

**Methodology Article**

# Discovering Gene Co-Expression Modules Using Fuzzified Adjusted Rand Index

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**Abstract:** Understanding the interrelationship among genes in a cellular system is fundamental to the investigation of cellular activities, because the interrelated genes are either functionally related, controlled by the same transcriptional regulatory process or generally take part in a common biological process, and most importantly are known to be co-expressed genes. Most latent Mtb genes have been discovered but their functions, interrelationship and correlations that will help to develop protocol (s) to tame the menace of tuberculosis disease at latency have not been fully uncovered. We have developed a computational technique called Fuzzified Adjusted Rand Index (FARI) to effectively discover the co-expressed genes from identified latent Mtb genes and perform functional analysis of the gene sets using an annotation database. FARI, a modification of Adjusted Rand index used to compare clustering results, is designed to analyze, establish and quantify the expression trend of two genes with different sample points. Rank matrix of all the genes in consideration is produced after each gene has been analyzed with others, and the rank matrix serves as the basis of the co-expression discovery. A synthetic gene expression dataset, the biological benchmark dataset (*E. coli*), and different set of genes containing latent Mtb genes from an experiment result were fed into the computational tool, and different gene sets (modules) representing co-expressed genes were discovered. The discovered gene modules from latent Mtb genes are used to uncover the hub genes and their molecular functions. We have been able to identify different co-expression network from this analysis and assign biological functional meanings to some of the important Mtb genes that emerge from the experiment. Also, discovering gene co-expression module births gene co-expression network, which is a preliminary step towards gene regulatory network discovery.

**Keywords:** Co-expression, Modules, Latent Mtb, Rank Matrix, Adjusted Rank Index

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## 1. Background

Cellular activities are complex systems and have their foundation in the relationships or correlations among the cell constituents, which are represented as genes. The interrelationship among genes in a cellular system is called Gene Co-expression Network (GCN) because genes of the same network are known to be either functionally related, controlled by the same transcriptional regulatory process or generally take part in a common biological process (i.e member of the same pathway or protein complex) [5]. A GCN is an undirected graph where each node represents a gene and an edge between two nodes represents only a correlation or dependency relationship between the genes [2,

5]. Gene co-expression networks are extracted from microarray or RNAseq data using expression pattern as the advent of microarray technology has given system biologist opportunity to study the dynamic behaviour of genes in multiple conditions [1, 5]. In a gene co-expression network, the genes signify a gene module and the edges indicate significant correlations [3]. Hence, a module is a set of genes with similar expression pattern in different samples of gene expression profiling. So, constructing GCN is a process of developing modular networks within a cellular system, which allows us to understand the properties of the system.

Gene co-expression networks are represented in modules where a module is a set of genes with similar expression trends in different samples, but does not attempt to infer the causality relationship among the genes [4, 5]. Unlike Gene

Regulatory Networks (GRNs), the direction and type of relationship between pair of genes are not determined in GCN. A GRN is a directed graph where an edge between two genes represents a biochemical process such as a reaction, transformation, interaction, activation or inhibition. Hence, discovering gene co-expression network is a preliminary step towards gene regulatory network discovery. A module represents a highly connected sub-graph extracted from a co-expression network, which is a cluster of genes that have a similar function or involve in a common biological process that causes the genes to interact among themselves.

Constructing GCN is therefore the process of discovering gene co-expression modules leading to developing modular networks within a cellular system. This is done by using gene expression profiles of a number of genes from microarray or RNAseq for several samples or experimental conditions. These modular networks are constructed by looking for pairs of genes which show a similar expression pattern across samples, since the transcript levels of two co-expressed genes rise and fall together across samples [1-5]. Two principles are important and fundamental in constructing GCN; first is to calculate co-expression measure and then selecting the significant threshold. Several methods have been developed to construct GCN using these fundamental principles in various modified and extended format.

The most direct method for constructing GCN, detect gene modules and identify the hub genes within modules is Weighted Gene Co-expression Network Analysis (WGCNA) [2, 3]. WGCNA uses the Pearson Correlation to measure the magnitude of co-expression between nodes in a network. Li et al. [2] modified the existing WGCNA pipeline using the Linear Mixed-effect Model (LMM) to account for the within-pair correlation in data from paired designed. Random Matrix Theory (RMT) is used in a study to identify co-expression networks based on the microarray data. The focus is to determine the correlation threshold for revealing modular co-expression networks by characterizing the correlation matrix of the microarray profiles [1]. Gibson et al. [7] describes RMT as a knowledge-independent thresholding technique where highly connected genes in the thresholded network are grouped into modules that provide insight into their collective functionality. A variety of RNA-seq expression data was analyzed in another study to determine factors affecting functional connectivity and topology in co-expression networks, using a Guilty-By-Association framework in which genes are assessed for the tendency of co-expression to reflect shared function [6]. Another important method called Mutual Information (MI) was compared with other correlation measures over several data sets [8]. Although, one of the correlation measures called bi-weight mid-correlation outperformed MI in terms of elucidating gene pairwise relationship, there is a close relationship between MI and correlation in all the data sets, which reflects the fact that most gene pairs satisfy linear or monotonic relationships. The performance is based on gene ontology enrichment.

In this work, we propose a rank-based algorithm by

modifying the clustering evaluation technique called Adjusted Rank Index. The modified technique is called Fuzzified Adjusted Rank Index (FARI). Each gene is iteratively compared with all other genes for expression trends exploring both local and global pattern similarities. When two genes are checked for expression trend, a ranking value is generated and used to determine whether the two genes will be in the same expression module because a highly ranked gene against another gene is considered to have the same expression pattern with the gene in question. This is the reflection of the ordinary adjusted rank index, where a high value between 1 and 0 gives clustering similarity. A rank matrix that shows the ranking of each gene against all other genes in the dataset is later produced, and this is according to expression similarities of pairs of genes.

Secondly, a threshold value of 5 (single celled organism) or 9 (multi-celled organism) genes per module is used to extract four or eight highly ranked genes with each gene to form a module. We picked the threshold of 5 and 9 genes because studies have shown that each gene is estimated on average to interact with four to eight other genes [2], and based on the fact that gene networks are topologically sparse, meaning that genes are regulated by a small constant number of other genes such as 2-4 in bacteria and 5-10 in eukaryotes. This process produces the number of discovered modules that equate the number of genes in the expression profiling because each gene produced a module with its highly ranked genes. We then pruned the number of modules by removing duplicates and redundancies. The third step involves the evaluation of the remaining modules to identify hub genes and their biological functions using a biological database for functional interpretation of gene lists.

Our method is applied to construct and analyze co-expression networks based on the microarray large dataset from an extensive study of MTB. Finally, we discuss and report interesting results, which may be basis for further investigation.

## 2. Measuring Expression Trend

Computing association between a pair of genes gives insight into whether they are co-expressed or not, which is central to the construction of both co-expression network and regulatory network. The expression trend of two genes exposes their pattern similarity, where co-expressed genes show their expression levels increasing or decreasing together under the same experimental conditions or time-points across the samples. Most of the existing methods are based on correlation measures and Mutual Information (MI), which uses global similarity to draw the relationship between genes but expression profiles share local similarity rather than global similarity [5]. MI leads to information loss due to the discretization of expression values and bi-clustering tends to be computationally expensive though suitable [5].

We use both local and global similarity approaches in an attempt to measure expression trends of two genes at every

time-point or experimental conditions. Figure 1 shows the expression patterns of two genes *recA* and *uvrA* in *ecoli* dataset having the same trend, while figure 2 shows the expression patterns of *uvrA* and *uvrY* having different trend. Figure 3 shows a mixed regulation patterns. Expression trend measures are used to build the contingency table for two genes so as to calculate the adjusted rank index for the genes, which is used to determine whether they are co-expressed or not (details in section 4). The local similarity approach measures the expression trend of 2 the two genes at the same

time-point/condition. That is, the expression pattern of gene *X* and gene *Y* at  $(X_1, Y_1), (X_2, Y_2), (X_3, Y_3) \dots (X_n, Y_n)$ . The global similarity check considers the expression pattern of  $(X_1, Y_2), (X_1, Y_3), (X_1, Y_4) \dots (X_1, Y_n)$ , to further reinforce the analysis and observation of expression trend of the two genes. This is done to every sample of each gene against samples of the other gene. The global similarity check has little impact on the outcome of the similarity measure unlike the local similarity check.

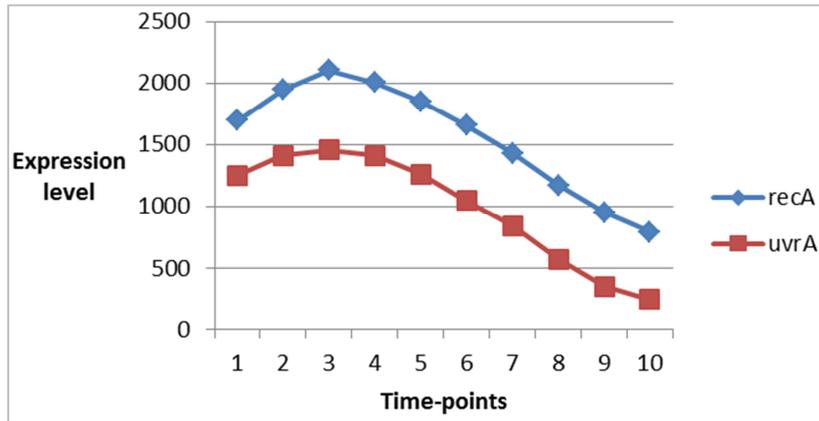


Figure 1. Expression patterns of two genes *recA* and *uvrA* in *ecoli* dataset having the same expression trend.

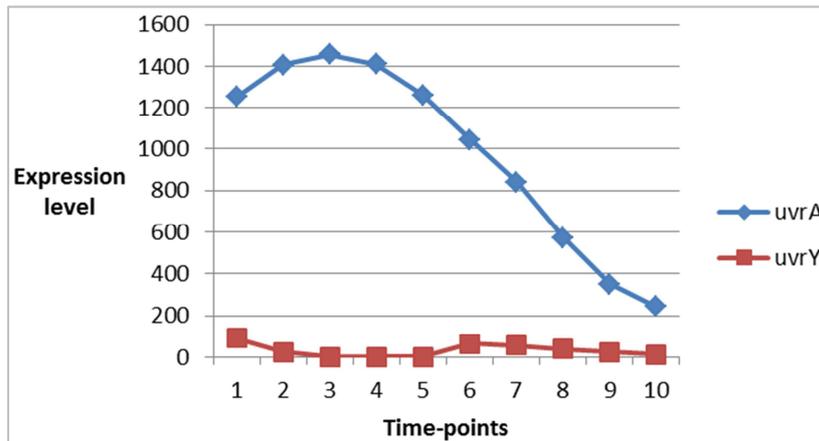


Figure 2. Expression patterns of two genes *recA* and *uvrA* in *ecoli* dataset having the different expression trend.

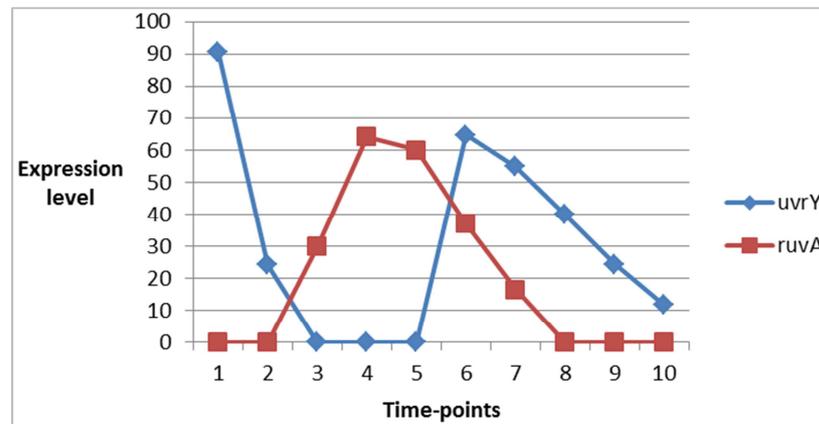


Figure 3. Expression patterns of two genes *recA* and *uvrA* in *ecoli* dataset having the mixed expression trend.

### 3. Method

The approach used for the discovering of gene expression modules is to iteratively rank each gene against other genes to generate a rank matrix that will represent the level of expression trends each gene has with others. The statistical and computational model used to achieve this is called Fuzzified Adjusted Rand Index.

#### 3.1. Fuzzified Adjusted Rand Index (FARI)

The traditional Adjusted Rand Index (ARI) is a data clustering metric that measures the similarity between two clustering results. It returns a single value indicating the level of agreement between two partitions. An ARI score of 1 indicates that the two clustering results are the same while 0 indicates that the two clustering results are not the same. Computing ARI starts by building the *Contingency Table* (similar to confusion matrix) for the two clusters. The contingency table is filled in by calculating the size of intersection of each group in the clusters against each other, which is formed by the number of items that are either in agreement or disagreement in the groups of the two clusters. However, it is impractical to get the measure of agreement of gene expression values because they are usually real values. In order to overcome this challenge, fuzzy concept of rule sets is incorporated in the process of building the contingency table.

ARI is given as:

$$adjustedRandIndex(x, y) = \frac{Index - ExpectedIndex}{MaxIndex - ExpectedIndex} \quad (1)$$

where *Index*, *MaxIndex* and *ExpectedIndex* are calculated from the *contingency table* built from the two clusters:

$$ARI = \frac{\sum_{ij} \binom{n_{ij}}{2} - [\sum_i \binom{a_i}{2} \sum_j \binom{b_j}{2}] / \binom{n}{2}}{1/2 [\sum_i \binom{a_i}{2} + \sum_j \binom{b_j}{2}] - [\sum_i \binom{a_i}{2} \sum_j \binom{b_j}{2}] / \binom{n}{2}} \quad (2)$$

Where  $n_{ij}$ ,  $a_i$ ,  $b_j$  and  $n$  are values from the contingency table:

$$\binom{m}{k}, \text{ combination of } m \text{ and } k, \text{ for } 1 \leq k \leq m.$$

$$\binom{m}{k} = 0, \text{ for } k < 0, m < k.$$

#### 3.2. Contingency Table Algorithm

The building of contingency table is very central to the use of adjusted rank index because all the values used in the calculation of the adjusted rand index are taken from the contingency table. A contingency table is a tabular form of relationship between variables filled in with integer numbers, which shows the level of agreement or disagreement among the categorical variables of the two clusters.

Given a set  $S$  of  $n$  elements, and two groupings or partitions (clusters) of these points, i.e:

$$X = \{x_1, x_2, \dots, x_r\}$$

$$Y = \{y_1, y_2, \dots, y_s\}$$

The overlap/intersection between  $X$  and  $Y$  can be summarized in a contingency table  $n_{ij}$ , each entry  $n_{ij}$  denotes the number of objects in common between  $X_i$  and  $Y_j$ .

$$\text{i.e, } n_{ij} = |X_i \cap Y_j|$$

The overlap is a measure of proximity between a pair of genes across samples, showing the transcript levels of two co-expressed genes rising and falling together. Since gene expression data are real values; hence, it is difficult to calculate number of common objects in two gene sample profiles. Fuzzy rules concept is applied to eliminate this challenge, where levels of agreement of samples of a gene against other samples of the other gene are distributed into different bins and clusters. Different values (measures) representing class labels are attached to bins and clusters accordingly. Each value is then used to fill contingency table of two gene objects of different samples.

#### 3.3. Building of Fuzzy Rules

The process to separate data into groups according to their respective class labels, which is the first step in fuzzy rule generation is performed by applying two conditions. The conditions are whether the two samples between a pair of genes are the same time-point or not. The first condition separates data into discrete interval (bins), while the second condition separates the data into clusters.

Given a pair of genes  $X$  and  $Y$  and the expression values rescaled to interval  $[0, 1]$  by use of a linear transformation;

- i. The first condition checks similar expression pattern of two samples  $X_i$  and  $Y_i$ . This is at the same experimental condition or time point (i.e local similarity)

Let  $X_p$  and  $Y_p$  be expression patterns of genes  $X$  and  $Y$  at point  $i$ , we have two discrete values as class labels  $n_{ij} = 10$  and  $n_{ij} = 0$ .

The membership function, which is the first step in fuzzy rule generation of these groups is constructed as follow:

$$X_p = \exp(X_i - X_{i-1})$$

$$Y_p = \exp(Y_i - Y_{i-1})$$

If  $(X_p > 0 \text{ and } Y_p > 0)$  OR  $(X_p < 0 \text{ and } Y_p < 0)$  Then:

$$n_{ij} = 10 > \text{bin } 1$$

Else,

$$n_{ij} = 0 > \text{bin } 2$$

where  $X_{i-1} = 0.0$  if  $i = 1$ .

- ii. The second conditions checks similar expression pattern of two samples  $X_i$  and  $Y_j$  when  $i \neq j$ . other similarity across samples (i.e global similarity).

Let  $AD$  be the absolute difference (AD) of expression values of genes  $X$  and  $Y$  at  $X_i$  and  $Y_j$  when  $i \neq j$  being the size of their intersection, the values of the intersection are partitioned into six (6) different clusters as the class label using integer values,  $scale = [5, 4, 3, 2, 1, 0]$ .

The membership function is constructed as follow;

$$AD = \exp(|X_i - Y_j|)$$

**Table 1.** The data point clusters defined for AD.

Data-points	Clusters
0.00 – 0.049	Cluster 1
0.05 – 0.09	Cluster 2
0.10 – 0.19	Cluster 3
0.20 – 0.349	Cluster 4
0.35 – 0.49	Cluster 5
0.50 – 1.00	Cluster 6

$$n_{ij} = \mu_{AD}: AD \rightarrow [5, 4, 3, 2, 1, 0]$$

The values assigned to each partition shows the measure of agreement or disagreement between gene expression values, where the highest value indicates relatedness and lower value indicates disagreement. The ranges of partitions are assumed between 0 and 1 because the original gene expression data has been normalized between 0 and 1.

### 3.4. Generation of Rank Matrix

Application of FARI to construct gene expression modules from expression data is an iterative process, where the algorithm is applied to a pair of genes at a time. At every point of its application, a single value is returned signifying the level of closeness in expression trends of the two genes. This value is stored in a kind of an adjacency matrix before picking the next pair of genes to analyze, until all the gene objects are compared in pairs. The table below gives the description of the rank matrix.

**Table 2.** Description of a rank matrix. Each cell gives the rank value of similarity expression trend of a Gene in the row against another Gene in the column.

	Gene1	Gene2	Gene3	Gene4	Gene5
Gene1	0.99	0.65	0.12	0.81	0.83
Gene2	0.18	0.98	0.11	0.87	0.42
Gene3	0.87	0.11	0.99	0.43	0.91
Gene4	0.88	0.38	0.39	0.99	0.47
Gene5	0.97	0.46	0.69	0.05	0.98

## 4. Result and Discussion

### 4.1. Co-expression Modules Construction

This work presents the power of a novel method called Fuzzified Adjusted Rank Index (FARI) to determine the magnitude of co-expression of a pair of genes among other several genes by checking similar expression pattern of two genes samples locally and globally. Local similarity determines the level of co-expression where a gene sample is at the same sample point or experimental condition with the other gene, while global similarity determines the level of co-expression a gene sample across samples or experimental conditions of the other gene. These metrics are used to determine the overall magnitude of co-expression of the pair of genes. Input dataset used include a synthetic data, *E. coli*

SOS DNA repair data and Mtb microarray data (GSE11199) generated by Thuong et al. [15], which was updated in 2017. The experiment was to identify tuberculosis susceptibility genes from ex vivo Mtb-stimulated human macrophages. Gene expression levels of over 38,500 genes were measured in 12 subjects with 3 clinical phenotypes: latent, pulmonary, and meningeal TB (n = 4 per group), which contain probe sets for 47,000 transcripts. A web server called *g: Profiler* (a web server for functional interpretation of gene lists) was used to convert the probe IDs to their corresponding gene names and functional annotations after the co-expressed modules have been created. There are two categories of exceptional probe IDs, the first category is a set of few probe IDs that got converted to more than one gene names. This set of genes made the number of genes in some modules to be increased and they are treated the same as they were discovered to have the same functional annotation attached to them. The second category is the set of probe IDs, which their gene names are not available in the annotation database and are indicated as *N/A*. These ones are filtered out of their corresponding co-expression modules making the number of genes in some modules to be reduced.

Due to the size of the dataset and the number of genes generated from this experiment, corroborated by Luo et al. [1] that the process of identifying cellular network in an automatic and objective fashion from genome-wide expression data remain challenging, we investigated the co-expression of the genes in scales and ranges such as the first 100 genes or genes 500 – 850. We later analyzed the modules generated from different investigations to identify the hub genes and analyze the functional activities of the hub genes using an annotation databases. A gene module is a cluster of densely interconnected genes in terms of co-expression [2]. FARI analyses the expression patterns of the genes under investigation and produces a rank matrix showing different values that depict the magnitude of co-expression of each gene with all other genes.

The co-expression modules are constructed from each gene under investigation. That is, for each gene, we extract the genes that have the same expression pattern with it using the rank matrix produced by FARI. So, four or eight co-expressed genes are extracted for each gene as a target to form a gene co-expressed module. This procedure is based on three factors; firstly, owing to the submissions that modular co-expression network structure and topology (number, size, content and connection) are subjective depending on the threshold chosen, secondly that co-expressed genes do interact together [1, 5], and thirdly that each gene is estimated on average to interact with four (in bacterial and prokaryotes) to eight (in Eukaryotes) other genes [2].

### 4.2. Analysis of the Rank Matrix with Synthetic Data and *E. coli* SOS DNA Repair Data

The major analysis involved in the construction of gene co-expression module or network is the analysis of expression pattern of two gene objects across several samples or experimental conditions. FARI is the novel statistical and

computational model developed to do this analysis, which produces rank matrix of values depicting the levels of co-expression of each gene with other genes. Two dataset are used to examine and validate the efficiency of our model, the first is five (5) synthetic noiseless gene expression dataset containing 30 genes with 50 time-points, containing 250 samples altogether [11]. The second is *E. coli* SOS DNA repair dataset containing 8 genes with 50 samples [11-13].

After proper inspection of the rank matrix generated from the two datasets, we discovered that the diagonal values are mostly the highest values across each row. These are the rank values gotten when expression pattern of a gene is analyzed

against itself because the process is automated. It is instructive to know that the traditional Adjusted Rank Index from which our model is developed produces values between 1 and 0 when used to compare clustering results, and gives 1 when the clustering results are closely related while it gives 0 when they are not related at all. Going by this fact, we normalized the initial rank matrix produced between 0 and 1 in order to represent the true picture of the expression pattern.

Table 3 shows the rank matrix generated for *ecoli* while the synthetic gene expression dataset is given in the supplementary file.

Table 3. Rank Matrix of Ecoli SOS DNA repair data.

	uvrD	lexA	umuDC	recA	uvrA	uvrY	ruvA	polB
uvrD	1.0000	0.2644	0.0000	0.2155	0.1147	0.5949	0.3439	0.3197
lexA	0.6280	1.0000	0.0000	0.1254	0.3040	0.7783	0.5437	0.4007
umuDC	0.1554	0.0042	1.0000	0.1708	0.0914	0.0000	0.3515	0.9280
recA	0.6941	0.5908	0.0000	1.0000	0.6423	0.5698	0.5650	0.8359
uvrA	0.2825	0.1390	0.0325	0.0631	0.9451	0.5480	0.0000	1.0000
uvrY	0.4123	0.1935	0.0000	0.1930	0.0549	1.0000	0.4560	0.3096
ruvA	0.7370	0.4303	0.3723	0.4403	0.2915	0.5993	1.0000	0.0000
polB	0.2608	0.2490	0.3275	0.5930	0.3704	0.2254	0.0000	1.0000

### 4.3. Co-Expression Modules and Networks from the Ecoli SOS DNA Repair Data

Identification of co-expression modules in particular gene expression dataset involves the process of grouping the genes with the same expression pattern into different clusters. Our method found the number of clusters being equivalent to the number of genes under investigation because the expression patterns were analyzed per each gene. Moreover, each module contains not greater than five genes because each gene is estimated on average to interact with four (in

bacterial and prokaryotes) to eight (in Eukaryotes) other genes [2]. Table 4 shows different modules from *Ecoli* SOS DNA repair data while Figure 4 shows the frequency of each gene in modules. *uvrY*, *uvrD* and *polB* are suspected to be the hub genes, which is established with the co-expression network (Figure 5) constructed from the module. We query this discovery by searching the *E. coli* SOS DNA repair network genes on KEGG database (<https://www.genome.jp/kegg/pathway.html>) and discovered that these genes engage in more pathway networks than all other genes as shown in Table 5.

Table 4. Co-expression Modules of Ecoli SOS DNA Repair Data.

Module1	Module2	Module3	Module4	Module5	Module6	Module7	Module8
uvrD	lexA	umuDC	recA	uvrA	uvrY	ruvA	polB
uvrY	uvrY	polB	polB	polB	ruvA	uvrD	recA
ruvA	uvrD	ruvA	uvrD	uvrY	uvrD	uvrY	uvrA
polB	ruvA	recA	uvrA	uvrD	polB	recA	umuDC
lexA	polB	uvrD	lexA	lexA	lexA	lexA	uvrD

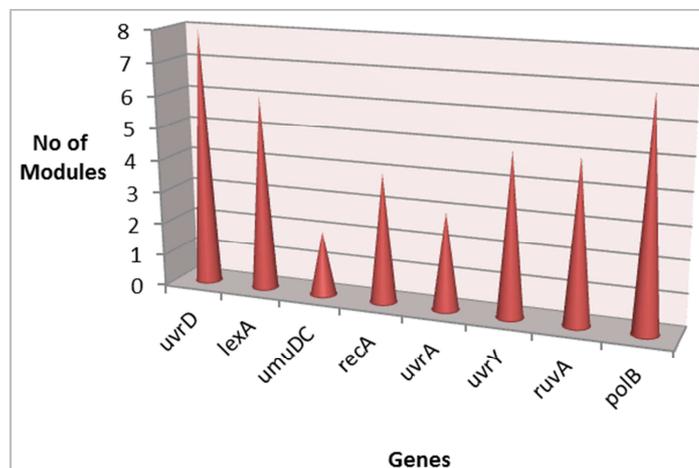


Figure 4. Frequency of each gene participating in co-expression modules.

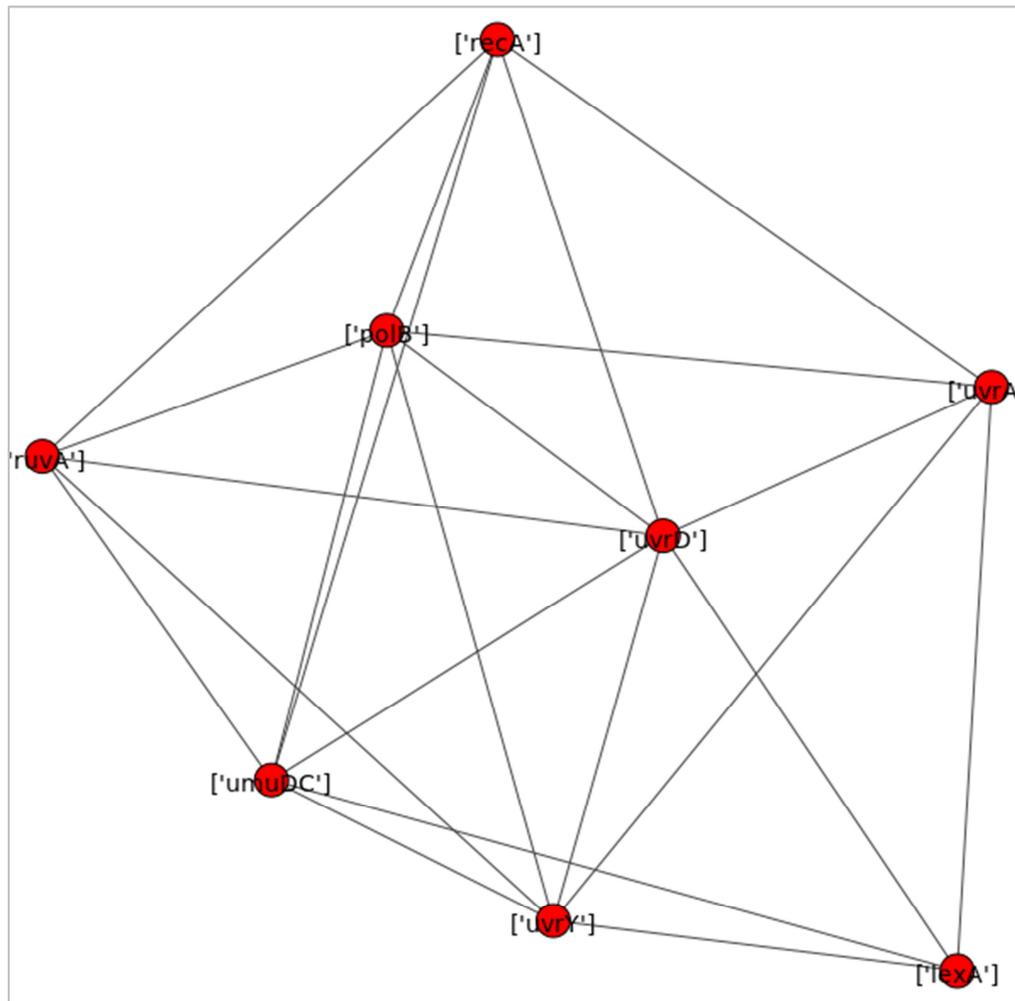


Figure 5. Co-expression network of Ecoli SOS DNA Repair Data.

Table 5. KEGG Pathways of E. coli SOS DNA Repair Network.

Gene	Entry	Name	Description	Class
	map03410	Base excision repair	Base excision repair (BER) is the predominant DNA damage repair pathway for the processing of small base lesions, derived from oxidation and alkylation damages.	Genetic Information Processing; Replication and repair
	map01100	Metabolic pathways	-	Metabolism
	map00230	Purine metabolism	-	Metabolism; Nucleotide metabolism
<i>polB</i>	map00240	Pyrimidine metabolism	-	Metabolism; Nucleotide metabolism
	map03030	DNA replication	A complex network of interacting proteins and enzymes is required for DNA replication. Generally, DNA replication follows a multistep enzymatic pathway.	Genetic Information Processing; Replication and repair
	map05166	Human T-cell leukemia virus 1 infection	Human T-cell leukemia virus type 1 (HTLV-1) is a pathogenic retrovirus that is associated with adult T-cell leukemia/lymphoma (ATL).	Human Diseases; Infectious diseases: Viral
	map05203	Viral carcinogenesis	There is a strong association between viruses and the development of human malignancies.	Human Diseases; Cancers: Overview
	map03430	Mismatch repair	DNA mismatch repair (MMR) is a highly conserved biological pathway that plays a key role in maintaining genomic stability.	Genetic Information Processing; Replication and repair
<i>uvrD</i>	map03420	Nucleotide excision repair	Nucleotide excision repair (NER) is a mechanism to recognize and repair bulky DNA damage caused by compounds, environmental carcinogens, and exposure to UV-light.	Genetic Information Processing; Replication and repair
	map02026	Biofilm formation - Escherichia coli	Bacteria inhabiting a biofilm are protected from physical stress, antimicrobials, and the host immune system, and thereby cause severe medical, environmental, and technical problems.	Cellular Processes; Cellular community - prokaryotes
<i>uvrY</i>	map02020	Two-component system	Two-component signal transduction systems enable bacteria to sense,	Environmental Information

Gene	Entry	Name	Description	Class
			respond, and adapt to changes in their environment or in their intracellular state.	Processing; Signal transduction
	map02025	Biofilm formation - Pseudomonas aeruginosa	Surface colonization and subsequent biofilm formation and development provide numerous advantages to microorganisms.	Cellular Processes; Cellular community - prokaryotes
	map05111	Biofilm formation - Vibrio cholerae	Surface colonization and subsequent biofilm formation and development provide numerous advantages to microorganisms.	Cellular Processes; Cellular community - prokaryotes
<i>recA</i>	map03440	Homologous recombination	Homologous recombination (HR) is essential for the accurate repair of DNA double-strand breaks (DSBs), potentially lethal lesions. It is investigated that RecA/Rad51 family proteins play a central role.	Genetic Information Processing; Replication and repair
<i>uvrA</i>	map03420	Nucleotide excision repair	Nucleotide excision repair (NER) is a mechanism to recognize and repair bulky DNA damage caused by compounds, environmental carcinogens, and exposure to UV-light.	Genetic Information Processing; Replication and repair

#### 4.4. Co-Expression Modules and Networks from the *Mtb*-Stimulated Human Macrophages Data

Due to the size of the dataset and the number of the genes generated from the experiment, we investigated different co-expression of the experiment in ranges of gene sets; where each set represent the input data of each investigation. We decided to break the dataset into subsets based on regions because Gene-to-Gene analysis has shown that the biochemical activities within a region in DNA sequence are functions of contributions of individual gene within the neighbourhood [19]. That is, the genomic location has some impact on gene expression which generally has influence on the gene function within a framework of expression defined by that neighbourhood. The theoretical study, [18] listed gene neighbourhood as one of the factors that affect gene expression but was quick to assume that the existence of gene expression neighbourhoods is not necessary for the correct and coordinated expression of genes that have the same expression profiles. The gene sets are described in Tables 6 and 7 below, where each is used to generate different co-expression modules.

**Table 6.** Details of the Data Inputs in Scales.

S/N	Gene Scales in the Dataset	No of Gene
1	1 – 50	50
2	1 – 100	100
3	1 – 200	200
4	1 – 350	350
5	1 - 500	500

**Table 7.** Details of the Data Inputs in Ranges.

S/N	Gene Scales in the Dataset	No of Gene
1	1 – 350	350
2	101 – 450	350
3	201 – 550	350
4	301 – 650	350
5	401 – 750	350
6	501 – 850	350

The breaking down of the original dataset gives us 11 input datasets, which is just a fractional part of the original dataset. Table 6 gives the dataset in scales, which describes the scope and magnitude of gene coverage of the original dataset (i.e the first 50, 100, 200, 350 and 500 genes). Table 7 describes the input dataset in ranges from the original dataset, which is in form of interval data points at the size of 350 genes per interval (i.e from 1-350, 101-450, 201-550, 301-650, 401-750 and 501-850). This procedure is employed in order to appropriately capture the hub genes in the dataset from the co-expression modules, by comparing the co-expression modules at different scales and ranges instead of using the whole dataset at once that could lead to under-representation of the underline expression pattern due to the size of the dataset and the potential noise in the data. Only the first 500 genes from the original dataset were investigated using the scaled datasets while the first 850 genes were investigated using the datasets by ranges.

#### 4.5. Analysis of Hub Genes

Hub genes are the notable and central nodes in a co-expression network with highly interconnected nodes, which have been shown to be functionally significant [20]. In this study, we identify the hub genes by calculating the frequency at which each gene appears in the co-expression modules generated by each dataset, and the genes with not less than 15 connected nodes are considered to be the potential hub genes for each dataset. We later identify the common hub genes from the co-expression networks constructed from each dataset across the ranges, which are considered as “real” hub genes for further analysis. Frequency of each gene participating in co-expression modules and co-expression network of the first 50 genes in the dataset are displayed in Figures 6 and 7. Both the hub genes of the scaled dataset and the hub genes from the datasets in ranges are given in the supplementary file, including the common and the most common hub genes.

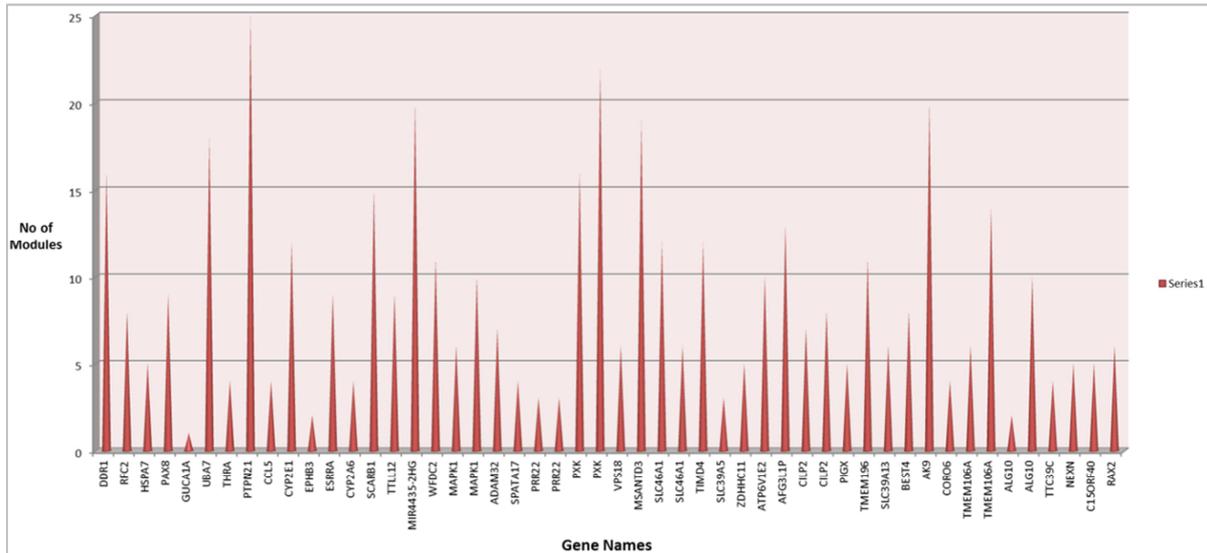


Figure 6. Frequency of each gene participating in co-expression modules of 1-50 Genes in the Dataset.

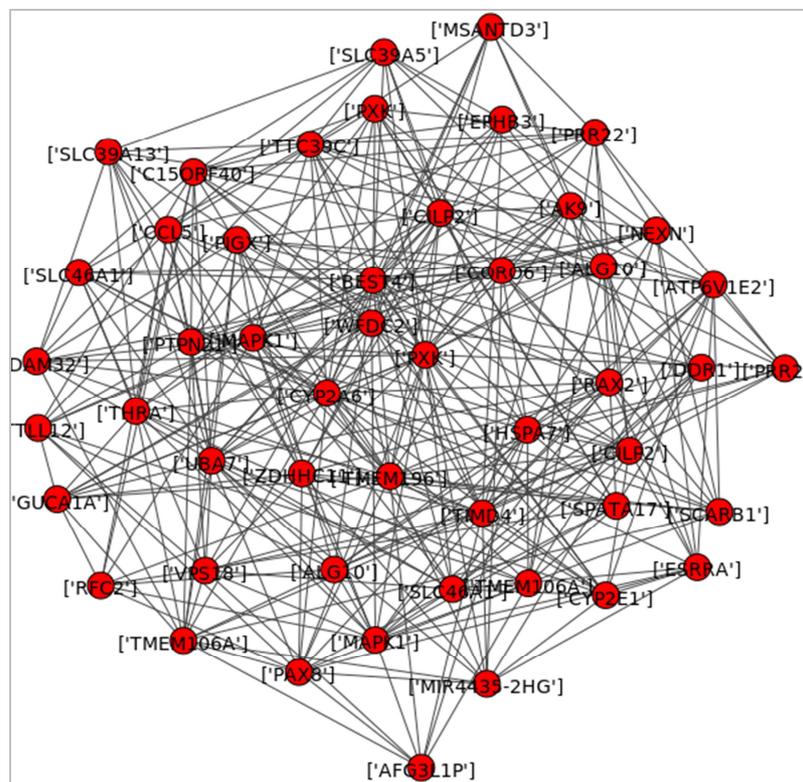


Figure 7. Co-expression network of 1-50 Genes in the Dataset.

The results from the scaled datasets shows that that the hub genes discovered when small dataset is used are also parts of the hub genes when large dataset is used, though not as highly connected as others in the large dataset. They include PTPN21, CNOT7, FAM122C, MSANTD3, LEAP2, GIMAP1, GAPT, AK9, UBA7, MIR4435-2HG, RBBP6, PXK, CFAP53, SCARB1, CCDC65, C4ORF33, FAM71A, MIR5193.

4.6. Functional Analysis of Identified Hub Genes

The functional activities that the most common (real) hub genes engage in were identified through an annotation

database called *g: profiler*. We decided to analyze the hub genes from dataset in ranges and investigate their functional activities (Table 8) because the datasets intersect at different points, which will make the whole dataset representational. The constructed co-expressed gene networks of each datasets in ranges showed that there are other highly connected genes apart from the identified most hub genes. We picked the genes that have more than 50 interactions from each network and find their functional activities (Table 9).

Table 8. Functional activities of most common hub genes.

Gene	Functional Activities
<i>KNL1</i>	kinetochore scaffold 1
<i>CNBD2</i>	cyclic nucleotide binding domain containing 2
<i>ABRA</i>	actin binding Rho activating protein
<i>SLC2A13</i>	solute carrier family 2 member 13
<i>USP28</i>	ubiquitin specific peptidase 28
<i>ARL11</i>	ADP ribosylation factor like GTPase 11
<i>SLC4A1</i>	solute carrier family 4 member 1
<i>RXFP1</i>	relaxin family peptide receptor 1
<i>CNBD2</i>	cyclic nucleotide binding domain containing 2

Gene	Functional Activities
<i>ARPP21</i>	cAMP regulated phosphoprotein 21
<i>CARD16</i>	caspase recruitment domain family member 16
<i>ZMYM6</i>	zinc finger MYM-type containing 6
<i>TAF1L</i>	TATA-box binding protein associated factor 1 like
<i>RECQL4</i>	RecQ like helicase 4
<i>DEFB105B</i>	defensin beta 105B
<i>HAS3</i>	hyaluronan synthase 3
<i>CBLL2</i>	Cbl proto-oncogene like 2
<i>DEFB105A</i>	defensin beta 105A

Table 9. Functional activities of hub genes with highest interactions in each dataset.

Gene Set	Hub Genes with >50 Interactions	No of Interactions involved	Functional Profiling
1-350	<i>ACVR1C</i>	69	activin A receptor type 1C
	<i>ZSCAN20</i>	66	zinc finger and SCAN domain containing 20
	<i>NLRC4</i>	62	NLR family CARD domain containing 4
	<i>MSANTD3</i>	53	Myb/SANT DNA binding domain containing 3
	<i>LACTB</i>	53	lactamase beta
	<i>KNL1</i>	50	kinetochore scaffold 1
101-450	<i>ACVR1C</i>	72	activin A receptor type 1C
	<i>ZSCAN20</i>	71	zinc finger and SCAN domain containing 20
	<i>NLRC4</i>	60	NLR family CARD domain containing 4
	<i>LACTB</i>	59	lactamase beta
	<i>RTP3</i>	57	receptor transporter protein 3
	<i>KNL1</i>	57	kinetochore scaffold 1
	<i>RAB42</i>	56	RAB42, member RAS oncogene family
	<i>C9ORF66</i>	51	chromosome 9 open reading frame 66
	<i>RAB42P1</i>	56	RAB42, member RAS oncogene family, pseudogene 1
	<i>ZMYM6</i>	81	zinc finger MYM-type containing 6
201-550	<i>NLRC4</i>	69	NLR family CARD domain containing 4
	<i>RAB42</i>	63	RAB42, member RAS oncogene family
	<i>RTP3</i>	59	receptor transporter protein 3
	<i>KNL1</i>	58	kinetochore scaffold 1
	<i>C9ORF66</i>	54	chromosome 9 open reading frame 66
	<i>CNBD2</i>	51	cyclic nucleotide binding domain containing 2
	<i>SIGLEC10</i>	51	sialic acid binding Ig like lectin 10
	<i>SIGLEC11</i>	51	sialic acid binding Ig like lectin 11
	<i>RAB42P1</i>	63	RAB42, member RAS oncogene family, pseudogene 1
	<i>ZMYM6</i>	75	zinc finger MYM-type containing 6
301-650	<i>RAB42</i>	65	RAB42, member RAS oncogene family
	<i>KNL1</i>	63	kinetochore scaffold 1
	<i>SIGLEC10</i>	55	sialic acid binding Ig like lectin 10
	<i>C9ORF66</i>	54	chromosome 9 open reading frame 66
	<i>CNBD2</i>	51	cyclic nucleotide binding domain containing 2
	<i>RAB42P1</i>	65	RAB42, member RAS oncogene family, pseudogene 1
401-750	<i>SLC36A1</i>	78	solute carrier family 36 member 1
	<i>ZMYM6</i>	61	zinc finger MYM-type containing 6
	<i>RAB42</i>	55	RAB42, member RAS oncogene family
	<i>RAB42P1</i>	55	RAB42, member RAS oncogene family, pseudogene 1
501-850	<i>SLC36A1</i>	70	solute carrier family 36 member 1
	<i>PCDH15</i>	64	protocadherin related 15
	<i>ZMYM6</i>	58	zinc finger MYM-type containing 6

## 5. Conclusion

Although, co-expression module techniques generally depend on proximity measures based on global similarity to draw the relationship between genes, but it is observed that

expression profiles share local rather than global similarity [5]. By using FARI, we are evaluating each gene sample discriminant power and we rank the genes according to the computed ARI values while making connection between the curse of dimensionality and sparseness property of biological network. In this paper, the described model is used to create

co-expression modules in Mtb data, which is used to construct co-expression networks from which highly-connected genes are characterized by their functions. FARI gives us an insight into the relationship between genes, which eventually gives us the opportunity to pick the most plausible genes as the best combination of affecting/regulatory genes in constructing gene regulatory network unlike creating hypothetical connections by using conditional combinations of gene as input in the study or using constraint to prune the network in these studies [10-12].

Meanwhile, further analysis could include the enrichment analysis of the gene modules using Kyoto Encyclopedia of Genes and Genome (KEGG) and Gene Ontology (GO) databases. Also parallelism could be incorporated into FARI so that the comparison of gene pairs would be done simultaneously according to the computing power of the machine instead of iteratively.

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