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Review

# Sustainable development of process facilities: State-of-the-art review of pollution prevention frameworks

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**Abstract**

Pollution prevention (P2) strategy is receiving significant attention in industries all over the world, over end-of-pipe pollution control and management strategy. This paper is a review of the existing pollution prevention frameworks. The reviewed frameworks contributed significantly to bring the P2 approach into practice and gradually improved it towards a sustainable solution; nevertheless, some objectives are yet to be achieved. In this context, the paper has proposed a P2 framework 'IP2M' addressing the limitations for systematic implementation of the P2 program in industries at design as well as retrofit stages. The main features of the proposed framework are that, firstly, it has integrated cradle-to-gate life cycle assessment (LCA) tool with other adequate P2 opportunity analysis tools in P2 opportunity analysis phase and secondly, it has re-used the risk-based cradle-to-gate LCA during the environmental evaluation of different P2 options. Furthermore, in multi-objective optimization phase, it simultaneously considers the P2 options with available end-of-pipe control options in order to select the sustainable environmental management option.


*Keywords:* Pollution prevention; Life cycle assessment; P2 framework; P2 evaluation

## Contents



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## 1. Introduction

Until recently, end-of-pipe pollution control and management was the major practice in most of the industries to reduce the pollutants emissions, however, this is not a sustainable solution in the long term. It requires large infrastructure and manpower, which can be costly if not implemented properly [1–3]. Therefore, presently governments, environmental legislators and researchers are focusing more towards the implementation of pollution prevention techniques, where the pollution is prevented before its generation [4–6]. P2 is an important part of the environmental management system (EMS), which does not deal with offsite recycling, energy recovery, treatment and disposal. According to the US pollution prevention act, pollution prevention means “source reduction and other practices, which reduce or eliminate the creation of pollutants” [5]. It is suggested to achieve through: equipment or technology modifications, process or procedure modifications, reformulation or redesign of products, substitution of raw materials and improvements in housekeeping, maintenance, training, or inventory control. The federal government of Canada defines pollution prevention as the use of “processes, practices, materials, products, substances or energy that avoids or minimizes the creation of pollutants and waste and reduces the overall risk to the environment” [6].

P2 has substantial benefits over end-of-pipe pollution control and management. Apart from the reduced production cost, improved competitiveness, enhanced customer trust, improved environmental performance and worker health and safety benefits, it conserves energy and materials through their optimal utilization [7]. Industries are the major source of pollution; therefore, the implementation of an effective pollution prevention methodology can lead to a cleaner and healthier environment. Some researchers and environmental organizations such as the US Environmental Protection Agency (EPA) and Environment Canada have developed pollution prevention frameworks to be used in industries. These frameworks have gradually improved the P2 methodology towards sustainable solutions. Nevertheless, some limitations and ambiguities are still prevailing, which need to be addressed. Therefore, a significant research is warranted in this area.

This paper reviews available pollution prevention frameworks and finally proposes a systematic and sustainable pollution prevention methodology ‘IP2M’. The proposed methodology is built with risk-based life cycle assessment and also includes health and safety as an important parameter for P2 option selection. It is applicable to process and allied industries at early design stage as well as during any modifications to existing industries.

## 2. Review of the existing P2 frameworks

In the literature, pollution prevention is sometimes termed as waste reduction, source reduction, waste elimination or waste avoidance [8]. The basic elements of pollution prevention are source reduction and in-process recycling. On the other hand, waste minimization usually includes the pollution prevention with off-site recycling [9]. As pollution prevention is the preferred option of waste minimization, therefore, some waste minimization framework could also be used for practicing the pollution prevention in industries. For comparison purpose a snap shot of different pollution prevention frameworks and opportunity assessment tools are presented in Table 1.

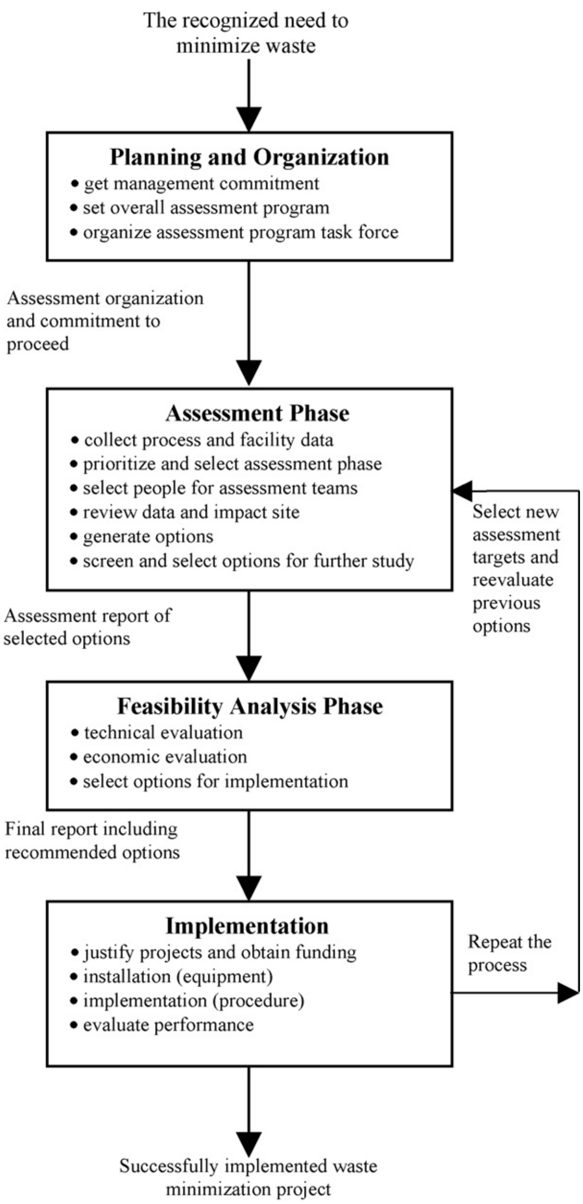


Fig. 1. Waste minimization framework (EPA, 1988).

### 2.1. Frameworks developed by the US EPA

The US EPA contributed in the early development of different pollution prevention frameworks. These frameworks are being practiced in the United States since the pollution prevention act has been approved. Depending on the context of different organizations and applications, these frameworks have been slightly revised. The summary of the frameworks is briefly described below.

#### 2.1.1. Waste minimization framework

This framework was developed by the US EPA [68], prior to the pollution prevention act and enforced the industries to implement the pollution prevention concept within their facilities. It has five major steps (Fig. 1):

(a) Planning and organization, which includes management commitment, setting of overall assessment program and organization of assessment program task force
(b) Assessment phase, which mainly consists of data collection, prioritization of assessment phase, reviewing data and impact site, option generation, and screening and selecting the option for further review
(c) Feasibility analysis phase based on technical and economic evaluation
(d) Report preparation on assessment
(e) Implementation

As an initial attempt, the framework provided an excellent basis for describing the basic phases of waste minimization. The main limitation of the framework is that, during the feasibility analysis of different pollution prevention options, it considers only the technical and economic evaluations, leaving other important parameters such as health and safety.

#### 2.1.2. Facility pollution prevention framework

The facility pollution prevention framework was developed by the US EPA in 1992 [11] to help small to medium-sized production facilities to establish broad-based multimedia pollution prevention programs in all business and geographic areas. It describes how to identify, assess, and implement opportunities for preventing pollution and how to stimulate the ongoing search for such opportunities. It consists of a series of sequential phases: (i) establish the pollution prevention program, (ii) organize program, (iii) do preliminary assessment, (iv) write program plan, (v) do detailed assessment, (vi) define pollution prevention options, (vii) do feasibility analysis, (viii) write assessment report, (ix) implement the plan, (x) measure the progress, and (xi) maintain pollution prevention program (Fig. 2). Compared to the previous framework, this framework is more detailed and suggests conducting the pollution prevention opportunity assessment in two steps rather than one-step assessment. The first phase of the framework, i.e., establishment of the pollution prevention program, needs to be reviewed based on the feed back of preliminary assessment. Furthermore, in feasibility analysis phase, it includes the environmental objective apart from the technical and economic objectives, which would lead to the adequate selection of an overall environment friendly option. To make a sound environmental evaluation, it is suggested that the information should be collected on the environmental aspects of the relevant product, raw material or constituent part of the process. This information would consider the environmental effects not only of the production phase and product life cycle but also of extraction and transportation of the raw materials and of treating waste. During the environmental evaluation, energy consumption should also be considered in the whole life cycle.

#### 2.1.3. State of Ohio EPA pollution prevention framework

In 1993, the Ohio EPA [12] has introduced a pollution prevention framework, which is applicable to the reduction of all waste regardless of environmental media, quantity, or toxicity. It is a revised version of the US EPA facility pollution prevention framework. It has one additional step namely ‘cost

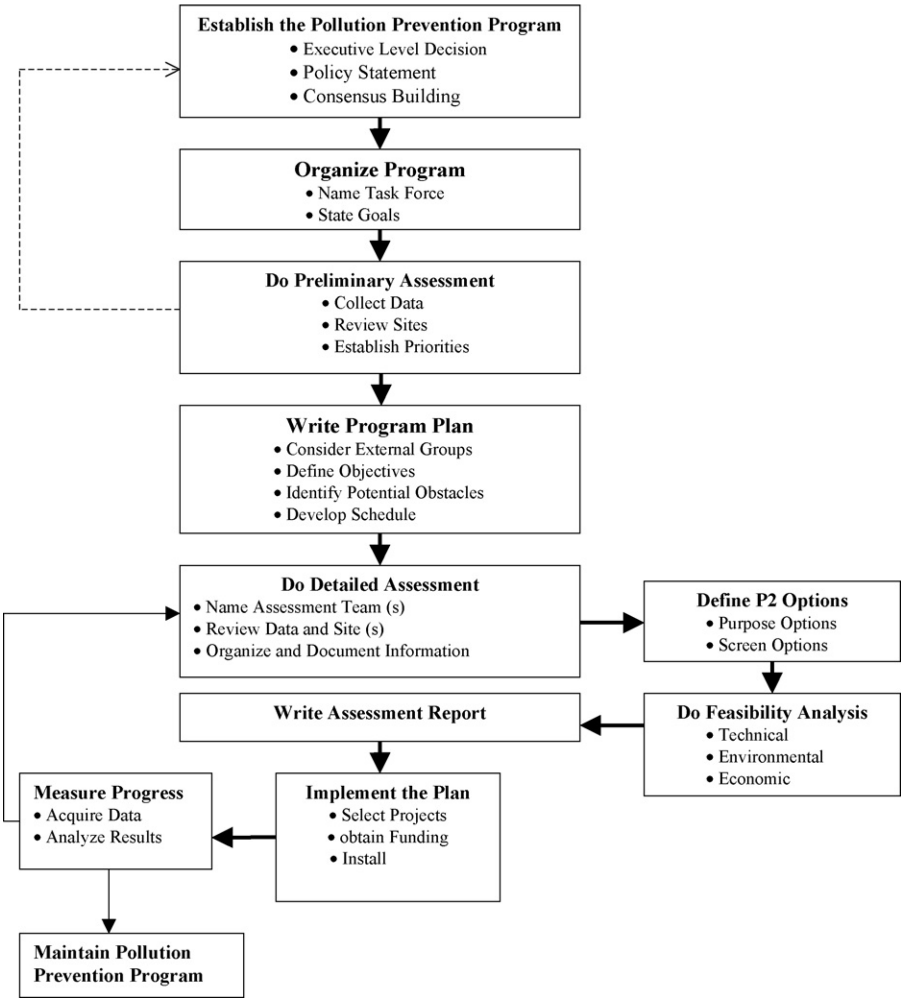


Fig. 2. Facility pollution prevention program overview [11].

considerations' as compared to the facility pollution prevention framework, which has come just before the feasibility analysis phase (Fig. 3). The most significant difference between the two frameworks is that in feasibility analysis phase, the US EPA framework suggests conducting a technical feasibility analysis first, then environmental and finally an economic feasibility. This gives more priority to environmental interest over economics.

However, in the Ohio EPA framework, economic feasibility has been given more importance over the environmental interest, so environmental evaluation has been considered as the last objective. It indicates that if economic feasibility fails then there is no need to proceed for the environmental evaluation for a particular P2 option. In the 'progress measuring phase', if the progress is not satisfactory then the US EPA facility P2 framework suggests repeating all the steps, starting from the detailed assessment step. However, the Ohio EPA framework does not give any specific guidelines in this situation.

*2.1.4. Limitations of the EPA frameworks*

The conceptual frameworks developed by the EPA provide the guidelines for implementing the pollution prevention from the initial stage to final stage, which is broadly accepted in different industries across the US as well as some other countries. Nonetheless, they have one common limitation in the feasibility analysis phase of P2 options. The feasibility analysis is done sequentially based on different criteria such as technical, environmental, economic, etc. If any P2 option does not become feasible with respect to a particular objective function then it is not proceeded for further evaluations. Furthermore, in the P2 assessment phase, the frameworks do not give any specific guidelines about which different engineering tools are to be employed and how. In feasibility analysis phase, risk and process safety issue is not considered.

The frameworks do not use multi-criteria optimization, which might not lead to an adequate selection of P2 option. They also do not provide any solutions if none of the P2 options are feasible.

## 2.2. Modification of the EPA frameworks

*2.2.1. Modification by Patek and Galvic*

In order to address the limitations of the EPA frameworks, Patek and Galvic [13] suggested some modifications to the EPA waste minimization framework. The first modification involves the use of some potential tools for P2 opportunity identifications, which include mass and energy balance, thermodynamic analysis, analysis of steam distribution, utilization and condensate

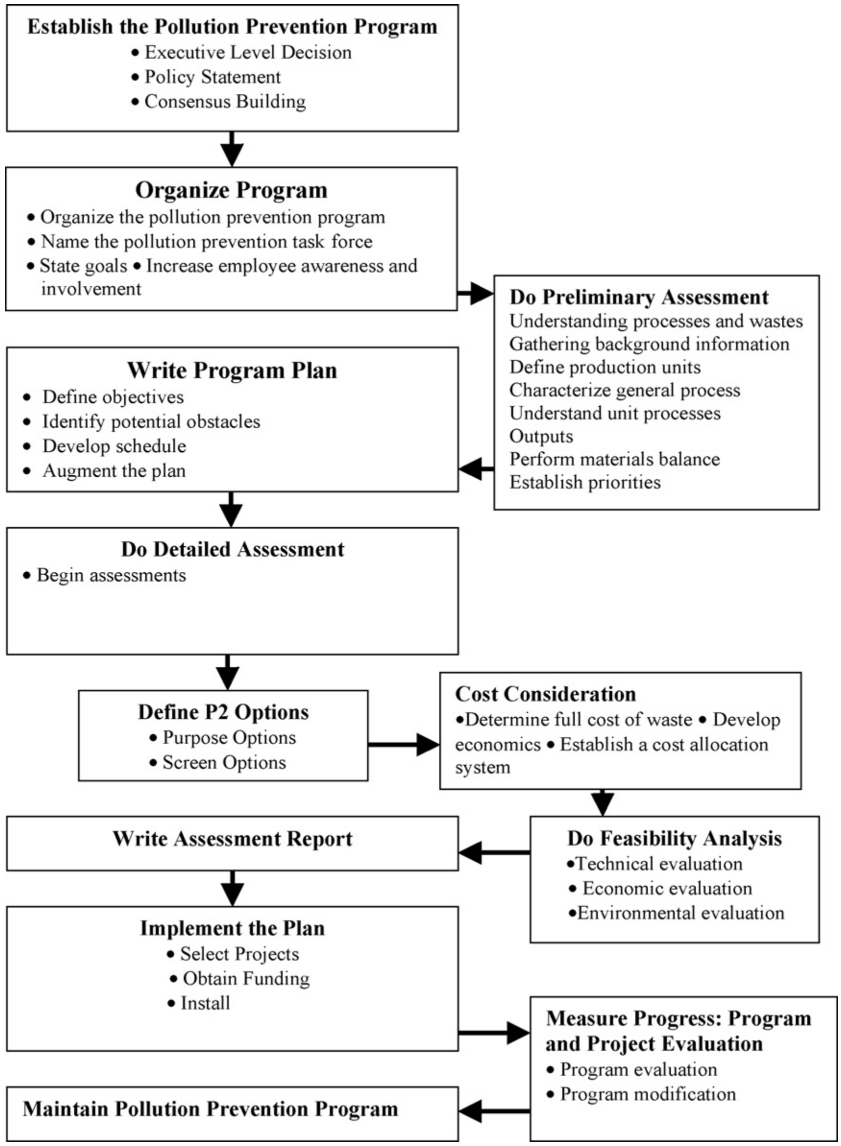


Fig. 3. Ohio EPA pollution prevention framework [12].

system. This phase has been added after the assessment phase. Secondly, it adds a multi-criteria optimization tool after the feasibility analysis phase, which would help in selecting the overall best option based on multi-criteria evaluation.

#### 2.2.2. *Modification by the Environment Canada*

The Environment Canada is using the facility pollution prevention framework of the US EPA with only one modification. It has added one additional step namely, ‘information gathering’, in between the ‘preliminary assessment’ and ‘writing of program plan’ phase. The modification does not make any significant difference.

### 2.3. *Other existing frameworks*

The US Congress Office of Technology Assessment (OTA) has identified five broad areas of pollution prevention: (i) in-process recycling, (ii) process technology and equipment, (iii) plant operations, (iv) process input, and (v) end product. In-process recycling involves the potential wastes or their components to be returned for re-use within the existing operation. Process technology and equipment incorporate changes in the basic technology and production equipment including modernization, modification or better control of process equipment. Plant operations include better predictive and preventive maintenance, better materials handling, improved process automation, separation of waste stream, increased use of sensors to detect and prevention of the non-routine waste. Process input involves the change in raw materials with different specifications and end product deals with changes in design composition or specifications of end products. In order to select the technically and economically feasible pollution prevention technique, they have suggested conducting an adequate waste audit. However, no information is provided about how the waste audit alone can help select the appropriate pollution prevention opportunities [14].

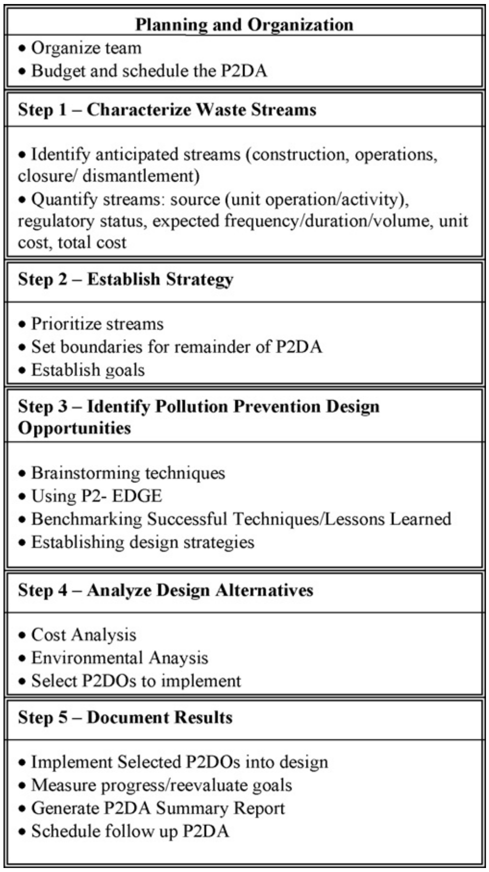


Fig. 4. Basic framework for P2DA [9].

Douglas [15] has performed a hierarchical decision procedure that provides a simple technique for pollution prevention at the early stage of the design. The procedure consists of eight phases: type of problem, input–output structure of the flow sheet, recycle structure of the flow sheet, specification of the separation system, energy integration, evaluation of the alternatives, and preparation of flow sheet at each level to identify the waste generated.

Berglund and Lawson [16] proposed that successful pollution prevention needs eight aspects to be considered at the early stage of a plant design: (i) product design, (ii) process design, (iii) plant configuration, (iv) information and control system, (v) human resources, (vi) research and development, (vii) the supplier's role and relationship, and (viii) organization. They proposed three phases: the first phase includes good operating practice, waste segregation and simple recycling. The second phase is related to the addition or modifications of equipments and process modifications and control. The third phase is associated with more complex recycle and re-use techniques and changes in process by substituting raw materials, catalysts, product, etc.

These frameworks partially contributed to the implementation of P2 in process industries. However, they could not provide complete guidelines for practicing it in the real world. They also did not give any information about different objective functions that need to be considered. Furthermore, some important elements of P2 program such as management and employee's role, and P2 progress monitoring, were overlooked.

### 2.3.1. *Site-specific frameworks*

The US Department of Energy (1996) developed a P2 framework named 'P2DA' for the implementation of P2 at early design stage of a plant [9]. The framework is shown in Fig. 4. It has six major steps: (1) planning and organization, (2) characterization of waste emissions, (3) establish strategy, (4) identify pollution prevention design opportunities, (5) analyze pollution prevention design opportunities, and (6) document results. The design assessment is carried out using facility life cycle assessment. For P2 opportunities identification, it employs a 'P2-edge' tool besides some traditional techniques such as brainstorming sessions, cause/effect diagrams, nominal group techniques, and benchmarking the best practices and technologies of industry. The selection of the best environmental opportunity is mainly based on the cost analysis, which considers the gate-to-gate life cycle rather than complete cradle-to-grave life cycle.

The Illinois Department of Energy and Natural Resources (ENR) [17] has proposed a conceptual framework for implementing the pollution prevention program. The framework, as shown in Fig. 5, comprises the following major phases:

1. Obtaining support from top management
2. Getting the program started by beginning to institutionalize the process
3. Characterizing the process
4. Identifying potential pollution prevention opportunities for the facility
5. Determining cost of current waste generation and establishing a system of proportional waste management charges for those departments that generate waste

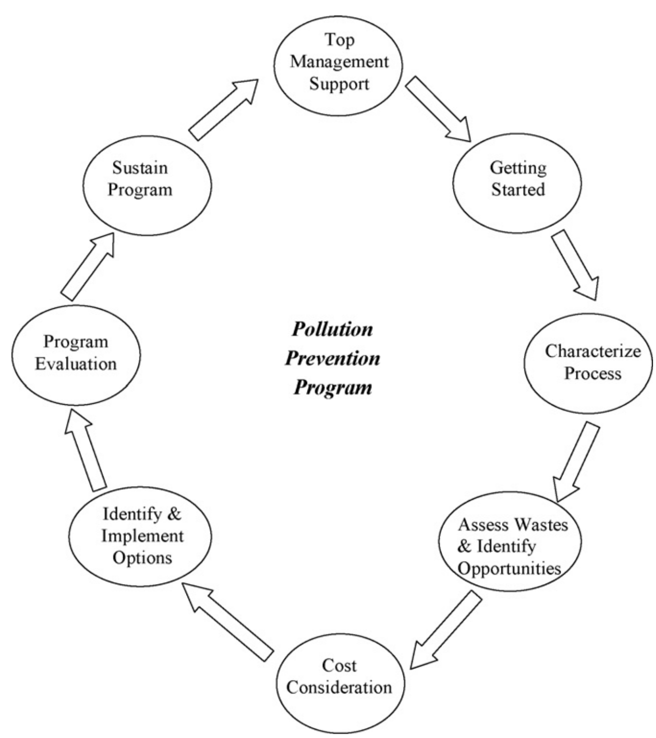


Fig. 5. Pollution prevention loop [17].

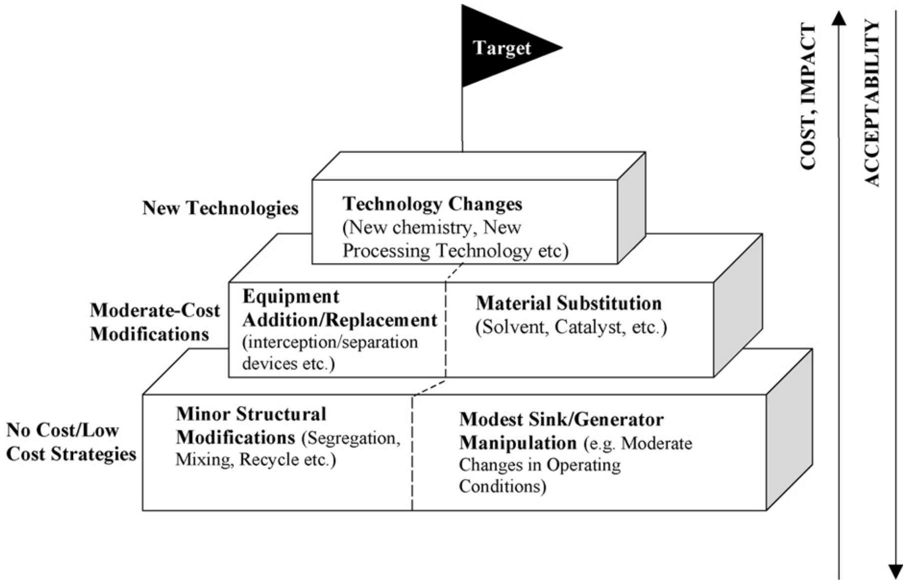


Fig. 6. Hierarchy of pollution prevention strategies [18].

6. Selecting the best pollution prevention options for the company and implementing these choices
7. Evaluating the pollution prevention program on a company-wide basis as well as evaluating specific pollution prevention projects
8. Maintaining the pollution prevention program

This framework considers the evaluation of different pollution prevention opportunities based on the separate evaluation of cost and technical criteria. The feasibility of any P2 options is determined by comparing with the baseline data. The different P2 options are ranked in terms of the environmental benefits and subsequently the cost and technical parameters are evaluated. If the top ranked option becomes feasible then it goes for implementation, otherwise the feasibility of the next option is checked similar to the EPA approaches.

Noureldin and El-Halwagi [18] have proposed a hierarchy of P2 strategies, which have three phases: no cost/low cost strategies, moderate cost modifications and implementation of new technologies (Fig. 6). The first phase involves stream segregation or mixing, recycles and changes in operating conditions. Moderate cost modifications include the addition or replacement of equipment and substitution of materials such as solvent, catalyst, etc. Implementation of new technologies includes the use of environment benign chemistry, new processing technology, etc. The significant contribution of the framework is that the analysis of P2 opportunities is conducted by employing mass integration strategy (MIS). MIS uses the concept of global flow of mass within the process to identify performance targets and optimize the allocation, separation and generation of streams and species [19,20]. According to this P2 methodology, the acceptability of options is higher for no cost/low cost strategies and lower for new technologies, and acceptability is based mainly on cost and environmental impacts. It indicates that cost has linear relationship with environmental impact i.e., as the cost of the modifications is higher, the environmental impact of such modifications is assumed to be better. Therefore, the same weight is applied to cost and environmental impact for accepting the P2 opportunities, which sometimes may give a misleading result.

One common limitation of the above three frameworks is that the evaluation is based on the site-specific data, i.e., it is confined to the narrow system boundary, which only includes the manufacturing or processing site. Therefore, during raw material substitution or environmental impact evaluation, it does not consider the cradle-to-gate or cradle-to-grave life cycle of the process/material. This might not lead to the selection of the best practicable process, the best available technology (BAT) and materials in terms of environment, health, and safety benefits.

### *2.3.2. Frameworks based on life cycle assessment*

Life cycle assessment can be used for environmentally benign product and process design. Azapagic [21] has proposed a methodology for process design based on the life cycle assessment (Fig. 7). The methodology uses LCA throughout the design

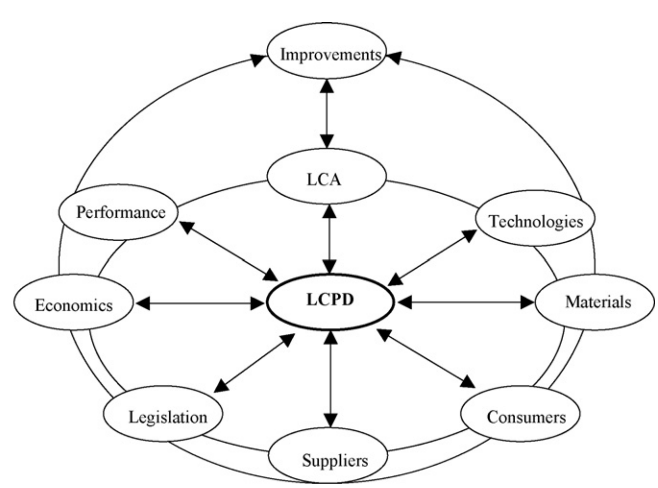


Fig. 7. Methodological framework for life cycle process design [21].

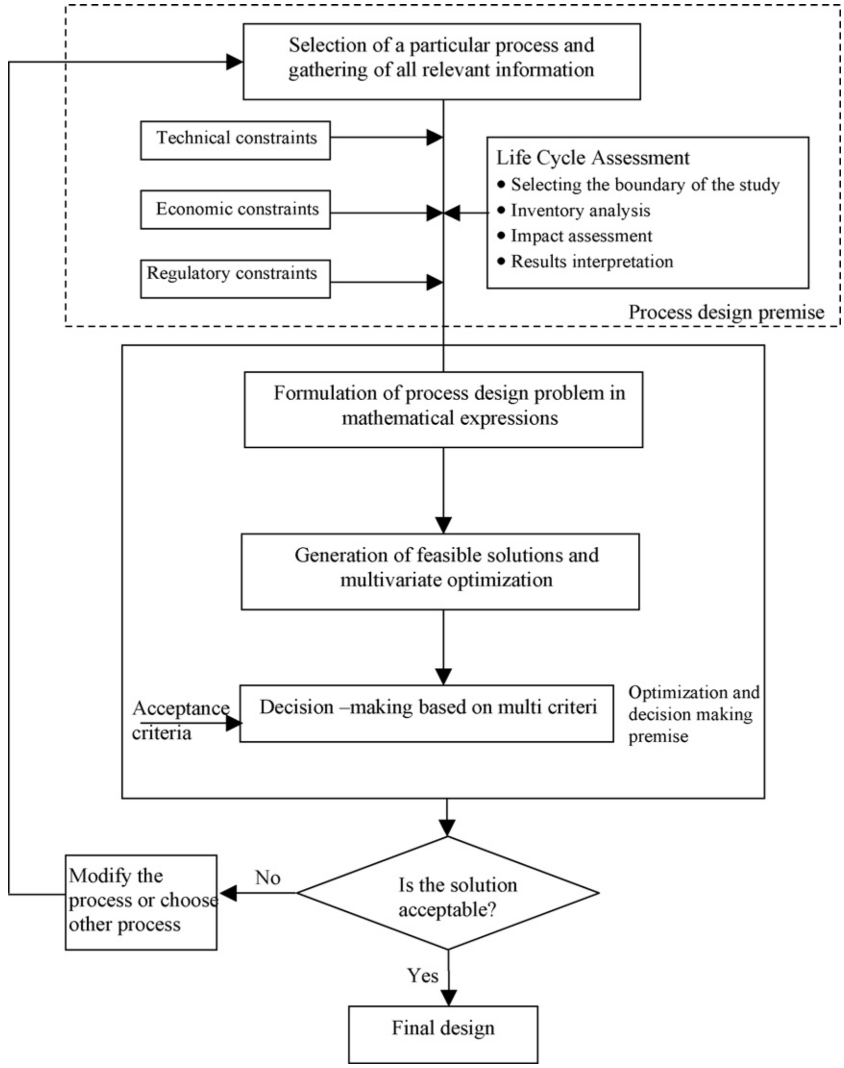


Fig. 8. Basic algorithm of GreenPro [24].

process and thereby environmental consideration has been incorporated from the early design stage. The system boundary has been extended to include the quantitative evaluation of life cycles of different technologies and raw materials. The framework suggests that the process selection should be based on the optimization of a number of objectives apart from the technical, economic and environmental objectives, which includes suppliers and consumers requirements, legislative requirements, performance and materials, etc. The limitation of the framework is that the optimization of a large number of criteria is practically very difficult and would result in a tremendous computational load. As all criteria cannot be given higher importance, therefore, such optimization increases the complexity without making much improvement in the results. A similar approach of integrating LCA with the conventional process deign framework has been proposed by Pistikopoulos et al. [22], and Kniel et al. [23].

Khan et al. [24] proposed GreenPro, a systematic methodology for process design. It considers minimization of environmental impact of a process by integrating the LCA technique within a normal process design and optimization framework (Fig. 8). It used the LCA tool for assessing the environmental impact of a process or product through its complete life cycle. It proposed cost-effective process selection at the early stage of a plant design by employing the environmental objectives along with the technology and economics. The framework has integrated LCA with process modeling and multi-objective optimization tools. It enables optimal process design to reduce energy use and waste generation.

The above-discussed frameworks are mainly focused to the environment friendly process design based on life cycle analysis at early design stage only. Khan et al. [25] later proposed a revised methodology for environmental management—considering process modification or redesign with the target of pollution prevention, P2 opportunity analysis tools are very crucial to be integrated with the LCA tool. Though the above-discussed methodologies were successful in their specific use, the framework fails to provide the integrated solution of pollution prevention. Although initial design is an important stage of pollution prevention, pollution prevention opportunities need to be investigated in all stages/areas of plant design, operations and maintenance.

Table 1
Comparison of the major existing frameworks

| Framework | Comprehensiveness | P2 opportunity assessment tools | Option evaluation criteria | Option selection criteria |
|---|---|---|---|---|
| Waste minimization [68] | Integrated (i.e., it integrates all the essential elements of P2 program) | Not mentioned in framework but LCA is suggested in the report body | Technical<br>Economic | Priority-based feasibility checking (PBFC) |
| Patek and Galvic [13] | Integrated | HEN, MEN etc. | Technical<br>Economic | Multi-objective optimization |
| EPA facility [11] | Integrated | LCA suggested in the report body | Technical<br>Environmental<br>Economic | Priority based feasibility checking (PBFC) |
| US DOE [10] | Integrated | Gate to gate LCA | Economic<br>Environmental | Priority based feasibility checking |
| Illinois ENR [17] | Integrated | Not mentioned | Economic<br>Technical | Priority based feasibility checking |
| Noureldin and El-Halwagi [18] | Only for process redesign/modification | Mass integration tool | Economic | Lower cost more acceptable although environmental benefit is low |
| Azapagic [21] | Only for initial process design | LCA is integrated with conventional process design framework | A number of criteria including technical, economic and environmental | Multi-criteria optimization |
| GreenPro [24] | Only for initial stage process design | LCA is integrated with conventional process design framework | Technical<br>Economic<br>Environmental | Multi-criteria optimization |

## 3. Identification of pollution prevention opportunities

Identification of the pollution prevention opportunities is the most important step of the P2 framework as the success in P2 program greatly depends on it. Significant research has been devoted to develop adequate tools or approaches to perform a quantitative environmental evaluation for identifying P2 opportunities. Some common tools are guide words techniques analogous to the HAZOP studies [26], mass and energy integration tools [28], graphical mass balance [29], process simulation [11,30], WAR algorithm [31,32], total site analysis [33], life cycle assessment [34] and net work synthesis technique [35–39]. Some of the important tools are briefly reviewed here.

### 3.1. WAR algorithm

WAR algorithm stands for Waste Reduction Algorithm. It has introduced an environmental assessment technique for evaluating different process designs from the view of pollution prevention. It was first introduced by Hilaly and Sikder [40]. It is a methodology that allows tracking of the pollutants throughout the process with the aid of pollution balance. Afterwards Cabezas et al. [31] amended this concept to introduce potential environmental impact balance (PEI) instead of pollution balance. The potential environmental impact is a conceptual quantity that cannot be directly measured, however, one can calculate PEI from related measurable quantities using functional relation between the two. The WAR algorithm is based on the impact conservation equation and it quantifies the impact of the pollutants throughout the process.

In WAR algorithm, six potential environmental impact indexes are considered that characterize the PEI generated within the process and the output of PEI from the process. Potential environmental impact of each chemical to a particular impact category is calculated based on the potential hazard-based score, which is normalized with the average hazard score of the same impact category for a significant number of chemicals. WAR algorithm does not either use the overall single impact score for easy comparison of different P2 options or use the optimization technique to select the overall best P2 option. In WAR algorithm, there is a lack of reasonably justified method to assign environmental weighting factors to different impact categories, which makes the overall impact index uncertain. As the impact calculation is based on the potential hazard value, in WAR algorithm all levels of pollutants are considered to have adverse environmental effects, which might incorporate uncertainty [1]. Furthermore, WAR algorithm incorporates the gate-to-gate LCA, therefore, the overall environmental friendliness of an option selected using WAR algorithm is questionable.

### 3.2. Mass integration and mass exchange networks

Mass integration is a holistic approach to the optimal allocation, generation, and separation of streams and species. It addresses pollution using a combination of strategies involving manipulation of process equipment, structural changes in the flow sheet, re-routing of streams and addition of new units [18]. Mass integration has strong impact on process systems in terms of pollution prevention. It is based on the fundamental principle of chemical engineering combined with system analysis employing graphical and mathematical optimization based tools [19]. The first step of conducting mass integration analysis is the development of a global mass allocation representation of the whole process from a species viewpoint. For each targeted species (e.g., each pollutant), there are sources and process sinks. Each sink/generator can be manipulated through design and operating parameters change. The sources must be prepared for the sinks through segregation and separation using mass exchange network [20,41]. Mass exchange network (MEN) synthesis is a combined synthesis and evolutionary design method [42]. It systematically optimises, considering the thermodynamic feasibility of mass exchange and economic evaluations to synthesize separation networks for achieving maximum possible mass exchange at minimal cost. In last few years, significant number of research have been carried out in this area and consequently, MEN concept is extended to a much wider range of problems. This includes the simultaneous synthesis of mass exchange and regeneration networks [35]; synthesis of reactive MEN [43,44]; synthesis of combined heat and reactive MEN [44]; synthesis of waste-interception networks [41,45]; heat-induced separation networks [45–48]; and water minimization problem [33,38,49–59].

One serious limitation associated with the mass integration is that it only allows for reducing the ultimate concentration of the contaminants, however, they are not capable to address the pollutants considering the relative toxicity of each pollutant.

### 3.3. Total site analysis

Total site analysis is an approach for predicting the emissions of CO, $CO_2$, $NO_x$, and $SO_x$ based on the correlation between energy use and pollutants emission [33]. It can be used as a pollution prevention tool in certain applications despite the fact that it is not dedicated to environmental considerations. The limitation of the approach is that it is unable to predict the process-related emissions when they are not directly related to energy use and its applicability is very limited. Furthermore, it cannot identify upstream and downstream pollution sources related to a process system.

### 3.4. Life cycle assessment

Life cycle assessment (LCA) is a quasi-objective process for evaluation of the environmental loads caused by a product, process or single activity. The evaluation is obtained through quantification of the energy and materials consumption and wastes release into the environment. The assessment includes the entire life cycle of the product, process or activity encompassing extraction and processing of raw materials, manufacturing, transportation and distribution, use/re-use/maintenance, recycling, and final disposal [60,61]. Three types of LCA are generally used for process or product development: cradle-to-grave, cradle-to-gate and gate-to-gate LCA. Cradle-to-grave LCA is usually used for product development. It defines the system boundary from materials extraction to disposal. Cradle-to-gate and gate-to-gate LCA are generally used for process development. Cradle-to-gate takes account of all the environmental burdens starting from materials extraction until the final production, while gate-to-gate LCA only accounts the burdens within the plant boundary, i.e., from plant input gate to delivery gate.

LCA has two main objectives: the first is to quantify and evaluate the environmental performance of a process from ‘cradle to grave’ and thus to help the decision makers choose between alternative processing routes. In this context, LCA provides a useful tool for identifying the best practicable environmental option (BEPO). Another objective of LCA is to help identify options for improving the environmental performance of a process system [62]. In this way LCA can be employed as a stand-alone tool or combined with other P2 opportunity assessment tools for identifying the P2 opportunities over a broader environmental domain [34]. Significant effort has been devoted to develop LCA databases and commercial tools for making the LCA more acceptable and easily applicable. Some common tools are ‘Sima Pro’, ‘TRACI’, ‘Eco-it’, ‘Eco-Scan’, ‘TEAM™’, ‘CMLCA’, etc., while common databases are ‘IVAM LCA’, ‘The ecoinvent centre’, ‘Life cycle inventory database’ ‘GEMIS’, ‘CORINAIR’, etc. However, LCA still suffers with some drawbacks, which need to be addressed [63]:

(i) LCA is a highly data-intensive method, and the success of any given study depends on the availability of precise data, which is still an issue in LCA [1].
(ii) LCA system is still very time consuming and expensive; time and effort is wasted to duplicate the work already done by others [64].
(iii) Life cycle inventory (LCI) data are not still available for many industries, in particular for chemical process units [64].
(iv) In LCA method, serious difficulty arises during the evaluation phase, i.e., when effect scores of different impact categories are weighed against each other [65].
(v) LCA does not tell the investigator what is the ultimate limit of the environmental performance that can be achieved and thus, it cannot help in proposing a specific corrective measure for attaining the target [1].
(vi) Significant uncertainties exist in LCA studies, which are very likely to introduce complexity in decision-making [64,66,67].

## 4. Overall limitations of the existing frameworks

To date, significant progress has been noticed in the direction of pollution prevention; nevertheless, it is far from complete. A significant number of limitations do exist which are listed below.

(i) Lack of the adequate P2 identification phase
(ii) Lack of the adequate feasibility analysis phase
(iii) Lack of the consideration of other environmental management options (Fig. 9) during P2 option selection. Due to the continuous improvement of technology, a recycling or end-of-pipe control approach may become more feasible technique than the selected pollution prevention option. There is a need to confirm that the selected P2 option is the optimum amongst the available environmental management options, otherwise sub-optimal P2 option may be selected, which would cause unsustainable solution.
(iv) Lack of the consideration of risk and safety criteria during the feasibility analysis of different P2 options. Risk and safety assessment of P2 options is very important to reduce the potential damage to human health and ecosystems.

In this perspective, the present work is aimed to develop a systematic pollution prevention framework 'IP2M' (Fig. 10) by addressing the above limitations, which is described below.

## 5. Details of IP2M framework

### 5.1. Brief description of each element of IP2M

#### 5.1.1. Establishment of P2 program

Top management support is very crucial to get a pollution prevention program started or to incorporate it into already existing activities and make the P2 as an organizational goal. Top management support can be achieved by outlining the advantages of P2. They should be informed that apart from the regulatory compliance, ecological and workers health and safety benefits, successful execution of the P2 program would benefit business in numerous ways, which include:

(i) Cost savings through materials and energy conservation
(ii) Increased productivity
(iii) Improved product quality
(iv) Reduction of potential long term liabilities

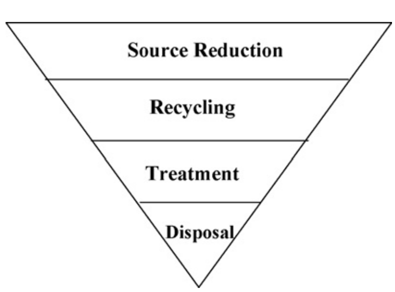


Fig. 9. Hierarchy of environmental management options [11].

(v) Reduced waste treatment, handling and disposal cost
(vi) Improved public and corporate image

Once the management of all levels recognizes the value of adoption of P2, a policy statement should follow and be communicated to all employees. The next important step is to motivate all the employees to commit to successful implementation of the P2 program. The management should provide adequate trainings to all employees regarding the benefits of P2 so that they take P2 program as their own interest.

#### 5.1.2. Organization of the program

The step includes the formation of P2 task force and P2 assessment team. The task force should consist of representatives from all sections of the company, including administration, operations, technical evaluation team, maintenance, quality control, inventory, purchasing, finance, etc. It should also include workers' representative from different sections, which would help to bring all the workers in the P2 program. The P2 task force will have the following responsibilities:

(i) Setting pollution prevention objectives and time schedule
(ii) Providing employees training and incentive program
(iii) Oversee the program through its assessment, evaluation and implementation stages
(iv) Overall evaluation of the P2 opportunity, selection and monitoring the progress
(v) Maintaining the P2 program

The pollution prevention assessment team should consist of members having comprehensive knowledge in process, process machinery, process safety, environment, materials, process operations, maintenance and good computational, and analyzing capabilities. The pollution prevention assessment team with the help of the task force will identify the P2 options, group the options, evaluate and select the best option for implementation.

#### 5.1.3. Preliminary assessment

The purpose of the preliminary assessment is to identify the potential areas for detailed P2 study. In this phase, one important component is to gather and analyze the background information from the facility. It needs the proper understanding of processes involved and the wastes generated. The information include the type and quantity of raw materials used, the type and quantity of wastes generated, the individual production mechanisms, interrelationships between the unit processes and the cost involvement in production, utilities, waste treatment, waste handling, and disposal. For the existing plant, the amount of waste generated can be obtained from the waste audit, while for the plant at design stage, it could only be estimated via process modeling. Once all the background information has been collected, before conducting a detailed assessment, wastes and unit processes should be prioritized to determine which should be examined first. Establishing the priorities of streams are based on their toxic behaviors, quantity of waste, treatment, and other related costs.

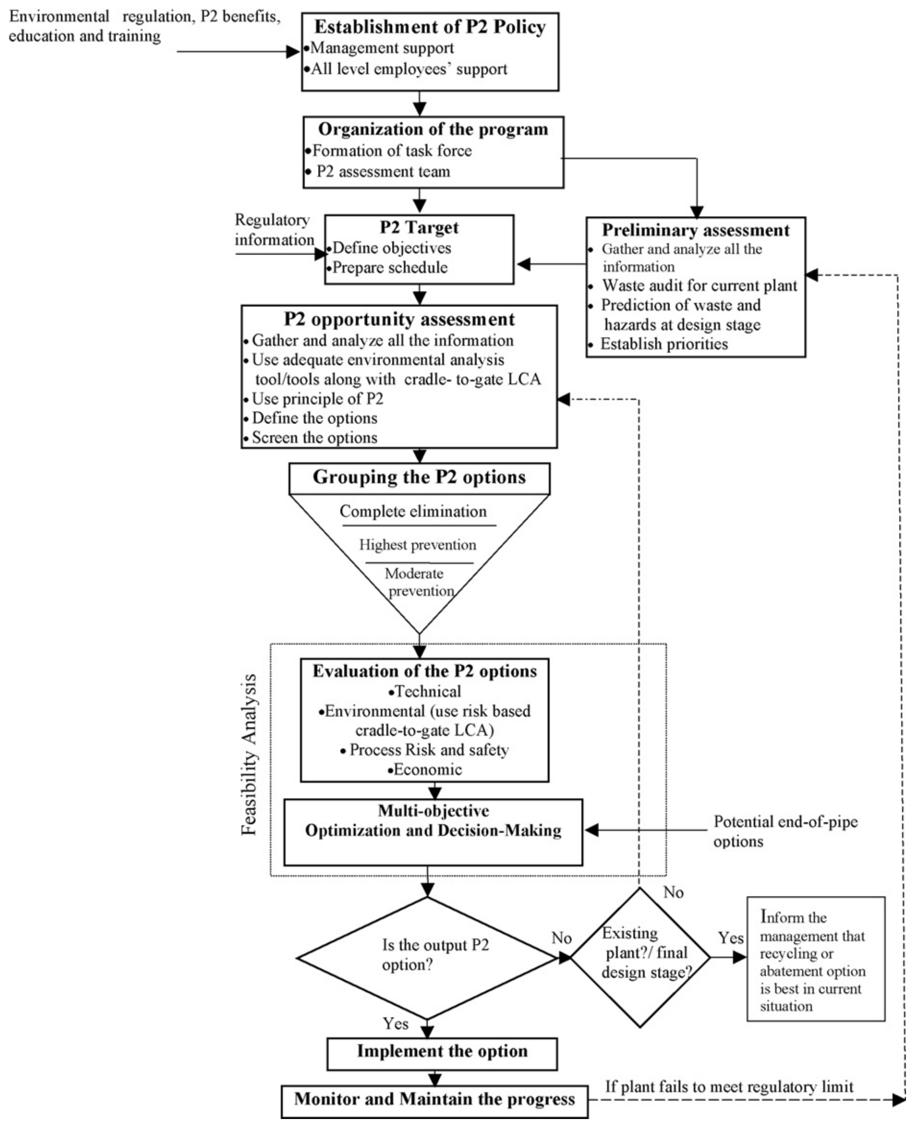


Fig. 10. Proposed pollution prevention framework (IP2M).

*5.1.4. P2 target*

P2 targets depend on the background information collected in the preliminary assessment phase and the regulatory level of a particular pollutant. It has two major elements: defining objectives and preparation of schedule. Objectives need to be stated in quantitative terms. After defining the objectives, the assessment team needs to set a time schedule for different stages in order to achieve the targets. The time schedule considers the potential obstacles that might have to be encountered.

*5.1.5. P2 opportunity assessment*

Once the P2 target is defined, an in-depth study is needed to look into the unit operations associated with the target streams and then expanding the assessment throughout the entire facility to find out all the possible P2 options. A critical review and analysis of the detailed information on process, raw materials, equipments and costs help significantly to identify different P2 opportunities. The following information needs to be considered in the four different areas:

- Process information
  - Process flow diagram.
  - Flow through actual process.
  - Process parameters.
  - Correlation among different process parameters.
  - Energy use.
- Materials information
  - Physical and chemical properties of raw materials.
  - Toxicity of materials and regulatory limit.
  - Product composition and batch sheet.
  - Product and raw materials inventory record.
  - Life cycle toxicity and energy use and wastes information related to raw materials.
- Equipment information
  - Equipment specifications.
  - Performance data.
  - Energy use.
- Accounting information
  - Waste treatment, handling and disposal cost.

- Water and sewage cost.
- Cost for non-hazardous waste disposal.
- Product, energy and raw materials cost.
- Operating and maintenance cost.

The study also needs to be carried out in the area of supplemental operations such as utilities, maintenance, and house keeping. During the P2 opportunity analysis, the principles of pollution prevention, which include mainly raw materials substitution, process redesign or modification, equipment addition/replacement, improved housekeeping, maintenance, etc., need to be kept in mind. For P2 opportunity analysis, numerous tools are available, which include mass integration and energy integration tools, graphical mass balance method, process simulation, life cycle assessment, etc. Except LCA tool, virtually all the available tools help to identify the P2 opportunities in the narrow system boundary by analyzing and optimizing process flow sheet or operating and design parameters of units. While, LCA integrates global environmental issues during process or raw materials selection and identifies the P2 opportunities over a broader domain. However, it does not have capability to analyze the process design or optimize the process parameters. In this context, an integration of LCA with other P2 opportunity analysis tools is crucial. In IP2M, it is suggested to use the cradle-to-gate LCA tool, a process simulation tool Aspen-HYSYS, a mass integration, and a heat integration tool in integrated manner.

After defining different P2 opportunities, screening is essential to sort out less costly and risk-free options for immediate implementation. The other options need to go through detailed feasibility analysis phase prior to the implementation.

#### *5.1.6. Grouping the options*

The available options need to be grouped in order to help organize the evaluation procedure. The options need to be grouped based on principle of hierarchy—complete pollution elimination, highest pollution prevention, and then moderate pollution prevention. A group of P2 options are identified in this step that need to be evaluated in the next phase before implementation. If each option is evaluated separately before grouping, then after evaluation decision of grouping would be difficult as in separate evaluation the interactions between two options cannot be identified and grouping may produce different results than that anticipated from the separate evaluations. In this way, prior grouping can also significantly reduce the evaluation time.

#### *5.1.7. Evaluation of the options*

In this phase, different grouped options are evaluated based on different objective functions. In existing P2 approaches, the P2 alternatives are evaluated based on technical, environmental and economic considerations only. In today's industries, risk and safety issues are recognized as important parameters due to the increased number of accidents. In order to reduce the potential impact to human health and ecosystems, a risk and safety assessment is an essential component of process evaluation. Therefore, in this approach, risk and safety is considered as an additional objective function to insure that the selected P2 option is within the acceptable safety limit.

Technical evaluations examine ease of installation, maintenance, and operation. It also examines the extent of future modification and its degree of simplicity. An environmental evaluation compares the relative pros and cons of each P2 alternative with regard to their effects on environment. It investigates the impacts of a process option on human health and ecosystems. It also considers different global issues such as global warming, acid rain, ozone layer depletion, photochemical smog formation, etc., which have direct or indirect impacts on human health and ecosystems. It is challenging to determine the environmental consequences of weighing factors, which depend on several factors such as social context, industry location, and nature of the exposed population, country's overall pollution statistics, and likelihood of environmental occurrences. The success of pollution prevention initiative greatly depends on the robustness of the adopted environmental assessment tool. Therefore, in IP2M, risk-based cradle-to-gate life cycle assessment tool is incorporated for the environmental evaluation of P2 options.

Risk and safety assessment is concerned with the reliability of the process systems. It examines the options and determines the probability of any adverse impacts with respect to each option and the magnitude of such impacts. The economic evaluation estimates the total costs and benefits expected from each group of options including cost savings and payback period.

#### *5.1.8. Multi-objective optimization*

When the P2 options have been evaluated in terms of different objective functions, then optimization should be carried out in order to select the optimum P2 option. In IP2M, the multi-criteria optimization and decision-making module simultaneously considers different P2 alternatives along with the potential end-of-pipe options in terms of different objective functions. This results in the P2 option, only when it becomes the most feasible environmental management option, otherwise the feasible end-of-pipe option will be selected.

For decision-making, in most of the existing P2 approaches, priority based feasibility checking technique is adopted. In this approach, if an option is not feasible with respect to the first priority objective function, then it does not proceed further. This does not always translate into the selection of the best option. In IP2M, optimization is suggested to carry out without considering the constraints. If the optimum P2/end-pipe-option exceeds any of the constraints in terms of any objective functions, then the optimized option needs to be reviewed in order to find out the possible improvements to satisfy the constraint. When the improvement is not possible, then the next prioritized option should be selected. The proposed optimization approach will allow the assessor to look at and think over the overall beneficial option and the possible direction of the improvements.

The evaluation of each P2 option in terms of any objective functions, $k$, will give a single score $S_{s,k}$. In the proposed optimization approach, the score obtained for each objective function is to be multiplied by a weighting factor $w$ to obtain a weighted score $W_{s,k}$. By adding the weighted scores for all the objective functions, the overall score, $S_{\text{overall}}$, of a P2 option will be obtained.

$$S_{\text{overall}} = \sum_{k=1}^{n} W_{\text{s,k}}, \quad (1)$$

where $n$ is the number of objective function. $S_{\text{overall}}$ will be the basis for selecting the best P2/end-of-pipe option. Assigning of weighting factors and the value of different constraints depend on the company's policy based on the current situations. P2 task force together with the consent of top-level management decides those values.

#### *5.1.9. Selection of the option*

Option selection is the most important phase. It depends on company's current standing. If the plant is at initial design stage, the best P2 option obtained in the multi-criteria optimization phase should be implemented. However, while at this stage the P2 option becomes unfeasible compared to the available end-of-pipe option, all the steps from P2 opportunity assessment needs to be thoroughly reviewed again for identifying the feasible P2 option (Fig. 10). This is important because at initial design stage, usually greater P2 opportunities exist. However, in case of existing plant or plant at final design stage, when the possible P2 options have already been incorporated, then further P2 options are not likely to be technically or economically feasible compared to the available end-of-pipe options. Therefore, at this stage if the P2 options become unfeasible, then the end-of-pipe option selected in the multi-criteria optimization phase should be implemented. In this way the proposed P2 approach can also serve as an environmental management tool.

#### *5.1.10. Implement the option*

Once the P2 option is selected, the top management needs to be updated with a detailed report describing its technical, environmental, safety, and economic aspects. The report needs to clearly state the total implementation cost and anticipated return on investment with payback period. The report would help the management in taking the decision for its implementation.

#### *5.1.11. Monitoring and maintaining the progress*

Progress monitoring is important in order to get guidelines for future modifications. It embodies the quantitative measurement of reduction of the volume of waste and toxicity level as compared to the baseline value. Besides, the P2 project needs to be evaluated for its cost effectiveness, which could be done by determining either the payback period or net present value or return on investment. After implementation of the P2 option, if the emission level is observed to be higher than the current regulatory level or at any instant in future, due to the change of the regulatory requirements if the plant fails to comply with the regulatory requirements, the P2 program needs to be thoroughly reviewed from the preliminary assessment phase. This step is essential in identifying and implementing the feasible P2 option to comply with the current or future regulatory requirements.

### *5.2. Features of IP2M*

The different features of IP2M are discussed below.

(a) It encompasses all the essential components of the P2, very systematically.
(b) It proposes two-steps assessment. The preliminary assessment is useful for setting up the P2 objectives focusing all areas of concern, while the later step is concerned with the identification of the P2 opportunities subject to the set objectives.
(c) It has added a phase 'grouping the options' based on the principle of hierarchy. This phase is important for organizing the options for evaluation.
(d) It integrates a cradle-to-gate LCA tool, a process simulation tool (Aspen-HYSYS), a mass integration tool, and a heat integration tool in the P2 opportunity assessment phase. The LCA tool will allow for the identification of P2 opportunities over a broader environmental domain and the process simulation tool combined with the mass integration and heat integration tools will help take strategic decision for flow sheet modifications, equipment sizing and operating parameter changes. Use of these tools in the P2 opportunity assessment phase will allow the assessor for identifying the P2 opportunities extensively.
(e) The evaluation of P2 options is based on multi-objectives. In this phase, IP2M has added one important objective, risk and safety, which examines the reliability of the process systems and predicts the probability of an accident to occur. In this way, it insures that the selected P2 option is safe for workers.
(f) As the success of the P2 program greatly depends on the robustness of the environmental evaluation approach, in IP2M, for the environmental evaluation of the P2 options, risk-based cradle-to-gate LCA tool is incorporated.
(g) In multi-criteria optimization phase, IP2M simultaneously considers different P2 options with the potential end-of-pipe options in terms of different objective functions, which insures to select the optimum management option.
(h) At the initial design stage of the facility, IP2M encourages to adopt the P2 option rather than using any end-of-pipe options. However, at this stage if the P2 options are not feasible, it suggests reassessing the process systems thoroughly to identify the feasible P2 option. At final design stage, IP2M suggests the implementation of the end-of-pipe option if it appears better compared to the P2 options.

### *5.3. Applicability of IP2M*

A qualitative study has been carried out to illustrate the applicability of IP2M, briefly. The research is ongoing to demonstrate the applicability of different blocks of the framework quantitatively. The present case study considers the P2 program in an existing plant for the production of viscose staple fibre. This case study has earlier been used by Khan et al. [25] to demonstrate the applicability of their proposed environmental management framework. The process is briefly described below.

Rayon-grade pulp is steeped in a caustic soda solution and the excess lye is separated in slurry process to obtain a mat of alkali cellulose. After shredding, the alkali cellulose is reacted with carbon disulphide to yield cellulose xanthate. The xanthate so formed is dissolved in dilute caustic soda to give viscose, which is filtered, de-aerated and ripened before extrusion through spinnerets into a spinning bath containing sulfuric acid, sodium sulfate and special additives. Cellulose is regenerated in the form of fine filaments. These filaments are cut into the required staple lengths, washed with disulphide, bleached and soft finished product dried to obtain viscose staple fibre, which is then baled in bailing press. Part of the carbon disulphide is recovered for re-use. The composition of the spinning bath is maintained by continuous removal of sodium and sulfuric acid.

#### *5.3.1. Establishment and organization of P2 program*

Top management should decide for undertaking pollution prevention program in their plant. This decision should be conveyed as a policy statement to all workers and staff and take adequate initiatives to train and motivate the workers. P2 task force is to be formed which will comprise the representatives from all the sections including workers. The P2 assessment team should be formed.

#### *5.3.2. Preliminary assessment and target setting*

After characterizing the wastes and analyzing the waste removal cost, the following P2 targets are identified:

- Reduction of Zn emission.
- Reduction of effluent discharge which consist of four waste streams: (i) lime water stream, (ii) acid water stream, (iii) alkaline stream, and (iv) balance acid stream.

#### *5.3.3. P2 opportunity assessment and options grouping*

The following P2 options can be identified in the viscose fibre plant by employing different engineering tools such as process simulation, mass integration, heat integration, and life cycle assessment tools:

- Use of the latest energy-efficient equipment such as multi-stage flash evaporators, continuous crystallizers and rotary compressors for stream and power conservation.
- Flow sheet reconfiguration and optimization of operating parameters.
- In-plant recovery.
- Adequate maintenance and housekeeping.

The maintenance and house keeping options could be screened for immediate implementation and the other options need to be grouped for detailed evaluation.

#### *5.3.4. Evaluation and multi-objective optimization and decision making*

The evaluation based on the technical, environmental, risk and safety and economic criteria are to be carried out for different P2 options. After the evaluations, the optimization needs to be performed based on the overall single score, as mentioned in section 5.1.8, to select the best P2/end-of-pipe option.

#### *5.3.5. Implementation and progress monitoring and maintenance*

The selected options are to be implemented and progress should be measured, and if any of the target pollutants exceed the current regulatory limit or at any time in future the plant fails to comply with the changed regulatory requirements, the P2 program needs to be reviewed.

## 6. Summary and conclusions

The IP2M is designed for the systematic implementation of pollution prevention program during process design and retrofit applications. It is applicable for all types of process industries. It has been evolved with a significant number of features, which address the shortcomings of the previous frameworks developed in this area, and thus, leads to a sustainable solution. The most important aspects of the framework are: (i) it has integrated the cradle-to-gate LCA tool with other adequate P2 opportunity assessment tools such as mass integration, heat integration, process simulation tool, etc., in P2 opportunity analysis phase, (ii) it uses the risk-based cradle-to-gate LCA during the environmental evaluation of the options, (iii) in evaluation phase, it has incorporated risk and safety as an additional objective function to insure that the selected P2 option is safe from occupational health and process safety aspect, and (iv) finally the multi-criteria optimization and decision-making module simultaneously considers different P2 alternatives along with the potential end-of-pipe options in terms of different objective functions, which results in the P2 option, only when it becomes the most feasible environmental management option, otherwise the feasible end-of-pipe option will be selected.

These contributions in P2 evaluation and multi-criteria optimization phase help the analyst to select an environmental management option, which is overall beneficial concerning different objective functions including risk and safety. In addition, the integrated use of cradle-to-gate LCA tool along with other adequate P2 opportunity identification tools would make the P2 opportunity assessment more robust and help to find out the P2 options, which are friendly over the global environmental domain.

The effectiveness of the IP2M is not still authenticated by the quantitative case studies, however, the research is ongoing in that direction and the results will be reported soon.

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