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Multi-Stage Wet Scrubbing for Industrial Odor and VOCs Abatement: Design Features and Full-Scale Case Studies

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Industrial emissions are technically demanding because of their chemical complexity, containing components that may differ by several orders of magnitude in water solubility, reactivity and odor threshold. This paper describes the engineering role of wet scrubbing in odor and Volatile Organic Compounds (VOCs) abatement, with specific emphasis on multi-stage wet scrubbers developed and applied by Tecnoimpianti Water Treatment S.r.l. (TWT). Wet scrubbing is discussed as a gas-liquid mass-transfer and chemical-conversion process in which each stage can be designed for specific pollutant families through pH control, oxidation, packing selection, recirculation strategy, demisting and automation. Three field case studies are then presented. These cases show that multi-stage wet scrubbing is a robust and flexible best-available-technique-compatible option for soluble and reactive odorants, particularly when embedded in an integrated treatment train for hydrophobic VOCs and variable industrial matrices.
Keywords: odor emissions; VOCs; wet scrubber; packed tower; multi-stage deodorization; industrial air treatment

1. Introduction

Odor emissions from industrial activities are a distinctive form of air-pollution because they are perceived through a sensory response rather than only through the mass concentration of a single compound. Wastewater treatment plants, waste-treatment facilities, rendering plants, chemical and pharmaceutical processes, plastic processing, foundries, livestock activities and other industrial installations may release complex mixtures that become relevant even at very low concentrations. Odor pollution is now widely recognized as an environmental issue that requires dedicated measurement methods and cannot be adequately managed through conventional chemical monitoring alone (Conti et al., 2020). The engineering problem is therefore to convert a subjective perception into reproducible parameters that can support design, performance verification, impact assessment and communication with regulators and communities. Dynamic olfactometry, chemical analysis, instrumental odor monitoring systems, field inspection and dispersion modeling each provide different information. None is sufficient in isolation for all purposes: olfactometry quantifies the sensory response of a gas sample, chemical analysis identifies compounds and process causes and dispersion modeling links source emissions to receptor exposure (Bax et al., 2020). The importance of source characterization is especially evident for area sources and wastewater-related emissions. The characteristics of the source influence not only the selection and design of the abatement systems but also the choice of the most appropriate sampling techniques required to maximize the accuracy and reliability of the measurement results (Capelli et al., 2013).
In the current industrial landscape, there is occasionally a lack of awareness regarding the selection of the most appropriate abatement technologies, based on the specific composition of the pollutants to be eliminated. Furthermore, the costs of the various alternatives often lead to the selection of the most economical option without an adequate assessment of the efficiency that could reasonably be expected. The research community, therefore, faces the need to develop a greater understanding of the underlying phenomena of established technologies, aimed at their optimal selection and potential operational optimization, and to share this knowledge with the industrial community. The aim of this paper is to share some best practices by presenting

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three successful industrial case studies of combination of multi-stage wet scrubbers with other abatement techniques.

2. Wet scrubbers for odor and VOC control

Wet scrubbing is one of the main technologies available for odor and soluble gas control. European BAT documents for wastewater and waste-gas management recognize wet abatement, adsorption, biological treatment and thermal oxidation as techniques that may be used individually or in combination according to pollutant properties and process context (Brinkmann et al., 2016). The practical question is therefore not whether a scrubber is universally effective, but when and how a scrubber should be engineered to address a specific odor matrix. TWT field experience indicates that high odor removal can be achieved when wet scrubbing is designed as a staged, chemically controlled and monitored process rather than as a simple humidification or air-washing unit.

2.1 Process principles and domain of applicability

Wet scrubbing purifies a gas stream by transferring one or more pollutants from the gas phase to a liquid phase. Only substances that are sufficiently soluble in the selected washing liquid or that react fast enough after entering the liquid phase can be efficiently removed by wet scrubbing. Hydrophobic and poorly reactive VOCs may pass through a scrubber with limited removal if an aqueous solution is used (like in most cases) and may require adsorption on activated carbon, biological treatment, condensation, thermal oxidation or other complementary technologies. For this reason, for the purpose of odor abatement, it is important to consider what compounds generate the odor, their solubility, reactivity and odor thresholds.

The non-linearity between chemical concentration and odor concentration is central. Odorants can have extremely different detection thresholds. A low mass concentration of an extremely odorous sulfur compound can dominate the perceived odor, whereas a much higher concentration of a less odorous solvent may have a smaller sensory impact. Consequently, design and performance assessment must combine chemical and olfactometric information (Bax et al., 2020).

2.2 Scrubber configurations and design variables

Wet scrubbers for gas treatment include spray towers, tray scrubbers, floating-bed scrubbers, and packed-bed scrubbers. Packed-bed towers are widely used for gas absorption because the packing distributes the liquid over a large, wetted surface area and promotes gas-liquid contact (US EPA, 2025). TWT's odor-control applications mainly use vertical countercurrent towers or, where height restrictions require it, horizontal crossflow arrangements. In general, vertical countercurrent packed towers provide higher mass-transfer efficiency for a given footprint because the cleanest liquid contacts the cleanest gas near the outlet, preserving the concentration driving force.

The design of a wet scrubber is multi-variable optimization (Table 2). Gas velocity affects pressure drop, flooding margin, droplet entrainment and contact time. Packing type affects interfacial area, fouling tendency, hydraulic capacity and maintenance. Liquid recirculation rate and make-up/blowdown strategy control mass transfer and salt or by-product accumulation. Reagent selection and control logic determine whether target compounds are neutralized, oxidized or simply transferred to the liquid. Nozzles type, number and position influence liquid distribution, while demisters prevent carryover of droplets that could damage downstream equipment, corrode ducts or saturate activated carbon. The control instrumentation is finally an essential element for the proper management of the process (Cassinari et al., 2024).

The gas-to-liquid transfer problem is complicated by field constraints. A correct design must account for inlet concentrations, expected outlet limits, temperature, humidity, emission variability, process intermittency, ATEX classification, available water quality, wastewater management, acoustic zoning, sampling ports, construction access, working-at-height requirements, seismic classification and interference with plant operations.

2.3 Why multi-stage wet scrubbing improves odor control

Single-stage wet scrubbing can be adequate for simple streams dominated by one soluble or highly reactive compound. However, odorous emissions from industrial and municipal facilities like wastewater sludge handling, hospital-waste treatment and thermoplastic processing are generally different. They may contain reduced sulfur compounds, ammonia and amines, organic acids, aldehydes, ketones, chlorinated or aromatic VOCs, humid vapors, particulate matter and process-specific intermediates. One recirculating liquid chemistry cannot be optimized for all these families simultaneously.

A multi-stage scrubber divides the gas-treatment process into sequential functional zones. A first stage may remove particulate matter, condensable material or a high fraction of soluble load while protecting downstream packing. A dedicated acid stage can target alkaline compounds such as ammonia and amines. A basic or oxidative stage can target acidic or reduced sulfur compounds such as hydrogen sulfide and mercaptans. A neutral water wash or final polishing stage can remove residual reagents and reduce carryover. Independent recirculation loops allow each stage to operate at its own pH, oxidation-reduction potential, blowdown rate, and reagent strategy.

This architecture has three practical advantages. First, it increases robustness under variable inlet composition because stage-specific settings can be adjusted without redesigning the entire plant. Second, it improves efficiency per unit footprint by maintaining favorable mass-transfer and reaction conditions along the tower sequence. Third, it reduces operational risk: fouling, reagent depletion or an excursion in one stage can be detected and corrected before downstream units are compromised. When hydrophobic VOCs or poorly soluble odorants are present, multi-stage scrubbing can be combined with activated carbon or other polishing systems. The combined line should be designed as an integrated treatment train, because a wet stage can also condition the gas for downstream adsorption by removing moisture-soluble or corrosive components, while excessive droplet carryover would have the opposite effect.

A flow diagram of a multi-stage wet scrubber can be seen in Figure 1.

Table 2: Principal engineering variables in multi-stage wet-scrubber design

Variable group	Examples	Effect on performance and operability
Gas-side parameters	Flow rate, temperature, humidity, velocity, pressure drop, emission variability	They define residence time, hydraulic loading, mass-transfer driving force, fan selection and operating envelope.
Liquid-side parameters	Recirculation rate, make-up/blowdown, pH, ORP, conductivity, reagent dosing	They control absorption capacity, reaction kinetics, reagent consumption, by-product accumulation and wastewater load.
Mass-transfer internals	Packing type, packing height, nozzles, liquid distribution, demister	They determine contact area, droplet carryover, fouling risk and maintenance frequency.
Staging architecture	Number of stages, independent sumps, stage order, polishing stage	They allow different chemistries for different compounds and prevent counterproductive reagent mixing.
Control and monitoring	SCADA, pH/ORP probes, differential pressure, flow meters, alarms, remote monitoring	They maintain performance under variable loads and support preventive maintenance.

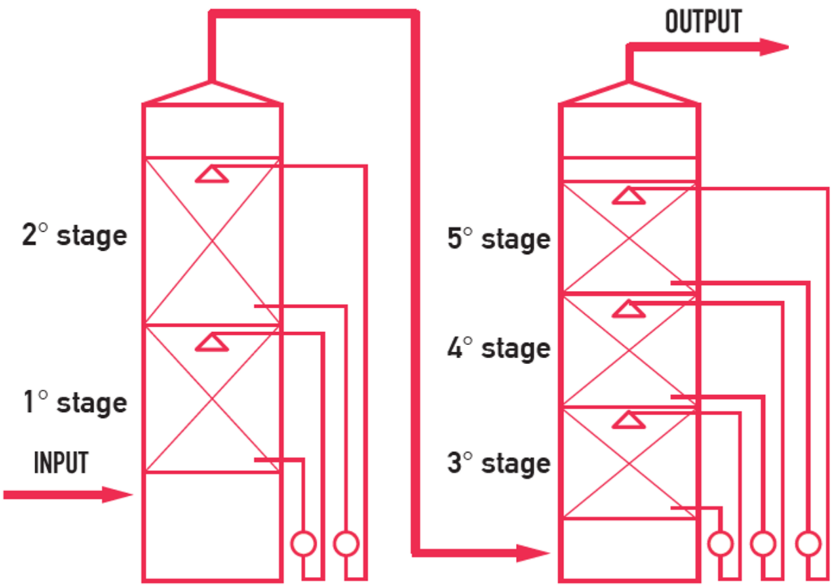

Figure 1: Flow diagram of a multi-stage wet scrubber

3. Case studies from TWT field experience

The following case studies are field applications by TWT. They cover three different matrices (Table 3):

- municipal and industrial wastewater treatment,
- hospital-waste thermal treatment and refuse-derived-fuel/SSF production,
- thermoplastic-compound production.

Table 3: Overview of the three field case studies

Sector and source	Main issue	TWT treatment concept
Municipal and industrial wastewater treatment; sludge oxidation, primary and digested sludge tanks, thickening, thermal sludge treatment	High odor load; earlier horizontal scrubber ineffective; need odor and chemical control near urban receptors	Five washing/deodorization stages in two vertical wet towers, with activated-carbon polishing for residual substances
Hospital-waste physical/thermal treatment and SSF production	Light solids, fibers, microplastics, paper/cardboard fluff and water condensation caused severe fouling and frequent cleaning	Ad hoc solid-particle pretreatment followed by five-stage wet treatment; downstream activated carbon retained as safety/polishing unit
Thermoplastic-compound production	VOCs, light particles, intense odor, humid vapors, partial water insolubility, residential proximity, and acoustic constraints	Modular activated-carbon filter followed by five-stage wet scrubbing with acid, basic and oxidative dosing flexibility; silencers and stack relocation

3.1 Wastewater treatment plant

The first case study regards one of the largest wastewater-treatment facilities in Lombardy, located north of Milan (Italy). The site treats wastewater from 26 municipalities and hundreds of production facilities, has a nominal capacity of 600,000 population equivalent and operates continuously. The odor-control problem was associated with sludge and thermal-treatment areas, including sludge oxidation tanks, primary-sludge collection tanks, anaerobically stabilized digested-sludge collection tanks, mechanically thickened sludge tanks, post-combustion sludge heat-treatment units and hydrolyzed-sludge tanks. An earlier horizontal scrubber was reported to be ineffective for the odor load. TWT replaced it with an Advanced Multistage Deodorization System (AMDS) consisting of five washing and deodorization stages in two vertical wet towers operating in series. The solution was designed to fit within the footprint of the demolished horizontal scrubber. The first tower contains two chemical washing stages, while the second tower contains three stages, including a final neutral water wash. Each stage uses random packings to promote contact between the upward gas stream and the recirculating liquid and each tower includes droplet separation at the outlet. The treated gas can be sent to an activated-carbon filter for final polishing. The reported performance demonstrates the importance of integrated treatment (Table 4). Scrubbing alone reduced the main soluble and reactive compounds substantially, but residual odor and VOCs required activated carbon because part of the matrix was not sufficiently water-soluble or reactive in the washing solutions. Downstream activated carbon polishing, all reported emission limits were met in the case-study dossier, with odor below 300 ou_E/m^3 and non-methane VOCs around 3 mg/Nm^3.

Table 4: Reported performance for scrubber and activated-carbon polishing

Parameter	Inlet	Oulet scrubber	Outlet activated carbon
Odor concentration	4,200 ou_E/m^3	650 ou_E/m^3	250 ou_E/m^3
Hydrogen sulfide	10 ppm	<0.5 ppm	<0.5 ppm
Mercaptans	<10 ppm	<0.5 ppm	<0.5 ppm
Non-methane VOCs	<100 ppm	<30 ppm	<3 ppm
Ammonia	20 ppm	<0.5 ppm	<0.5 ppm

3.2 Hospital-waste thermal-treatment and SSF-production plant

At a company located in the province of Foggia (Italy) that treats hospital waste by physical and thermal processes, the pre-existing configuration used two scrubbers operating in parallel, each originally treating approximately 8,000 m^3/h. The critical issue was not only odor and dust compliance but also fouling. The extracted air contained very light solid particles, including fluff, non-woven fabric, glove fragments, volatile microplastics and paper/cardboard fibers. In the presence of condensed water vapor, these materials rapidly fouled the two scrubbers, requiring internal cleaning every two to three weeks. TWT's design study included chemical characterization of the air stream, fluid-dynamic analysis of the suction systems, and evaluation of alternative technologies. The final concept connected the two inlet lines, used dampers to partition inflow, introduced ad hoc pretreatment for removal and segregation of solid particles and sent the pretreated stream to a five-stage wet system.

The stages wash the air sequentially with progressively cleaner aqueous solution, while allowing independent management of treatment conditions according to the compounds present. The existing activated-carbon plant downstream was retained primarily as a safety function, especially during maintenance of the wet-treatment system. The field objective was therefore dual: increase abatement efficiency and increase the maintenance interval. Post-installation chemical and olfactometric analyses reported significant efficiency and the average yield as approximately 90% (Table 5). The analytical campaign of October 10th, 2023 illustrates the order of magnitude of removal: Total Organic Carbon measured by FID (UNI EN 12619:2013) decreased from 180 mg/Nm^3 upstream to 18 mg/Nm^3 downstream, particulate matter decreased from 9.5 to 1.3 mg/Nm^3 and ammonia decreased from 1.2 to below 0.5 mg/Nm^3. These data support the design choice of combining particulate pretreatment with staged wet scrubbing rather than relying on a conventional single wet device.

Table 5: Analytical campaign results, October 10th, 2023.

Parameter	Inlet (mg/Nm^3)	Outlet (mg/Nm^3)	Reduction
Total Organic Carbon	180	18.0	90%
Total particulate matter	9.5	1.3	86%
Ammonia	1.2	< 0.5	> 58%
Ethanol	356	31	91%
Isopropyl alcohol	39	3.4	91%
Acetaldehyde	14	1.8	87%

3.3 Thermoplastic-compound production plant

At a company located in the province of Milan (Italy) that produces colored and natural thermoplastic compounds in granule form, the original odor-control system consisted of two scrubbers in series treating approximately 40,000 m^3/h. The plant is close to residential receptors, so odor reduction had to be considered together with noise control and operating continuity. The extracted air contained VOCs, light solid particles, high odor concentration and humid vapors. Because the mixture was variable and partly insoluble in water, the pre-existing system could not reliably meet the desired odor and chemical performance.

TWT's revamping began with upstream/downstream chemical and odor analysis and a noise assessment. The existing system was dismantled and replaced by a modular activated-carbon filter followed by a five-stage wet scrubber. The activated-carbon filter was responsible for reducing VOCs and was subdivided into four sections so that one module could be maintained while the system remained in operation. The downstream wet scrubber then provided five sequential washes, with the possibility of acid, basic and oxidative dosing in four of the five stages depending on the compounds present. Ancillary measures included moving the stack after modeling and applying silencers to the pumps, fan, stack and other emission points. Available olfactometric data show the improvement in the wet-scrubbing section (Table 6).

In August 2023, with the previous scrubber, odor decreased from 2,400 to 1,800 ou_E/m^3, corresponding to about 25% reduction. In October 2024, the new scrubber showed about 70% odor reduction. Because the activated carbon is located upstream, the VOC concentrations measured at the scrubber inlet in 2024 were already relatively low; the wet stages therefore functioned primarily as odor and residual-soluble-pollutant control downstream VOC adsorption.

Table 6: Odor monitoring before and after the new treatment configuration

Campaign and configuration	Scrubber inlet odor (ou_E/m^3)	Scrubber outlet odor (ou_E/m^3)	Reduction
August 2023, previous scrubber	2,400	1,800	25%
October 2024, new system - wet scrubber section	2,300	650	72%

4. Conclusions

Industrial odor abatement requires compound-specific engineering because of the complexity of the matrix and total VOC concentration alone is insufficient for predicting sensory impact or scrubber efficiency. Wet scrubbing is an effective abatement process when target odorants are soluble or chemically reactive in the washing liquid, yet it may need to be combined with other techniques to improve the overall efficiency. In this context, multi-stage wet scrubbing improves the process compared to single-stage wet scrubbing, by assigning different chemical and hydraulic functions to different stages, maintaining cleaner downstream washing solutions and enabling stage-by-stage control. This paper presents field data from three full-scale case studies where multi-stage wet scrubbers are combined with pre-treatments or post-treatments. First, in a wastewater treatment plant, a five-stage wet system followed by activated carbon can reduce a high wastewater-treatment odor load to below 300 ou_E/m^3 and achieve strong removal of H_2S, mercaptans, ammonia and VOCs. Then, in a hospital-waste thermal-treatment plant, a five-stage wet treatment system with solid-particle pretreatment can reduce both pollutant concentrations and maintenance burden, with approximately 90% average abatement. Finally, in a thermoplastic-compound production plant, integration of activated carbon and multi-stage wet scrubbing is more appropriate than wet scrubbing alone. The new scrubber section achieved about 70% odor reduction and improved substantially over the previous scrubber. The strongest design conclusion is that odor-control systems should be conceived as integrated and maintainable treatment trains. A multi-stage wet scrubber is an excellent core technology for many odor and soluble-VOC applications, but it must be tailored to the pollutant matrix, local regulatory limits, site constraints, and the long-term maintenance strategy.

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