
A	6.5875000	0.3535534	5.8945481	7.2804519	347.1612500	1	0.0
B	2.7625000	0.3535534	2.0695481	3.4554519	61.0512500	1	0E-7
C	0.8500000	0.3535534	0.1570481	1.5429519	5.7800000	1	0.0162095
A*A	-3.3850000	0.4873397	-4.3401683	-2.4298317	48.2451579	1	0E-7
A*B	-1.0500000	0.5	-2.0299820	-0.0700180	4.4100000	1	0.0357288
B*B	-1.4350000	0.4873397	-2.3901683	-0.4798317	8.6704211	1	0.0032342
A*C	-0.1250000	0.5	-1.1049820	0.8549820	0.0625000	1	0.8025873
B*C	-0.4250000	0.5	-1.4049820	0.5549820	0.7225000	1	0.3953251
C*C	-0.8600000	0.4873397	-1.8151683	0.0951683	3.1141053	1	0.0776171

Results, R_4:

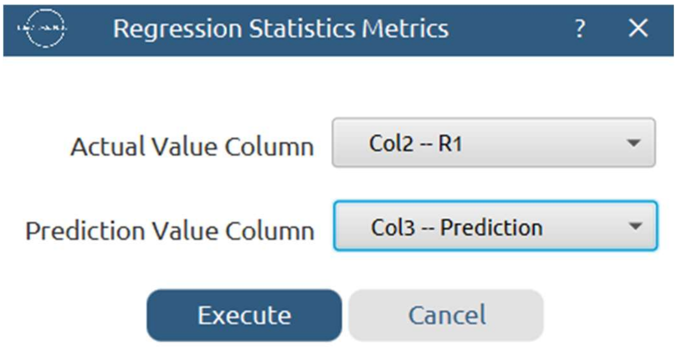
R4	Prediction
65.2	64.2375000
84.0	84.6875
76.3	75.6125000
90.0	90.9625
66.7	66.5375000
85.3	83.4875000
68.1	69.9125
88.6	88.7625000
70.0	71.125
82.6	83.4500000
79.8	78.9500000
85.4	84.275
78.5	78.1600000
78.0	78.1600000
80.4	78.1600000
77.1	78.1600000
76.8	78.1600000

Goodness of Fit	
	Value
Deviance	21.5295000
Scaled Deviance	21.5295000
Pearson Chi-Square	21.5295000
Scaled Pearson Chi-Square	21.5295000
Log Likelihood	-26.3867051
Akaike's Information Criterion (AIC)	72.7734101
Finite Sample Corrected AIC (AICC)	109.4400768
Bayesian Information Criterion (BIC)	81.1055436
Consistent AIC (CAIC)	91.1055436

Parameter Estimates							
Variable	Coefficient	Std. Error	Lower CI	Upper CI	Test Statistic	df	p-value
intercept	78.1600000	0.4472136	77.2834775	79.0365225	30544.9280000	1	0.0
A	8.9500000	0.3535534	8.2570481	9.6429519	640.8200000	1	0.0
B	4.4125000	0.3535534	3.7195481	5.1054519	155.7612500	1	0.0
C	2.1625000	0.3535534	1.4695481	2.8554519	37.4112500	1	0E-7
A*A	-0.7800000	0.4873397	-1.7351683	0.1751683	2.5616842	1	0.1094819
A*B	-1.2750000	0.5	-2.2549820	-0.2950180	6.5025000	1	0.0107723
B*B	1.4950000	0.4873397	0.5398317	2.4501683	9.4106316	1	0.0021573
A*C	0.4750000	0.5	-0.5049820	1.4549820	0.9025000	1	0.3421123
B*C	-1.7500000	0.5	-2.7299820	-0.7700180	12.2500000	1	0.0004653
C*C	-0.2050000	0.4873397	-1.1601683	0.7501683	0.1769474	1	0.6740099

Step 6: Regression Metrics

Create a tab named "Metrics – R1" and import the results from the spreadsheet "Regression – R1". Then, produce the regression metrics for the R_1 regression equation: *<u>Statistics → Model Metrics → Regression Metrics</u>*



Results:

	Col1	Col2 (D)	Col3 (D)	Col4 (D)	Col5 (D)
User Header	User Row ID	Mean Squared Error	Root Mean Squared Error	Mean Absolute Error	R Squared
1		33.1520647	5.7577830	5.0782353	0.9939857

Repeat this step for the rest of the response variables. Results, R_2:

	Col1	Col2 (D)	Col3 (D)	Col4 (D)	Col5 (D)
User Header	User Row ID	Mean Squared Error	Root Mean Squared Error	Mean Absolute Error	R Squared
1		0.0008812	0.0296846	0.0256471	0.9444047

Results, R_3:

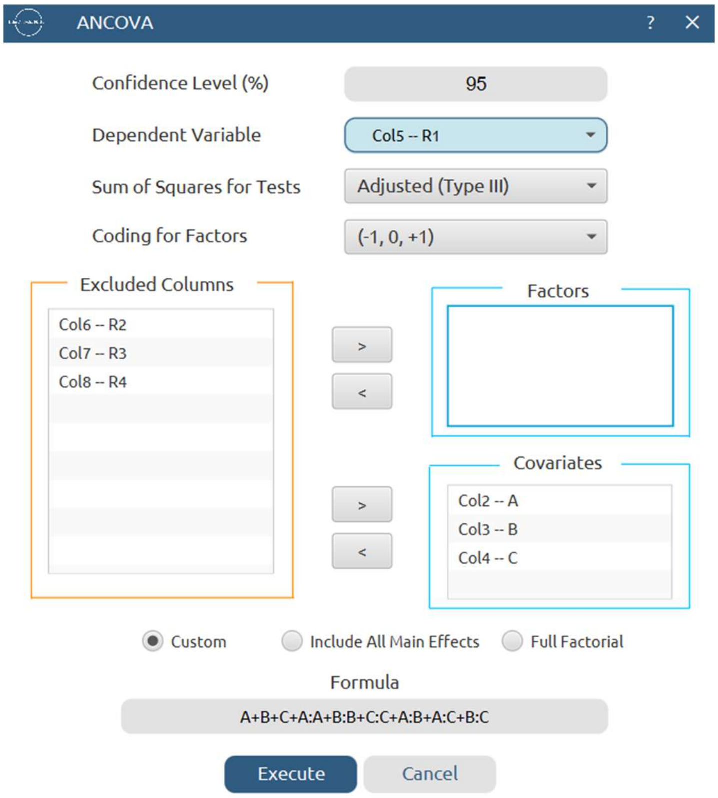
	Col1	Col2 (D)	Col3 (D)	Col4 (D)	Col5 (D)
User Header	User Row ID	Mean Squared Error	Root Mean Squared Error	Mean Absolute Error	R Squared
1		0.7103235	0.8428069	0.5241176	0.9756485

Results, R_4:

	Col1	Col2 (D)	Col3 (D)	Col4 (D)	Col5 (D)
User Header	User Row ID	Mean Squared Error	Root Mean Squared Error	Mean Absolute Error	R Squared
1		1.2664412	1.1253627	0.9623529	0.9757217

Step 7: Analysis of Covariance

Create a new tab named "ANCOVA – R1" and import the results from the spreadsheet "Normalized data". Afterwards perform analysis of covariance for R_1: *Statistics → Analysis of (Co)Variance → ANCOVA*



Results:

	Col1	Col2 (S)	Col3 (I)	Col4 (D)	Col5 (D)	Col6 (D)	Col7 (D)
User Header	User Row ID	Source	DF	Adj SS	Adj MS	F-Value	P-Value
1		A	1	79074.6912000	79074.6912000	982.1459765	0E-7
2		B	1	12559.5400500	12559.5400500	155.9955725	0.0000049
3		C	1	989.6800500	989.6800500	12.2923057	0.0099121
4		A*A	1	322.7369474	322.7369474	4.0085493	0.0853500
5		B*B	1	18.5684211	18.5684211	0.2306288	0.6457021
6		C*C	1	91.0421053	91.0421053	1.1307871	0.3229093
7		A*B	1	51.6961000	51.6961000	0.6420906	0.4492947
8		A*C	1	15.9201000	15.9201000	0.1977354	0.6699789
9		B*C	1	32.4900000	32.4900000	0.4035415	0.5454631
10		Error	7	563.5851000	80.5121571		
11		Total	16	93707.392			

Repeat this step for the rest of the response variables. Results, R_2:

	Col1	Col2 (S)	Col3 (I)	Col4 (D)	Col5 (D)	Col6 (D)	Col7 (D)
User Header	User Row ID	Source	DF	Adj SS	Adj MS	F-Value	P-Value
1		A	1	0.1352000	0.1352000	63.1775701	0.0000950
2		B	1	0.0060500	0.0060500	2.8271028	0.1365696
3		C	1	0.0004500	0.0004500	0.2102804	0.6604454
4		A*A	1	0.0934779	0.0934779	43.6812592	0.0003017
5		B*B	1	0.0008253	0.0008253	0.3856370	0.5542760
6		C*C	1	0.0000042	0.0000042	0.0019675	0.9658587
7		A*B	1	0.0121000	0.0121000	5.6542056	0.0490363
8		A*C	1	0.0049000	0.0049000	2.2897196	0.1739980
9		B*C	1	0E-7	0E-7	0E-7	0.9999999
10		Error	7	0.0149800	0.0021400		
11		Total	16	0.2694471			

Results, R_3:

	Col1	Col2 (S)	Col3 (I)	Col4 (D)	Col5 (D)	Col6 (D)	Col7 (D)
User Header	User Row ID	Source	DF	Adj SS	Adj MS	F-Value	P-Value
1		A	1	347.1612500	347.1612500	201.2445654	0.0000021
2		B	1	61.0512500	61.0512500	35.3905635	0.0005706
3		C	1	5.7800000	5.7800000	3.3505859	0.1098711
4		A*A	1	48.2451579	48.2451579	27.9670494	0.0011376
5		B*B	1	8.6704211	8.6704211	5.0261229	0.0599096
6		C*C	1	3.1141053	3.1141053	1.8052037	0.2210047
7		A*B	1	4.4100000	4.4100000	2.5564159	0.1538799
8		A*C	1	0.0625000	0.0625000	0.0362304	0.8544429
9		B*C	1	0.7225000	0.7225000	0.4188232	0.5381606
10		Error	7	12.0755000	1.7250714		
11		Total	16	495.8823529			

Results, R_4:

	Col1	Col2 (S)	Col3 (I)	Col4 (D)	Col5 (D)	Col6 (D)	Col7 (D)
User Header	User Row ID	Source	DF	Adj SS	Adj MS	F-Value	P-Value
1		A	1	640.8200000	640.8200000	208.3531898	0.0000018
2		B	1	155.7612500	155.7612500	50.6434776	0.0001909
3		C	1	37.4112500	37.4112500	12.1637172	0.0101608
4		A*A	1	2.5616842	2.5616842	0.8328939	0.3917841
5		B*B	1	9.4106316	9.4106316	3.0597283	0.1237359
6		C*C	1	0.1769474	0.1769474	0.0575318	0.8173127
7		A*B	1	6.5025000	6.5025000	2.1141922	0.1892593
8		A*C	1	0.9025000	0.9025000	0.2934346	0.6048330
9		B*C	1	12.2500000	12.2500000	3.9829072	0.0861612
10		Error	7	21.5295000	3.0756429		
11		Total	16	886.7800000			

References

(1) Nagi, A.; Iqbal, B.; Kumar, S.; Sharma, S.; Ali, J.; Baboota, S. Quality by Design Based Silymarin Nanoemulsion for Enhancement of Oral Bioavailability. *Journal of Drug Delivery Science and Technology* **2017**, *40*, 35–44. https://doi.org/10.1016/j.jddst.2017.05.019.