A Comparative Analysis of Wastewater Minimization and Treatment Using the Analytical Hierarchy Process

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ABSTRACT

The U.S. Environmental Protection Agency regards wastewater minimization as the first priority in an environmental management hierarchy that includes pollution prevention, recycling, treatment, and disposal or release. This hierarchy, however, should be viewed as a set of preferences rather than an absolute judgment that prevention is always the most desirable option. The management option selected should be contingent upon pertinent regulatory requirements, the level of risk reduction that can be achieved, and the technical and economic feasibility of the option.

This paper discusses various wastewater minimization practices—such as management strategies, life-cycle analysis, volume and toxicity reduction, and recycling—used by the food and beverage processing industry. In addition, it outlines an overall approach to wastewater treatment engineering—including wastewater characterization; treatment objectives; and the applicability of physical, chemical, and biological unit processes. Finally, it examines elements of the analytical hierarchy process (AHP) methodology for the purpose of determining optimal wastewater management options for a specific application.

KEYWORDS

Wastewater; food and beverage; pollution prevention; life-cycle analysis; volume and toxicity reduction; recycling; nonpoint source; treatment objectives; BOD; suspended solids; pH; characterization; physical, chemical, and biological treatment; analytical hierarchy process (AHP); alternative discrimination; pairwise comparison; priority synthesis

1.0 BACKGROUND AND INTRODUCTION

Wastewater management is a serious issue faced every day by industry and municipalities alike. Breweries, soft drink manufacturers, dairies, and food processing plants produce large volumes of wastewater that are high in organic matter. The result is wastestreams with high biochemical oxygen demand (BOD) concentrations and high treatment and disposal costs. Increased environmental regulation, public awareness, and overburdened municipal treatment plants have significantly escalated the costs of treating these wastestreams—forcing manufacturers to pay fines and tipping fees and causing industry executives to seek more reliable, efficient, and cost-effective ways to handle organic waste.

The Natural Resources Division of the Institute for International Research estimates that the U.S. spends more than $22 billion per year for wastewater treatment at publicly owned treatment works (POTWs). These utilities process 34 billion gallons of wastewater daily, including industrial wastestreams and municipal waste. Although industrial influent waste must first meet National Pollutant Discharge Elimination System (NPDES) requirements before being accepted by the POTWs, the composite wastestream from municipal and industrial sources often creates system overloads and causes secondary treatment difficulties.

The U.S. Environmental Protection Agency (EPA) regards wastewater minimization as the first priority in an environmental management hierarchy that includes pollution prevention, recycling, treatment, and disposal or release. This hierarchy, however, should be viewed as a set of preferences rather than an absolute judgment that prevention is always the most desirable option. The management option selected should be contingent upon pertinent regulatory requirements, the level of risk reduction that can be achieved, and the technical and economic feasibility of the option.

Pollution prevention (P2), or waste minimization, is the reduction, to the maximum extent feasible, of generated wastewater prior to treatment, storage, or disposal. Pollution prevention focuses on source reduction and recycling activities to reduce either the volume or the toxicity of generated wastewater, as well as related air emissions, hazardous and nonhazardous wastes, and solid waste. As with most innovative solutions to waste management problems, pollution prevention requires careful planning, creative problem solving, changes in attitude, potential capital investment and, most importantly, a strong commitment. The rewards for this commitment can be great. Pollution prevention can enhance the efficient use of resources, reduce waste treatment and disposal costs, and decrease wastewater-related financial liabilities.

While there is considerable controversy regarding what constitutes pollution prevention activities—partially due to evolving definitions and regulatory requirements over the past two decades—the term pollution prevention, as used in this paper, includes any management technique or process modification that ultimately reduces the volume or toxicity of a wastestream sent for treatment or disposal.

A significant paradigm shift over the past 20 years has affected industry’s outlook on wastewater management. Dramatic increases in disposal costs, legal and regulatory incentives, and public demand for industry to cease producing wastestreams have contributed to this shift.

The integrated pollution prevention approach described in this paper includes the following wastewater minimization practices[1]:

- Management strategies
- Life-cycle analysis
- Volume and toxicity reduction
- Recycling.

BACKGROUND AND INTRODUCTION

Improving effluent quality through wastewater treatment has garnered considerable attention over the past few decades due to the Clean Water Act (1972) and its amendments (1987). This legislation, combined with increased wastewater production by municipalities and industry, increased public health concerns, and increased chemical complexity of wastestreams revolutionized the fields of environmental engineering and wastewater treatment.

In addition to regulatory pressure, innovations in waste treatment technology resulted from demands by new chemical and food processing industries that produced effluent streams containing complex wastes. Comprehensive treatment systems that were long-lived, stable, economical, and able to handle a wide range of waste material were sought.

Typically, wastewater treatment involves a single or combined application of physical, chemical, and biological processes to remove waste from a flow stream. For instance, installing a screen in a wastestream to remove debris is a direct physical treatment process. On the other hand, adding chemicals to the wastestream to enhance flocculation and the subsequent physical settling of waste material is a combined chemical and physical treatment process.

In today's highly competitive business environment, food and beverage industry management is faced with the challenging task of minimizing production-related cost items, such as process wastewater management. Furthermore, as multiple wastewater minimization and treatment options are available, this task becomes increasingly more challenging. Thus, a reliable and effective decision-making algorithm becomes a valuable tool in this area.

The analytical hierarchy process (AHP) is a systematic procedure for representing elements of any problem. It analyzes situations by breaking them into smaller and smaller constituent parts, then performs a series of pairwise comparisons to evaluate the relative importance of each element in the hierarchy and derive priorities among the criteria for alternative solutions.

The following sections describe an integrated wastewater minimization approach, outline available engineering practices for wastestream treatment, and discuss elements and application of the analytical hierarchy process for the purpose of optimizing wastewater management.

2.0 INTEGRATED WASTEWATER MINIMIZATION APPROACH

The goal of minimizing wastewater generation at a manufacturing facility, given all available options and technologies, is facilitated by using an integrated pollution prevention approach. This integrated approach includes management strategies, life-cycle analysis, volume and toxicity reduction, and recycling practices.

2.1 Management Strategies

A sound wastewater pollution prevention strategy incorporates the following elements [1]:

- Planning and organization
- Characterization of wastewater and losses
- Development of wastewater minimization options
- Technical, regulatory, and economic feasibility
- Implementation
- Monitoring and optimization.

A firm commitment from management, in conjunction with the establishment of clear goals, is important to the successful implementation of waste minimization efforts. A wastewater minimization audit—which is critical to understanding the types and sources of pollutants in the wastestream—should be performed. This audit consists of evaluating the entire production process and completely characterizing its components and the byproducts that enter the wastestream (specific sources, generation rates, physical and chemical characteristics, and the cost of the current management method). Once the audit has been completed, wastewater minimization options are identified, evaluated, and implemented in order of their priority.

Methods that involve simple housekeeping changes—such as segregating wastestream components, sweeping floors before washing, carrying out preventative valve and pipe maintenance, limiting the storage of chemicals on the plant floor to necessary amounts only, and training employees to be aware of the consequences of their actions—can dramatically reduce wastewater generation.

More complex methods of reducing wastewater—such as changing production methods (process operating variables, feedstock, new process chemistry, equipment changes, and product elimination)—require additional effort and capital investment, and often are initially resisted by management. Therefore, such pollution prevention methods require detailed evaluation and analysis for their technical, regulatory, and economic feasibility before they are implemented. Either a present-worth analysis or cost/benefit analysis is typically used to perform such an assessment. Additionally, the decision-maker should consider less tangible, related factors such as reduced future liabilities, corporate public relations, and potential public benefits.

Because pollution prevention projects must compete with other capital expenditure projects for limited company funds, they must be investigated using economic analysis methods that evaluate annualized cost savings, the internal rate of return, and present-worth analysis. Various models to assess pollution prevention opportunities currently exist. The EPA offers one (1996) and

Anderson (1987) provides a second model based on theoretical econometric analysis that evaluates wastestream reduction alternatives.

2.2 Life-Cycle Analysis

The impact of industrial processes and activities on public health and the quality of the environment is far-reaching. One of the more promising techniques for quantifying and minimizing these adverse effects—life-cycle analysis (LCA)—provides a comprehensive framework for investigating the entire range of impacts on the environment as a result of a specific industrial activity or production process. LCA provides a valuable tool for identifying costs and benefits associated with product and process design modifications. Furthermore, LCA can aid in quantifying environmental impacts and wastewater reduction opportunities associated with a particular product or process.

In general, LCA comprises three phases[1]: inventory, impact/analysis, and implementation. LCA and its application in wastewater pollution prevention are described in the following sections.

Inventory Phase

This phase typically involves the following [1]:

- Team organization—Project directors, team leaders, and members are identified. Diverse teams that include all parties with a stake in the outcome have a higher likelihood of successfully achieving project goals.

- Identification of target product/process for LCA—Performing a detailed LCA of an organization's entire set of activities is impractical. However, based on the company's environmental concerns, specific target products/processes can be identified for analysis, and relevant quantitative information can be collected.

- Construction of an LCA diagram—Simple flowcharts are used to diagram the LCA for the targeted products/processes. The analysis should include the progression from raw materials, through the production process, to the end product. Resulting wastestreams for each target product/process are identified and characterized. The "boundary conditions," or scope of the LCA for a product/process of concern, are modified based on the needs of the investigation. The final LCA diagram should contain target products, processes, and activities; locations of waste discharge or energy usage; types of transfer mechanisms; and amounts of materials or pollution discharged. Diagramming the LCA facilitates pollution prevention by systematically analyzing wastestream components.

- Identification of input and output—The location and amounts of materials and wastes that enter and leave each stage of the life cycle are identified. All possible generation sources need to be considered.

Another important LCA tool involves normalizing wastestream generation rates to the production rates of finished products, which allows the decision-maker to distinguish between a real reduction in wastewater generation and the effects of fluctuations in production rate. Thus, a realistic baseline can be defined for setting environmental goals and tracking performance.

Impact/Analysis Phase

After the inventory phase has been completed, the impact of wastestream discharges and energy usage is evaluated. The interpretation of impacts on the life cycle can be based on regulatory requirements, risk or hazard assessment, or energy utilization rates. A list of priorities is then constructed for minimizing the impact of particular products, processes, or activities. At this point, the results of the LCA can provide a rational basis for making strategic decisions or conducting an in-depth investigation of specific materials, processes, and management practices.

Implementation Phase

The improvement phase includes identifying potential improvement options and performing a comparative evaluation of each option’s technical, economic, and regulatory feasibility. The analytical hierarchy process (AHP) methodology can be applied to perform this task.

Common strategies used by industry to minimize a wastestream include identifying clusters, investigating compliance alternatives, reducing volume and toxicity, and recycling. The EPA’s Office of Toxic Substances (OTS) recommends identifying use clusters—groups of chemicals used for same or similar purposes, such as biocides or lubricants—for targeting purposes. The OTS has concluded that examining use clusters (rather than single chemicals), evaluating their potential risks, and identifying less toxic substitutes are effective methods to minimize a wastestream. Identifying potential compliance alternatives and selecting options that minimize health risks and impacts on the environment, while meeting the company’s regulatory requirements and minimizing related costs, present ongoing challenges for industry. LCA can be used to gain a competitive advantage in this process by providing a rational framework for evaluating compliance alternatives. The following sections discuss volume and toxicity reduction and recycling as wastestream minimization strategies. It should be noted that these sections are not mutually exclusive since some practices may have overlapping effects.

2.3 Volume and Toxicity Reduction

Reducing wastewater volume can serve as an appropriate starting point for pollution prevention. Although some state environmental regulatory agencies, in defining “source reduction,” explicitly exclude reducing volume without reducing toxicity, industry nonetheless can realize certain economic benefits by practicing volume reduction. Toxicity reduction practices target reducing the toxic content of the wastewater stream without necessarily diminishing the volume of wastes produced. Toxicity reduction can be beneficial by reducing the overall cost of sewer disposal fees or by facilitating onsite treatment. Wastewater volume and toxicity reduction can be achieved at the plant level by a number of methods, including the following[1].

Modification to Plant Production Processes/Equipment and Material Substitution

Modifications to plant production processes and equipment can significantly reduce wastewater generation. Changing the raw materials, equipment, operating procedures, and materials storage and handling practices used minimizes the wastestream. Raw materials substitution includes processes such as equipment cleaning, disinfecting, lubricating, and product packaging. It is important to note that production management for the planning, design, and implementation of process modifications must be included for a successful wastewater minimization effort.

Material substitution is a valuable tool for reducing wastestream toxicity—as long as product quality or production efficiency is not compromised. Chemicals used for cleaning, lubricating, degreasing, pest control, and other basic maintenance tasks can be replaced with the less hazardous, less toxic substitutes that are currently available on the market. It is necessary to study material characteristics and understand the requirements of the process application before choosing replacement products.

Responsible Housekeeping Practices

Perhaps the easiest and least costly method of reducing the wastestream is good housekeeping and maintenance procedures. Wastestream segregation practices are a good example of this approach. Mixing a small amount of hazardous waste with a larger volume of nonhazardous wastewater would require treating the entire wastewater stream as hazardous waste and significantly increase treatment costs. For example, it is not uncommon for a portion of the waste flow to contain the majority of suspended solids loading. Therefore, if segregation can be achieved, only that portion would require treatment for solids removal. Proper labeling and handling of all lines and containers would greatly facilitate pollution prevention efforts on the plant level. The old rule, “Do not make it a liquid if it is dry,” applies to housekeeping practices such as floor sweeping and solid waste collection. The volume of items such as non-contact cooling water and stormwater runoff can be significantly reduced if the feasibility of separating process wastewater is investigated. (See Section 2.5, Nonpoint Source Pollution Prevention, for more details.)

Other good operating practices include[5]:

- Performing waste minimization assessments
- Conducting environmental audits/reviews
- Establishing loss prevention programs, e.g., spill prevention, control, and countermeasures (SPCC) plans
- Performing preventative maintenance
- Conducting ongoing personnel training and pollution awareness seminars
- Soliciting employee participation and input
- Optimizing plant production schedules
- Instituting a wastestream cost accounting system
- Allocating waste treatment and disposal costs to specific operations
- Monitoring and enforcing new housekeeping programs continuously.

2.4 Recycling/Reuse/Reclamation

As the point of diminishing returns is reached for volume or toxicity reduction practices, it may be feasible to recycle wastestreams to another process or other plants. In-plant recycling is generally preferred because of the potential liability associated with mishandling waste. Recycling practices include water, solvents, oil, and solid waste.

Wastestream and water recycling and reuse practices abound in the food and beverage processing industry. Some examples of wastestream component reuse include:

- Using chlorination to remove microbial contamination from non-contact process water and then using it for cleaning and washing in applications that do require highly pure water

- Reusing the third-rinse water for the next rinse when cleaning kettles and vats.

- Using spent caustic water for pH control at an onsite wastewater treatment plant, thereby reducing the cost of treating the wastestream and providing a valuable recovered product.

The critical evaluation of such practices and byproduct recovery possibilities should be part of the plant overall wastewater minimization audit.

Various vendors offer recycling/reuse services for special hazardous wastestreams that often require separate treatment and handling. These services provide environmentally sound alternatives to offsite disposal and effectively reduce overall plant wastewater generation. Specific vendors must be contacted in advance to determine and meet their criteria for acceptance and proper handling of these items.

2.5 Nonpoint Source Pollution Prevention

With the presence of impervious surface areas onsite, a significant amount of rainfall is converted to stormwater runoff. The resulting wastestream contains pollutants such as suspended solids, oil, grease, metals, and undesirable nutrients. Best management practices (BMPs) for handling this wastestream include both structural and nonstructural controls. Generally, structural controls include containment areas for aboveground storage tanks, structures that enclose or cover material handling and storage areas, and oil/water separators. Nonstructural controls include practices such as preventive maintenance, SPCC plans, housekeeping, and prevention or minimization of potential pollutant releases. It is recommended that formal stormwater management plans be drawn up and nonpoint sources of pollution be reviewed. The implementation of nonpoint source pollution control practices is essential to ensure successful P2 efforts and meet facility regulatory requirements.

2.6 Potential Barriers to Pollution Prevention Efforts

Any new or developing program must overcome potential barriers to ensure its successful implementation, and pollution prevention is no exception. Typical barriers to pollution prevention include the following.

Resistance to a Change in Mindset

Pollution prevention is a relatively new approach to environmental protection. The switch from pollution control (i.e., how to deal with wastes and pollution once they are produced) to P2 constitutes a major paradigm shift. As with any change, skepticism can greatly affect the successful implementation of a new approach. However, once the change has been implemented and proven worthwhile, skepticism is transformed to support. The key to success is to start small and, through proven performance, build upward, one step at a time.

Unexpected Changes in Regulatory Requirements

Recent changes to regulatory requirements may impede the implementation of P2 in various ways, such as:

- Providing conflicting media-specific goals or P2 mandates
- Imposing cumbersome permitting requirements on P2 technologies
- Mandating best available control technologies rather than promoting the most feasible technologies optimized on a site-specific basis.

Establishing a relationship with local regulators that is built on goodwill and faith and demonstrating commitment to P2 may ease some of the regulatory burdens caused by conflicts between P2 philosophy and current regulations.

Lack of Available Funding Sources

An initial capital investment is required for certain P2 measures. While funds to procure P2 supplies and equipment may be available from several different sources, obtaining sufficient funding for proposed process modifications can prove challenging. Therefore, P2 efforts should be considered during all budgetary exercises, and innovative approaches should be used in combination with other environmental projects.

Insufficient P2 Training and Awareness Programs

Since many P2 procedures involve changes in operation or equipment, proper personnel training and awareness are essential. Individuals not only must understand the benefits of P2, they must be provided with incentives to implement changes and recommended improvements.

3.0 OVERVIEW OF WASTEWATER TREATMENT ENGINEERING PRACTICES

In order to effectively design and operate a wastewater treatment facility, it is essential to pre-define the facility’s treatment objectives and characterize its influent wastestream.

3.1 Treatment Objectives

The Clean Water Act (CWA) and its amendments have spurred the development of wastewater treatment technology. Generally, legislation has been enacted in response to increased public health concerns over the acute and chronic effects of chemicals in wastestreams. The EPA classifies streams that receive treated waste effluent as *effluent-limited* or *water-quality limited.*[6] The latter concerns streams that do not meet in-stream water quality standards. Discharge-water quality into such streams is typically more stringent than usual effluent standards. *Effluent-limited* reflects streams that meet in-stream water quality standards. Discharge into such streams is done under the National Pollution Discharge Elimination System (NPDES), which mandates a minimum treatment level of the wastestream. Table 1 provides an example of specific NPEDS water quality requirements for secondary treatment standards.

Table 1. Secondary Treatment Standards
(Adapted from Peavy, et al., 1985)

Parameter	Average Monthly Value	Average Weekly Value
Biochemical oxygen demand $(BOD)_5$ (milligrams/L)*	30	45
Suspended solids (milligrams/L)	30	45
pH	-	6.0-9.0

*5-day BOD

The first concern in the design and implementation of wastewater treatment and disposal is meeting legislative standards for effluent streams from treatment plants; the second concern is economic. Both minimum construction and operation and maintenance costs are typically sought. The onsite wastewater treatment facility is then designed based on the two concerns, coupled with waste loads and characteristics.

3.2 Waste Characterization

Characterizing the wastestream will dictate the dimensions and choice of treatment process that is required to meet the treatment objectives. Characterization includes determining the mean and range of wastewater flow, physical characteristics (temperature, particulate content, odor and color), chemical characteristics (organic and inorganic constituents), and biological properties (toxicity, biodegradability, and microbial populations). These characteristics will often depend on the source of the wastestream. An industrial wastestream may be warmer and enriched with metals and synthetic chemicals. Municipal waste flow rates exhibit significant diurnal and seasonal fluctuations. Agricultural runoff water is often enriched with nutrients (such as nitrogen and phosphorous) and herbicides. Food and beverage industry wastestreams tend to have a high concentration of biodegradable organics with some recalcitrant chemicals (lubricants, biocides, etc.).

Flow rates are used to calculate the chemical loading, which in turn is used to determine the size of the treatment facility. Flow rate fluctuations (hourly, daily, etc.) dictate the size of pumps, conduits, ponds, and tanks. In addition, projected increases in wastewater production over a 10- to 20-year period are considered when sizing the treatment system.

The particulate content in the wastestream affects the sludge production during the treatment process. The temperature directly impacts chemical and biological reaction rates. Color and odor, which are immediate public concerns, must be addressed during the treatment process also.

Organic and inorganic constituents determine the extent of biological activity. Organic compounds range from readily degradable carbohydrates, proteins, and oils to various pesticides and chemical solvents. These compounds are typically quantified by measuring the five-day biochemical oxygen demand (BOD_5) and the volatile suspended solids (VSS). The BOD_5 value reflects the quantity of oxygen needed to break down the organic matter, while VSS is a measure of the volatile organic material at 550 degrees Celsius. Both quantities must be considered for the design and operation of the treatment plant.

Inorganic constituents include quantities such as pH, alkalinity, nitrogen and other trace nutrients, and metals. These quantities must be closely managed in order to maintain biological activity (especially for anaerobic processes) during waste treatment.

Microorganisms that are present in wastewater include bacteria, protozoa, fungi, and viruses. Bacteria and fungi transform and break down the waste, whereas other microbes (i.e., protozoa and viruses) pose a human health hazard. Since a broad range of microbes exists in wastewater, a representative microorganism (e.g., *E. coli* or coliform) is selected to examine the efficacy of the waste treatment.

3.3 Treatment Processes

As previously stated, effluent water quality, waste characteristics, and flow-rate fluctuations must be considered when designing a wastewater treatment facility. Often, however, the actual design is governed by factors such as the local climate, energy and space availability, or proximity to residences. During process design the impact of these factors on the effectiveness of the treatment process must be examined. The following sections provide a brief overview of physical, chemical, and biological treatment processes and some factors that enter into their design.

3.3.1 Physical Treatment Processes

This treatment involves the removal or modification of waste from the wastestream by physical activity only—screens, bar racks, gravitational particle settling, flotation, and filtration through porous media. Flow equalization and storage of biogas produced by biological processes are also physical operations that may be needed for waste handling. Typically, industrial processes operate five days per week in 12 to 14 hour shifts, with down times during weekends and holidays. This schedule results in significant fluctuations in waste flow that are balanced using flow equalization schemes in cases where biological treatment is used.

Screens and Bar Racks

Usually the first stage of treatment, these remove large debris that can clog pipes and pumps. The process is designed to accommodate the peak hourly flow reaching the plant.

Grit Removal and Settling Tanks

During this stage, the wastestream is introduced into large tanks where the flow velocity is significantly decreased; this results in the grit and particulates settling due to gravity. These tanks are designed to maintain a slow flow velocity during peak hourly flow rates, thereby minimizing the potential for particulates remaining in the wastestream.

Flotation

Unlike settling tanks, this process utilizes buoyancy and particulate affinity to the air-water interface[8] to remove suspended material from the wastestream. Air bubbles injected into the bottom of a flotation tank cause waste material to accumulate at the surface where it is removed with a skimming mechanism.

Filtration through Porous Media

In this process, the wastestream passes though a bed of porous media (usually sand) to remove suspended particulates. The mechanisms involved in particle removal include straining, sedimentation, and sorption. The filtration efficiency depends on sand size, porosity, bed depth, flow velocity, and particulate characteristics.[9]

3.3.2 Chemical Treatment Processes

This group involves adding chemicals to the wastestream to change specific physical or chemical properties of the waste for eventual treatment. Examples include adding chemicals to change the surface properties of suspended particulates to enhance coagulation, sorption, or precipitation, and to deactivate pathogens.

Chemical Precipitation

A variety of chemical compounds can be added separately or in combination to modify the solution chemistry of the wastestream and cause the precipitation of suspended or dissolved waste components. When used in conjunction with gravity settling, chemical precipitation can result in the removal of 90 percent of suspended waste material. Chemicals that are commonly added include alum [$Al_2(SO_4)_3.nH_2O$], lime [CaO or $Ca(OH)_2$], and ferric salts [$FeCl_3$ or $Fe_2(SO_4)_3.nH_2O$], which are used to precipitate nutrients from the wastestream.

Adsorption

The most common application of this method relies on the principle that suspended and dissolved waste materials have a tendency to accumulate on highly sorptive surfaces. Specifically, if a wastestream is passed through a tank packed with granular activated carbon

(GAC), the suspended waste will be significantly reduced due to its sorption on the GAC surface. Alternatively, powder activated carbon (PAC) can be added and mixed with the wastestream to remove suspended material before it reaches the next treatment step.

Disinfection

In this application, one of the most common examples of chemically treating wastestreams, chemicals are added to specifically disrupt and/or destroy microorganisms present in the wastestream (e.g., viruses, bacteria, and protozoa). Though the efficacy of this process depends somewhat on chemical concentration and contact time with microbes, up to 99 percent of the bacteria can be removed from the wastestream. The most common disinfection chemical is chlorine; bromine chloride and ozone can also be used for this purpose.

Other applications of chemical addition include corrosion control for screens and bar racks, pH control for biological processes, and odor control. A more detailed discussion of chemical application processes can be found in Tchobanoglous and Burton (1991).

3.3.3 Biological Treatment Processes

These processes exploit the ability of microorganisms (predominantly bacteria) to break down and assimilate waste material. Typically, environmental conditions are optimized to obtain the maximum microbial activity and the subsequent removal of waste from the influent. Factors such as temperature, pH, oxygen, and trace nutrient concentrations can be manipulated to specifically suppress or promote the growth of specific organisms in order to obtain specific biological treatment goals. Oxygen presence (aerobic) or absence (anaerobic) during the biological process is one of the main classification criteria of microbial activity. Aerobic processes are typically fast and result in the production of carbon dioxide gas (CO_2), whereas anaerobic biological activity is slower and produces methane gas (CH_4) and CO_2. To determine how effectively the biological activity treated the waste, microbial activity parameters must be estimated for the predicted environmental conditions and waste loading. The performance of these processes is usually quantified by measuring the reduction in BOD_5, chemical oxygen demand (COD), or trace nutrients in the wastestream.

Biological process vessels may be open or closed to the atmosphere, and microbes can exist suspended in liquid (suspended growth) or attached to surfaces (attached growth).

Suspended Growth

With suspended growth systems, the wastestream enters a tank or lagoon where a large fraction of the active biomass is in suspension. The most common aerobic suspended growth process is the activated sludge system, which involves waste digestion using a well-mixed, intensely aerated tank. Effluent from this tank is passed through a settling basin to allow the suspended microbes to settle out of the treated water. Other aerobic suspended growth systems include sequencing batch reactors (SBRs) and aerated lagoons.

Anaerobic suspended growth systems include anaerobic digesters (with and without recycling) and upflow sludge blankets. Due to the slow growth rates of anaerobic bacteria, these systems require slightly longer waste-biomass contact times; however, they are an attractive option because they produce methane gas.

Attached Growth

Under aerobic conditions, this treatment process involves growing a mixture of facultative, aerobic, and anaerobic bacteria on natural or synthetic media. This range of bacterial populations arises due to oxygen depletion in zones with high carbon loading and microbial activity. The most common, the trickling filter system, consists of a large tank that is filled with coarse medium for microbial growth. The wastestream is introduced to the top of the tank and is allowed to trickle down by gravity only, where it is collected as treated water. The water must also pass through a settling tank to remove organisms that have been flushed from the growth media.

Anaerobic attached growth systems include upflow packed beds and fluidized and expanded-bed reactors. In packed beds, the growth media is stationary, resulting in low biomass loss. Recently developed fluidized bed reactors use a hybrid system that provides high mixing ratios and immobilizes bacteria. The efficient wastestream-to-biofilm contact, along with high biomass concentrations, contribute to higher achievable organic loading rates. Methane production from anaerobic processes makes these systems attractive in certain cases, particularly for the food and beverage industry.

Figure 1 shows a typical process design scheme for industrial and municipal wastestreams.

4.0 THE ANALYTICAL HIERARCHY PROCESS

The analytical hierarchy process is a systematic procedure for representing elements of any problem. It analyzes a situation by breaking it into smaller and smaller constituent parts, then performs a series of pairwise comparisons to evaluate the relative importance of each element in the hierarchy and derive priorities among criteria for alternative solutions. AHP uses the following problem-solving approach[11]:

1. Decide on the most important elements and measures of performance for the problem.
2. Identify possible alternative solutions that would best address, repair, replace, test, and evaluate the elements.
3. Investigate how to implement solutions and measure system performance.
4. Use an iterative approach to optimize available elements and achieve satisfaction with problem solution.

AHP success in achieving an appropriate solution to an environmental concern is dependent on the problem solver’s knowledge or and experience with the system of concern. A life-cycle

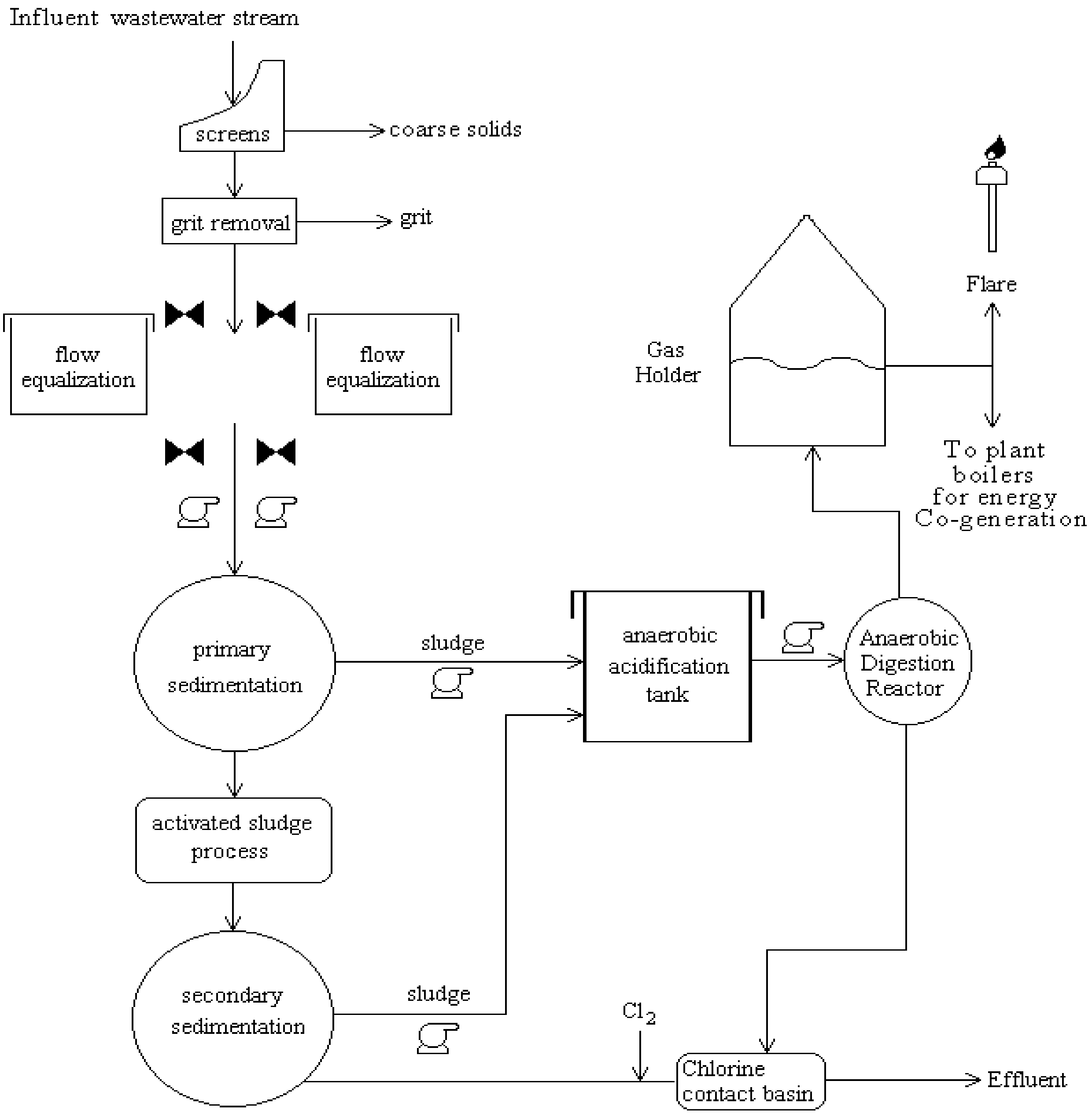

Figure 1. Typical Process Design Scheme for Industrial and Municipal Wastestreams

analysis would provide a wealth of related information and knowledge and facilitate this endeavor. Furthermore, it is critically important for management personnel involved in decision-making to participate in the problem depiction, design, and analysis process. Sufficient dialog and debate will ensure that the criteria and alternatives reflect the range of preferences and perceptions of the parties involved. It is crucial that the planners agree on the objective or focus of the hierarchy since this will shape all subsequent judgements[11].

The AHP methodology is built on basic human communication and logic dissemination skills, and is divided into three stages[11]:

- Problem identification and decomposition
- Alternative discrimination and comparative judgement
- Component and priority synthesis and solution formulation.

4.1 Problem Identification and Decomposition

The first step in applying the AHP methodology is to structure the problem in a hierarchic or network fashion during the identity and decomposition stage. Typically, the hierarchy is structured based on the objectives from a managerial viewpoint (Level 1—top), through criteria on which subsequent levels depend (Level 2—intermediate), to a list of potential alternative solutions (Level 3—bottom). This is known as a dominance-type hierarchic process, where the level of priority descends from the top.

Figure 2 illustrates an example of a hierarchic representation of a plant wastewater management problem. It is important for the problem analyst to attempt to achieve a complete hierarchic depiction of the problem—where every element of a given level functions as a criterion for all elements of the level below[12]. In cases where a complete depiction is not possible, the overall hierarchy may be divided into subhierarchies that share only a common top element and the appropriate set of priorities be used to evaluate each element.

This example will be used to illustrate the application of the AHP for a plant interested in optimizing wastewater management options. The first step is to decompose or structure the problem as a hierarchy. In this example, the top, or first level, is set as the overall satisfaction with plant wastewater management policy. It should be noted that this goal may well be part of the big picture—overall satisfaction with plant environmental management policy— which includes air emissions and solid waste generation. However, for the purposes of this discussion, the example is limited to wastewater management options. Assuming that plant management has identified five factors or criteria for measuring option performance. The important evaluation criteria are:

1. Ensuring environmental regulatory compliance
2. Minimizing wastewater management costs
3. Maintaining environmental health and worker safety
4. Meeting plant budgetary constraints
5. Addressing community environmental concerns and corporate public relations needs

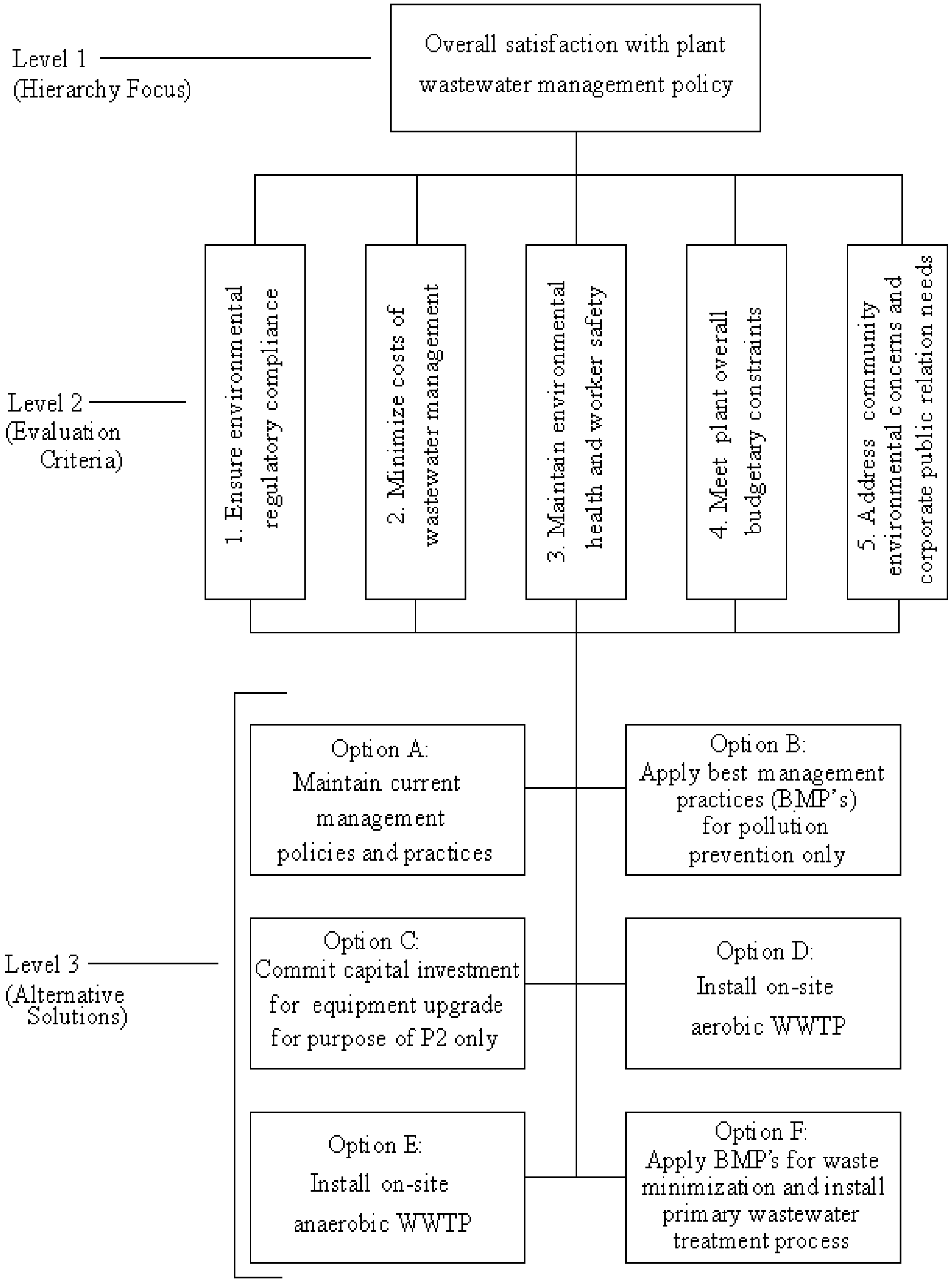

Figure 2. Example of a Hierarchic Depiction of a Plant Wastewater Management Problem

The third, or bottom, level contains five candidate options for handling plant wastewater that are to be evaluated in terms of the second level criteria. The elements of each level must be comparable in a pairwise fashion according to the elements in the level above. For example, one must be able to provide a consistent answer to questions such as: “With respect to regulatory compliance, what is the desirability of option A in Level 3 relative to options B, C, D, or E?” The objective at this stage is to establish the priorities of the bottom-level elements based on their relative impact on the focus of the hierarchy (level 1).

4.2 Alternative Discrimination and Comparative Judgment

Once a hierarchic representation of the problem has been completed, the system designer must establish priorities among the criteria and proceed with the evaluation process. This stage of the AHP is termed “pairwise comparisons.” The AHP methodology compares elements of a problem in pairs with respect to their relative impact, or importance to, a commonly shared property. AHP calls for a pairwise comparison of elements in the second level with respect to the overall objective or focus of the hierarchy (level 1). Similarly, alternatives in the third level must undergo pairwise comparisons with respect to the criteria in the second level.

The goal of this stage is to establish a set of matrices that reflect the system designers’ knowledge and judgment and their evaluation of each element in order to apply the AHPs linear algebra formulations. To achieve this, a numeric valuation of each criterion must be established. If a measurable numeric scale of comparison exists (e.g., cost, man-hours, required area, weight, etc.), it can be used to set-up the comparison matrices. Otherwise, the problem designers must use subjective—yet informed—judgements to define such valuations[12].

Saaty (1985) suggests a scale of relative importance (see Table 2) for immeasurable factors such as social, political or emotional factors.

Table 2. Suggested Scale of Relative Importance for Immeasurable Factors (Adapted from Saaty, 1985)

Definition	Intensity of Relative Importance	Comments
Equal importance	1	Two activities contribute equally to the objective
Moderate importance of one factor over another	3	Experience and judgment slightly favor one activity over another
Essential or strong importance	5	Experience and judgment strongly favor one activity over another
Demonstrated importance	7	An activity is strongly favored and its dominance is demonstrated in practice
Extreme importance	9	The evidence favoring one activity over another is of the highest possible order of affirmation

Definition	Intensity of Relative Importance	Comments
When compromise is needed	2, 4, 6, 8	Intermediate values between two adjacent judgements

At this point, the system designer is able to construct the pairwise comparison matrices for each level of the hierarchy. Initially, blank matrices are set up, with the evaluation criteria or options listed in the left column and the top row. In the matrix, one starts with an element in the left column and asks how much more important it is than the element on the top row. When an element is compared with itself, the scale value is one. When it is compared with another element from the top row and it is more important, the scale value is entered into the matrix in accordance with the definitions in Table 2. If the element is less important than the one in the top row, the scale value entered into the matrix is the reciprocal of the valued listed in the table.

For the example at hand, two sets of pairwise comparisons are conducted. The pairwise comparison matrix for levels 1 and 2 is presented in Table 3. (The values entered in the matrix are provided for illustrative purposes; actual values for specific applications will vary based on site-specific information.) It is important for the system designer to be consistent when assigning scale enumeration for elements.

Table 3. Wastewater Management Options:
Pairwise Comparison Matrix for Levels 1 and 2

Overall Satisfaction with Plant Wastewater Management Strategy	Regulatory Compliance	Cost of Wastewater Management	Environmental Health and Safety	Overall Plant Budgetary Constraints	Community Concerns and Public Relations Needs
Regulatory compliance	1	4	5	3	8
Cost of wastewater management	¼	1	2	1/2	3
Environmental health and safety	1/5	1/2	1	1/3	4
Plant budgetary constraints	1/3	2	3	1	6
Community concerns and public relations needs	1/8	1/3	1/4	1/6	1

Similarly, the pairwise comparison matrices for levels 2 and 3 are presented in Table 4. When several designers participate in the evaluation process, judgments are often debated and justifications using reason or data are required. Often, in cases of disagreement, geometric means are used for compromise purposes. The AHP methodology incorporates both measurable and intangible factors into the decision-making process. The interdependence of criteria—such as minimizing the costs of wastewater management and meeting plant budgetary constraints—must be considered carefully since there may be some perceived overlap. In this case, the cost of wastewater treatment was identified as a separate factor since it is one item of the overall plant budget, which includes other utility costs such as steam generation, electric, gas, and solid waste disposal, among others. Therefore, these criteria must be evaluated independently, with special care taken to avoid an overlap in accounting.

Table 4: Wastewater Management Options:
Pairwise Comparison Matrices for Levels 2 and 3

Regulatory Compliance	**A**	**B**	**C**	**D**	**E**	**F**
A	1	1/3	1/5	1/7	1/7	1/5
B	3	1	1/3	1/5	1/5	1/4
C	5	3	1	1/3	1/5	1
D	7	5	3	1	1/2	1
E	7	5	5	2	1	1
F	5	4	1	1	1	1

WW Management Costs	**A**	**B**	**C**	**D**	**E**	**F**
A	1	1	1/2	1/3	1/7	1/5
B	1	1	1/2	1/3	1/7	1/5
C	2	2	1	½	1/4	1/6
D	3	3	2	1	1/4	1/2
E	7	7	4	4	1	1/2
F	5	5	6	2	2	1

EHS	**A**	**B**	**C**	**D**	**E**	**F**
A	1	1/2	1/4	1/5	1/5	1/5
B	2	1	1/2	1/3	1/3	1/3
C	4	2	1	½	1/2	1/2
D	5	3	2	1	1	1
E	5	3	2	1	1	1
F	5	3	2	1	1	1

Overall Plant Budget	**A**	**B**	**C**	**D**	**E**	**F**
A	1	1/2	1/4	1/5	1/9	1/7
B	2	1	1/2	1/3	1/7	1/5
C	4	2	1	½	1/7	1/5
D	5	3	2	1	1/4	1/3
E	9	7	7	4	1	2
F	7	5	5	3	1/2	1

Community & Corporate PR Concerns	**A**	**B**	**C**	**D**	**E**	**F**
A	1	1/2	1/5	¼	1/4	1/5
B	2	1	1/3	½	1/2	1/3
C	5	3	1	2	2	1
D	4	2	1/2	1	1	1/2
E	4	2	1/2	1	1	1/2
F	5	3	1	2	2	1

4.3 Component and Priority Synthesis, and Solution Formulation

At this point, the principle of synthesis is used to formulate a solution. Priority synthesis is performed in two steps: local priority and global priorities.

4.3.1 Local Priority Synthesis

In synthesizing the local priorities vector, the pairwise comparison matrix from levels 1 and 2 (see Table 3) is manipulated as follows:

1. Start with the first row (n-entries), multiply, and then take the n^{th} root (fifth root in this example) of the product. Set this value as “a.”
2. Repeat step 1 for all rows in the matrix to obtain values b, c, d, and e.
3. Add the values of a through e to obtain the sum total.
4. Divide each value by the sum total to obtain the normalized local priorities vector for levels 1 and 2.

Table 5 contains the results for calculating the local priority vector for levels 1 and 2.

Table 5. Normalized Local Priority Vector for Levels 1 and 2

Overall Satisfaction with Plant Wastewater Management Strategy	**1. Regulatory Compliance**	**2. Minimize Wastewater Management Costs**	**3. Maintain EHS**	**4. Meet Overall Plant Budget**	**5. Community & Corporate Public Relations Concerns**
Normalized local priority vector for levels 1 and 2	0.493	0.135	0.096	0.236	0.040

The local priority vectors for the pairwise comparison matrices for levels 2 and 3 (see Table 4) are calculated in a similar fashion, and the results are shown in Table 6.

Table 6. Normalized Local Priority Vectors for Levels 2 and 3

	1. Regulatory Compliance	**2. Minimize Wastewater Management Costs**	**3. Maintain EHS**	**4. Meet Overall Plant Budget**	**5. Community & Corporate Public Relations Concerns**
A	0.032	0.050	0.044	0.030	0.046
B	0.058	0.050	0.080	0.051	0.086
C	0.126	0.080	0.139	0.077	0.277
D	0.243	0.139	0.245	0.129	0.157
E	0.334	0.328	0.245	0.432	0.157
F	0.207	0.353	0.245	0.280	0.277

4.3.2 Global Priorities Synthesis

Finally, global priority synthesis is used to formulate a solution. Priorities are synthesized from the second level down by multiplying the local priorities of their corresponding criteria in the level above and then adding the products. The second-level elements are each multiplied by unity—the weight of the hierarchy focus or the single top-level goal[1]. For example, the composite global priority of option A is obtained as follows:

$$(.493x.032) + (.135x.050) + (.096x.044) + (.236x.030) + (.040x.046) = 0.036$$

Table 7 shows the completed global priorities vector calculations.

Table 7. Normalized Global Priority Vector for a Wastewater Management Problem

	1 (0.493)	2 (0.135)	3 (0.096)	4 (0.236)	5 (0.040)	**Composite or global priorities**
A	0.032	0.050	0.044	0.030	0.046	**0.036**
B	0.058	0.050	0.080	0.051	0.086	**0.059**
C	0.126	0.080	0.139	0.077	0.277	**0.116**
D	0.243	0.139	0.245	0.129	0.157	**0.199**
E	0.334	0.328	0.245	0.432	0.157	**0.341**
F	0.207	0.353	0.245	0.280	0.277	**0.250**

The result of the analytical hierarchy process indicates that option E, install an onsite anaerobic wastewater treatment plant, would be the most beneficial choice of the options studied.

At this point, if the system designers are satisfied with the outcome, they can move to the implementation phase. If further discussions ensue or new data or options become available, the AHP hierarchy setup can be modified, and further iterations can be performed.

Evaluating the numerical consistency of AHP is beyond the scope of this paper. Interested readers may refer to Saaty, (1980 and 1985) for a discussion and further detail.

5.0 SUMMARY

Wastewater management is a serious issue faced every day by the food and beverage industry. Wastestreams from this industry typically contain high biochemical oxygen demand (BOD) concentrations and high treatment and disposal costs. Increased environmental regulation, public awareness, and overburdened municipal treatment plants have significantly escalated the costs of managing these wastestreams. As environmental technology advances in this field, increasingly more management options are becoming available to industry. Wastewater minimization is one option in an overall environmental management hierarchy that includes pollution prevention, recycling, treatment, and disposal or release.

This paper presented various wastewater minimization practices used by the food and beverage processing industry, as well as an overall approach to wastewater treatment engineering. In addition, elements of the analytical hierarchy process (AHP) were discussed for the purpose of determining the optimal wastewater management options for a specific application. AHP uses a series of pairwise comparisons with a valid scale to translate objective judgments into mathematical values for problem representation. Hierarchic levels are classified to maintain homogeneity based on evaluation criteria and available options. Finally, a mathematical model is employed to achieve priority and solution synthesis.

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