Innovative: International Multi-disciplinary Journal of Applied Technology
(ISSN 2995-486X) VOLUME 3 ISSUE 5, 2025

# TECHNOLOGICAL PROBLEMS OF HYDROGEN PEROXIDE PRODUCTION BY THE ANTHRAQUINONE PROCESS: A SYSTEMATIC REVIEW, CAUSAL ANALYSIS AND A DATA-COLLECTION PROTOCOL

**Turdiyev Javlon Suvonovich, Temirov Uktam Shavkatovich**
*Navoi State University of Mining and Technologies, Navoi, Uzbekistan*

**Abstract:**

Almost all hydrogen peroxide manufactured worldwide comes from the anthraquinone (AO) process, yet the technological problems of that process are studied as separate, largely disconnected topics. This review classifies those problems along the process chain and maps the causal links between them, using a corpus of 46 sources whose digital object identifiers were individually verified against the Crossref and OpenAlex registries. The problems of the hydrogenation, oxidation, extraction and distillation stages prove not to be independent: they converge at system level on four outcome indicators reagent and adsorbent consumption, explosion and fire hazard, energy intensity, and wastes and emissions. Eight causal links documented in the reviewed literature are distinguished from three that remain hypotheses and require measurement: the effect of residual hydrogen peroxide returned from extraction on catalyst activity, the effect of water accumulating in the working solution on carrier degradation, and the feedback of degradation products on the attainable hydrogenation degree. Together these three close a self-reinforcing loop which, if confirmed, would explain a slow but progressive deterioration of plant performance. Six topics yielded no source meeting the inclusion criteria: solvent losses and volatile organic compound emissions from the solvent-recovery vent; water and residual hydrogen peroxide treated as independent variables; leaching of palladium into the working solution; inert accumulation and purge policy in the hydrogen loop; aqueous effluent streams of an AO plant; and membrane reactors for hydrogenation. To make the hypotheses and gaps testable, a fifteen-item data-collection protocol is proposed that specifies for each item the measured quantity, analytical method, unit, target precision, sampling point, frequency and the specific link it tests, allowing the review to be connected directly to laboratory or plant data obtained later.

**Keywords:** hydrogen peroxide, anthraquinone process, catalyst deactivation, carrier degradation, working solution, off-gas safety, resource intensity, systematic review, data-collection protocol

## Introduction

Hydrogen peroxide is an oxidant used across the pulp and paper, textile, chemical, mining and water-treatment industries, and its decomposition leaves only water and oxygen; the technology of its manufacture and its properties are set out in the encyclopaedic literature [1]. Industrial production rests almost entirely on a single technology, the anthraquinone process, whose position relative to possible successors has been examined in a dedicated outlook [2], while the role of hydrogen peroxide in sustainable chemistry has been argued separately [3]. Theofanidis et al. compared the candidate alternatives direct $H_2$ + $O_2$ synthesis, electrochemical, bioelectrochemical and plasma routes against energetic, techno-economic, life-cycle and safety criteria and concluded that there are at present no real challengers to the AO process at industrial scale, that the alternatives are better suited to on-demand, local production, and that the climate impact of the AO process is significant because hydrogen is usually obtained by steam reforming of methane [4]. Any improvement in industrial hydrogen peroxide manufacture must therefore be sought inside the AO process rather than around it.

In this process hydrogen and oxygen never meet directly: they are combined through an alkylanthraquinone carrier in two consecutive and chemically independent steps. The carrier is hydrogenated over a palladium catalyst to the corresponding hydroquinone, then oxidised by atmospheric oxygen back to the original quinone, and it is at this second step that hydrogen peroxide is formed; the product is separated by extraction with water while the working solution (WS) returns to the loop.

The safety advantage of this arrangement is evident hydrogen and oxygen are never mixed in one vessel. The same arrangement, however, is the source of every technological problem the process has. The carrier and the solvents form a material inventory that circulates inside the plant, ages gradually and must eventually be replaced; the catalyst loses activity and has to be regenerated; air, as the oxygen source, is a stream of small useful effect but large mass; and concentrating the product requires vacuum operation on a thermally labile substance.

Each of these problems has been studied individually, and in considerable depth. Hydrogenation kinetics, deactivation mechanisms, support effects and over-hydrogenation of the aromatic ring have been investigated consistently. Slurry, trickle-bed, monolith and microchannel solutions have been compared for reactor design and intensification. Carrier degradation, working-solution ageing, regeneration of degradation products and solvent composition have become a research direction of their own. The kinetics and molecular mechanism of the oxidation step have been examined. Process-safety questions systemic risk, explosion characteristics of peroxide–working-solution mixtures, the influence of impurities on runaway decomposition, limiting oxygen concentration (LOC) and thermal runaway in activated-carbon beds have been treated in a growing body of work. Resource intensity, palladium recovery and the environmental burden are being assessed through life-cycle analysis and through comparison with direct and electrochemical synthesis. Each of these bodies of work is cited individually in Section 3, where the corpus is set out problem by problem.

These investigations, however, are conducted in isolation from one another. In catalytic studies the water content of the working solution often remains an uncontrolled factor; safety studies do not consider how changes in the hydrogenation section affect off-gas composition; and in environmental assessments the internal loss mechanisms disappear into aggregated indicators. The question that matters most in practice what a change in one stage changes in another is therefore left open.

This review has three aims. The first is to classify the technological problems of the anthraquinone process systematically along the process chain. The second is to separate the causal links between them and to state openly how well each link is supported by the literature. The third is to propose a concrete data-collection protocol for testing the gaps and hypotheses identified, so that the review can be connected directly to measurement data obtained later.

The work draws on no internal documents or design data of any industrial facility; every statement rests on openly published, DOI-verified sources.

## Materials and Methods

Search strategy and inclusion criteria. The search was conducted with English-language keywords: anthraquinone process, hydrogen peroxide production, 2-ethylanthraquinone hydrogenation, palladium catalyst deactivation, working solution degradation, limiting oxygen concentration, carbon bed thermal runaway, hydrogen peroxide life cycle assessment, and their combinations. Inclusion criteria were: (a) a peer-reviewed journal article or an authoritative encyclopaedic entry; (b) possession of a DOI; (s) direct relevance to a problem of the anthraquinone process. Conference abstracts, patents, manufacturers' technical materials and non-peer-reviewed reports were excluded. Patents are the primary source on some topics, such as the regeneration of degradation products, but they cannot be placed on the same footing as peer-reviewed work; they therefore remain outside the corpus, and this exclusion is recorded as a limitation. The final corpus comprises 46 sources, published between 1983 and 2025, with a median year of 2013; 48 % appeared in 2015 or later. By problem area the corpus divides as follows: catalyst and selectivity 13 sources (28 %), process safety 10 (22 %), resource intensity and environment 6 (13 %), general and encyclopaedic 5 (11 %), reactor design and intensification 5 (11 %), carrier degradation 4 (9 %) and the oxidation step 3 (7 %).

Verification of sources. The DOI of every source was checked through the Crossref and OpenAlex registries, and the bibliographic description (authors, title, journal, volume, pages, year) was compared against the record returned. Sources whose DOI did not resolve, or whose description did not match the record, were not included.

Strength of claims. A common weakness of reviews is that a specific result is attributed to a source on the strength of its title alone. To avoid this, three levels of claim are distinguished throughout this review. At the first level the full text or the abstract of the source was read and a specific result is cited; nine of the 46 sources are used in this way, and every numerical value quoted in the text comes from one of them. At the second level the bibliographic existence of the source is verified but its content was not read in full; such a source 37 of the 46 is cited for the subject of the study only, and no numerical result is attributed to it. At the third level the statement is a hypothesis advanced within this review; it rests on no source, is named as a hypothesis where it appears, and must be tested by measurement. The same distinction governs the causal map presented below: documented links are drawn as solid lines, hypothesised links as dashed lines. Each source is cited exactly once, at the point at which its content is used; citation numbers are never repeated and never grouped into ranges, so the reference list follows the order in which the problems are discussed, and any later mention of a source is made by naming its subject or the section in which it was cited.

## Results

### 1. Classification of problems along the process chain

The overall map of the problems along the process chain is given in Figure 1.

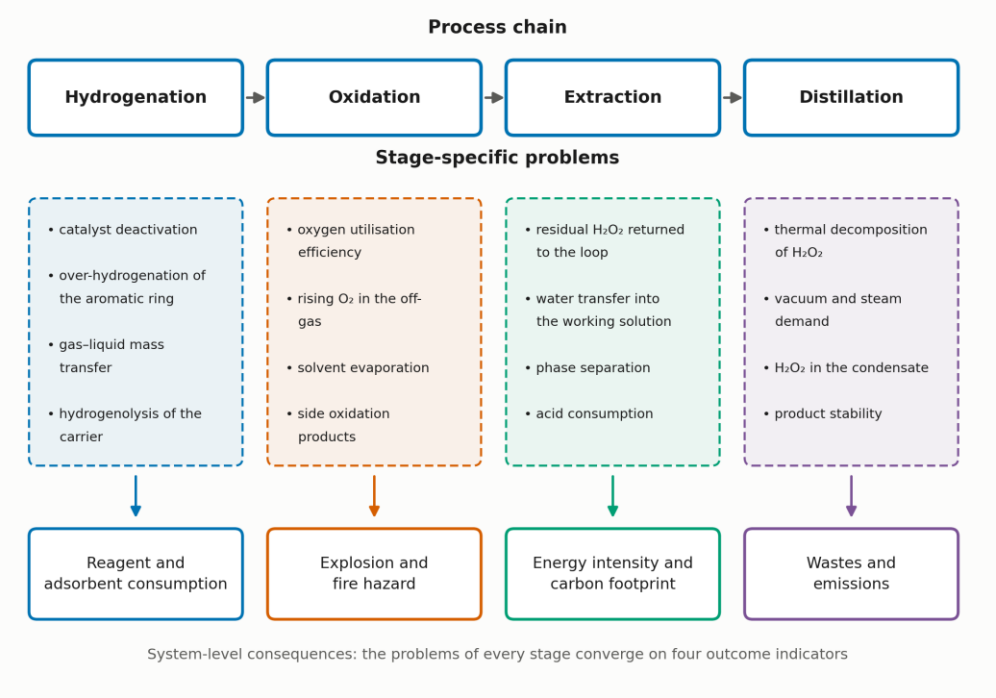



**Figure 1.** Stage-specific problems of the anthraquinone process and their system-level consequences.

Hydrogenation: catalyst and selectivity. The hydrogenation section governs the productivity of the whole loop, because the amount of hydrogen peroxide formed in one cycle is limited by the hydrogenation degree attained at this step.

Loss of palladium catalyst activity is the oldest and best-documented problem of the process. Santacesaria et al. modelled kinetics, mass transfer and catalyst deactivation together for the hydrogenation step [5]. Wang et al. studied the deactivation and regeneration of a $Pd/Al_2O_3$ catalyst and showed that the loss of activity arises mainly from coverage of the palladium surface by deposits, sintering not being the principal cause; among the regeneration methods examined, treatment with hydrogen peroxide solution and with boiling water proved effective [6]. Poisoning and deactivation mechanisms of palladium catalysts in general were systematised by Albers et al. [7].

The selectivity question was first posed systematically by Berglin and Schöön [8]. Although the carrier quinone should be hydrogenated at its carbonyl groups, hydrogenation of the aromatic ring also occurs on palladium; Santacesaria et al. studied this reaction specifically [9], and Drelinkiewicz described "deep hydrogenation" in the liquid phase over a $Pd/SiO_2$ catalyst [10]. The molecular-level mechanism has been analysed by density functional theory [11].

Ring hydrogenation is not uniformly harmful. It yields 2-ethyl-5,6,7,8-tetrahydroanthraquinone (THEAQ), which acts as an active carrier in the loop. As Kosydar et al. showed, two routes diverge on the palladium surface: ring hydrogenation leads to the active tetrahydro derivative, whereas hydrogenolysis produces irreversible degradation products; the same work also identifies the chemical source of degradation precisely, namely that degradation is initiated by the reduced forms of the carrier the hydroquinone and its tautomer 2-ethyloxanthrone [12]. The problem is therefore not ring hydrogenation itself but control of the ratio between these two routes.

The catalyst support influences that ratio strongly. Drelinkiewicz et al. modified an alumina-supported Pd catalyst with $Na_2SiO_3$ and found that the modification did not change the rate of the main reaction but appreciably altered the side reactions leading to the tetrahydro derivative and to degradation products [13]. Palladium dispersion has also been studied as an independent factor [14]. More recently the surface hydrophobicity of the support has been treated as a control parameter: Zhang et al. showed that the hydrophobicity of Pd/SBA-15 can be tuned by varying the residual carbon content, with the best performance at an optimum content [15]; work on hydrophobic functionalisation [16], structured NiO/Al supports [17] and in situ synthesised palladium [18] follows

the same direction.

Because hydrogenation is a three-phase gas–liquid–solid process, its rate is often limited by gas–liquid mass transfer rather than by chemical kinetics. This limitation is being addressed through trickle-bed [19], monolith [20], microreactor [21] and gas–liquid microdispersion [22] solutions. Reviewing slurry reactor technology, Li et al. noted that the fluidized-bed arrangement gives lower catalyst consumption, less anthraquinone degradation and higher catalyst utilisation efficiency than the fixed bed [23]. General progress with heterogeneous catalysts is summarised by Ingle et al., who conclude that supported metal catalysts offer better activity and selectivity with reduced degradation [24].

Carrier degradation and ageing of the working solution. The working solution is the largest and most expensive material inventory inside the plant, and its ageing is the long-term factor that governs the economics of the process.

Drelinkiewicz and Waksmundzka-Góra identified anthrone and anthracene derivatives together with their saturated isomers as degradation products and showed that palladium supported on alumina is appreciably more active in degradation than palladium on silica or on carbon [25]. This is a result of direct practical consequence: the choice of support determines not only activity but also the service life of the working solution.

Part of the degradation products can be converted back to the active quinone. Industrially this task is performed by a bed of activated alumina; Guo et al. proposed in situ synthesised solid base catalysts for the same purpose [26]. The solvent composition of the working solution is a separate direction. Bai et al. proposed N,N,N,N-tetrapropylmalonamide as the polar component and showed that it increases the solubility of quinones and hydroquinones, the gas hold-up and the volumetric mass-transfer coefficient, and raises the hydrogen peroxide yield per cycle relative to conventional solvents [27]. Solvent choice therefore acts on hydrogenation kinetics indirectly but strongly.

Oxidation and the gas phase. The kinetics of the oxidation step were studied by Santacesaria et al. [28], and its molecular mechanism analysed by Nishimi et al. [29] and by Korth and Mulder [30].

From a process standpoint, the principal problem of the oxidiser is the relationship between oxygen utilisation and off-gas composition. Because oxidation is carried out with air, unreacted oxygen leaves the system together with inert nitrogen. If oxygen utilisation falls, the oxygen fraction in the off-gas rises. Since this gas is saturated with aromatic solvent vapour and passes through the activated-carbon beds of the solvent-recovery unit, a rising oxygen fraction increases the fire hazard directly. The second problem is solvent evaporation and the associated loss: the gas leaving the oxidiser has been in prolonged direct contact with the working solution, so its solvent vapour content approaches the equilibrium value, and recovering it requires a dedicated unit. No peer-reviewed source on solvent losses and volatile organic compound emissions from the vent of an AO plant was found within this review.

Extraction and concentration. In extraction, hydrogen peroxide is transferred from the working solution into water. Equilibrium constraints mean that extraction is never complete: part of the product remains in the working solution and returns with it to the hydrogenation reactor. This is the origin of the central hypothesis of this review: the returned hydrogen peroxide may decompose on the palladium surface. The activity of palladium in decomposing hydrogen peroxide is well known in general, and the thermal safety of its catalysed decomposition has been assessed by dynamic analysis [31]; but no peer-reviewed source was found that treats the residual $H_2O_2$ returning in an AO loop as an independent variable affecting catalyst activity and hydrogen consumption. A second consequence of extraction is the transfer of water into the working solution. Water accumulating in the loop would be expected to affect hydrogenation selectivity and carrier degradation; this link was likewise not found as an independent subject of study. Concentration, finally, is thermally delicate. Hydrogen peroxide decomposes on heating, so distillation is carried out under vacuum at low temperature. This operation accounts for an appreciable share of the energy demand and is at the

same time one of the most sensitive nodes from a safety standpoint.

Process safety. The safety aspects of the AO process were recently consolidated in the systematic review of Meng et al. [32]. Three independent sources of hazard can be distinguished.

Hydrogen peroxide itself. Contaminated with metal ions or other impurities, hydrogen peroxide becomes prone to uncontrolled decomposition. Eto et al. studied the influence of various ions [33] and Wu and Qian the influence of organic and inorganic impurities in a batch reactor [34]. These sources show that product purity is not a quality indicator but a safety indicator.

Mixtures of working solution and $H_2O_2$. Jia et al. studied the explosion characteristics of mixtures containing hydrogen peroxide and working solution in the anthraquinone route [35] a source directly relevant to the vessels of an AO plant in which the organic phase and the peroxide are present together, namely the oxidiser and the extractor.

The gas phase and the carbon beds. The flammability of gas mixtures containing hydrocarbon vapour is defined by the limiting oxygen concentration (LOC). Zlochower and Green reported measured LOC values for nitrogen-diluted mixtures: 11.1 vol % for methane and 10.7 vol % for propane [36]. When these numbers are quoted, the measurement conditions must be stated: they were obtained in a 120 L chamber with nitrogen as diluent, a spark of about 58 J, and a 7 % pressure-rise criterion. Because a strong ignition source was used, these values lie below the figures more commonly quoted in handbooks (~12 vol %) and are therefore conservative from a safety standpoint. Britton et al. systematised methods for calculating and estimating LOC [37], and Osterberg et al. measured LOC experimentally for nine organic solvents, including an aromatic solvent, at temperatures and pressures relevant to aerobic oxidation [38] (cited for the purpose of the study and the list of solvents; its numerical values were not read within this review and are therefore not quoted). No LOC value measured at process conditions for the specific aromatic solvent used in an AO plant was found. The activated-carbon beds are an independent source of hazard in themselves: exothermic oxidation of adsorbed organic material can cause the bed to self-heat [39], [40]. A rising oxygen fraction in the off-gas therefore increases the hazard precisely at the most flammable node of the system.

Resource intensity and environment. The environmental burden of the AO process arises from two sources: the production of hydrogen, and the energy consumption of the process itself. The dominance of steam-reformed hydrogen in the climate impact of the process, established in the comparative outlook quoted in the Introduction, makes the first of these the larger term. Jia et al. performed a life-cycle assessment of hydrogen peroxide with the hydrogen source as an explicit variable [41]. From the standpoint of material flows two items stand out. The first is the regeneration adsorbent: the alumina that retains degradation products is consumed and generates a solid waste contaminated with organic matter. The second is palladium: recovery of palladium from spent catalyst is a technological problem of its own, considered by Sarıoğlan for palladium catalysts supported on activated carbon [42]. The alternative routes direct synthesis [43], [44] and electrochemical synthesis [45], [46] are directed at exactly these problems of the AO process: its multi-step character, the circulation of a carrier, and centralised production followed by transport.

## 2. Causal links between the problems

The problems set out above are individually well studied, but their interaction is rarely discussed. Figure 2 presents the map of these links; solid lines denote links documented in the reviewed literature, dashed lines the hypotheses advanced within this review that require confirmation by measurement.

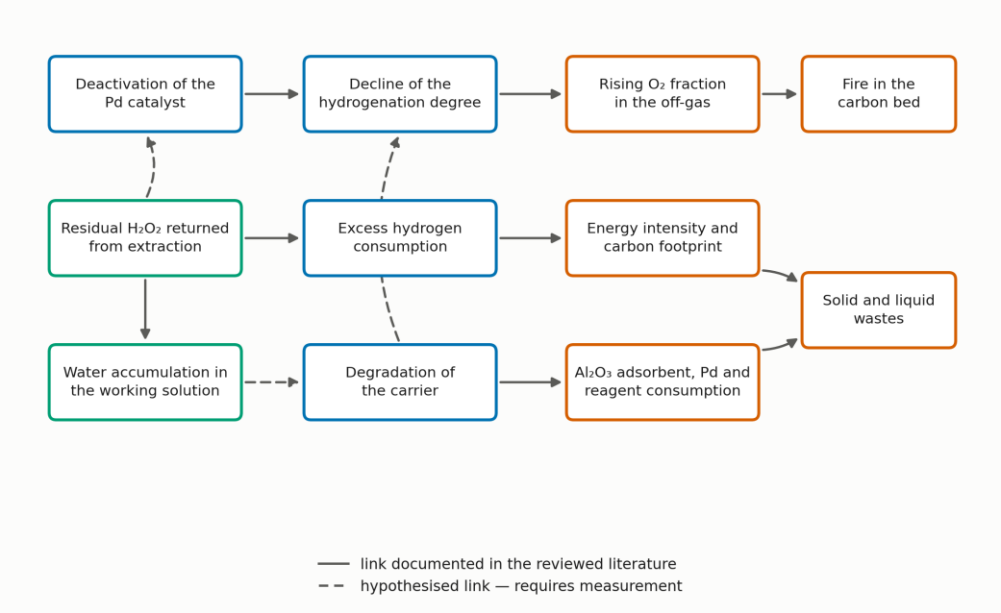



**Figure 2.** Causal links between the technological problems of the anthraquinone process.

Eight links are documented, each of them by the sources cited for the corresponding stage in Section 3.1. Catalyst deactivation lowers the hydrogenation degree; a lower hydrogenation degree, at unchanged air flow, raises the oxygen fraction in the off-gas; a rising oxygen fraction increases the risk of self-heating in the carbon bed. Carrier degradation raises the consumption of the regeneration adsorbent and of reagents, which becomes a solid waste stream. Excess hydrogen consumption acts directly on energy intensity and carbon footprint.

Three links have not been studied independently in the literature but are significant from a systems standpoint: (a) residual $H_2O_2$ returned from extraction → catalyst deactivation decomposition of hydrogen peroxide on the palladium surface and the associated change in oxidation state would be expected to affect catalyst activity; (b) water accumulation in the working solution → carrier degradation as a polar medium, water may affect the hydrogenolysis route; (s) carrier degradation → decline of the hydrogenation degree a falling concentration of active quinone limits the productivity of the loop.

## 3. Gaps in the literature

Six topics yielded no source satisfying the inclusion criteria:

1. Solvent losses and volatile organic compound emissions from the vent of the solvent-recovery unit. Only manufacturers' materials were found on this topic.

2. Water and residual hydrogen peroxide in the working solution treated as independent variables. These factors are commonly left as uncontrolled conditions.

3. Leaching of palladium into the working solution. Unlike the other deactivation mechanisms, no quantitative study was found.

4. Inert accumulation and purge policy in the hydrogen loop. This question may be covered inside the systematic safety review cited in Section 3.1, but no standalone study was found.

5. Aqueous effluent streams of an anthraquinone plant composition, quantity and treatment routes.

6. Membrane reactors for the hydrogenation step. The other intensification routes listed in Section 3.1 have been studied; a membrane solution was not found.

These gaps are of different kinds. Items 1, 5 and in part 4 are topics characteristic of industrial practice but seldom covered in academic publications; the data exist at plants but do not reach the

open literature. Items 2 and 3 represent a methodological gap: the relevant factors are frequently left uncontrolled in laboratory experiments. Item 6 is a direction not yet explored. It must be emphasised that this list does not mean that nothing has been written on these topics; it means that no source meeting the criteria of this review (peer-reviewed, DOI-bearing, directly relevant) was found. Patents and plant documentation may cover some of these subjects.

## Discussion

A self-reinforcing loop rather than additive degradation. The three hypothesised links were not selected at random: each of them forms a feedback path, that is, a deterioration in one stage propagates to another and returns to the first. Hypotheses (a) and (s) together close a loop deactivation → decline of the hydrogenation degree → decline of extraction efficiency → increase of returned $H_2O_2$ → intensified deactivation. If this loop exists, the performance of the plant would deteriorate slowly but in a self-reinforcing manner, which is a qualitatively different behaviour from the independent, additive degradation implicitly assumed when each problem is studied in isolation. Testing the loop requires the hydrogenation degree, the residual hydrogen peroxide returned from extraction, the water content of the working solution and the catalyst activity to be measured simultaneously over an extended period; items 1–4 of the protocol below are designed for exactly this purpose.

An asymmetry in the literature. The distribution of the corpus is itself informative. Catalysis is the most saturated area (28 % of the corpus), while the oxidation step and working-solution degradation are the least covered (7 % and 9 % respectively). This ratio indicates that research effort has been directed towards the molecular level, whereas process-level questions have received less attention. The same asymmetry appears in the gap list: five of the six gaps are process-level or plant-level topics. One consequence is that results already available at the molecular level have not been carried into practice: the reported dependence of degradation on the choice of support, and the reported effect of support modification on the side reactions, are of direct operational relevance, and the recent work on support hydrophobicity points in the same direction, yet none of it has been evaluated against working-solution service life at plant scale.

Safety and efficiency are coupled through one variable. The oxygen fraction in the off-gas reflects the efficiency of oxidation and, at the same time, the fire hazard in the carbon bed. This coupling has a practical implication: a measurement introduced for process-control purposes also serves as a safety instrument, and conversely, a deterioration in conversion is a safety-relevant event and not merely an economic one. The reviewed literature contains measured LOC values for simple hydrocarbons, and methods for estimating and measuring LOC, but the value for the aromatic solvent actually used, at process conditions, is missing which prevents the safety margin from being set numerically. Determining it is a prerequisite for using the off-gas oxygen fraction as a quantitative safety indicator rather than a qualitative one.

The environmental burden cannot be addressed through the hydrogen source alone. The conclusion quoted in the Introduction, that the climate impact is dominated by steam-reformed hydrogen, is compatible with the observation from Figure 2 that hydrogen consumption is itself increased by internal loss mechanisms. Reducing the residual hydrogen peroxide returned from extraction would, if hypothesis (a) holds, lower hydrogen consumption, the water load on the working solution and the rate of catalyst deactivation simultaneously. This is the practical reason why the three hypotheses deserve to be tested together rather than separately. Closing the material loops acts on the same indicators from the other side: recycling routes for spent alumina and for palladium, together with the return of solvent and condensate streams, reduce both the solid-waste stream and the primary-material demand of the process.

Limitations. The review is confined to publications in English and Russian; literature in other languages was not covered. Patents and non-peer-reviewed technical materials were excluded by the

criteria, so the gaps listed above must be read as "no source meeting these criteria was found" rather than "not studied at all". Of the 46 sources, the content of only nine was read in full or in abstract; the remainder are cited for the subject of the study alone, and no numerical result is attributed to them. The three causal hypotheses are not supported by any source and are named as hypotheses wherever they appear. The review reports no measurement data of its own, and the causal map is therefore a structured statement of what the literature does and does not establish, not an experimental result.

## Conclusions

The technological problems of the anthraquinone process were classified along the process chain on the basis of 46 DOI-verified sources. Stage-specific problems converge at system level on four outcome indicators: reagent and adsorbent consumption, explosion and fire hazard, energy intensity, and wastes and emissions. This problem map, organised along the process chain, is the first of the three contributions of the work.

The problems are not independent. Eight causal links are documented in the reviewed literature and three remain hypotheses. Those three may together form a closed, self-reinforcing loop: catalyst deactivation → decline of the hydrogenation degree → decline of extraction efficiency → increase of returned hydrogen peroxide → intensified deactivation. Separating documented links from merely plausible ones, and stating this loop explicitly as a systems-level proposition that follows from no single study in the corpus, is the second contribution. The existence of the loop is unconfirmed and requires measurement.

The literature on catalysis is the most saturated (28 % of the corpus), while oxidation and working-solution degradation are the least covered (7 % and 9 %). Research has concentrated at the molecular level, and process-level questions remain comparatively unexamined.

For six topics no source meeting the inclusion criteria was found: solvent losses and vent emissions; water and residual $H_2O_2$ as independent variables; palladium leaching; inert accumulation and purge policy in the hydrogen loop; aqueous effluent streams; and membrane reactors for hydrogenation.

From a safety standpoint the oxygen fraction in the off-gas serves as a key indicator, because it simultaneously reflects oxidation efficiency and the fire hazard in the carbon bed. Measured LOC values exist for simple hydrocarbons (methane 11.1 vol %, propane 10.7 vol %, obtained in a 120 L chamber with nitrogen dilution, a ~58 J spark and a 7 % pressure-rise criterion; Section 3.1), but the value for the aromatic solvent used in an AO plant, at process conditions, has not been determined.

## References


[1] G. Goor, J. Glenneberg, and S. Jacobi, "Hydrogen peroxide," in Ullmann's Encyclopedia of Industrial Chemistry. Weinheim, Germany: Wiley-VCH, 2007, doi: 10.1002/14356007.a13_443.pub2.

[2] J. M. Campos-Martin, G. Blanco-Brieva, and J. L. G. Fierro, "Hydrogen peroxide synthesis: An outlook beyond the anthraquinone process," Angewandte Chemie International Edition, vol. 45, no. 42, pp. 6962–6984, 2006, doi: 10.1002/anie.200503779.

[3] R. Ciriminna, L. Albanese, F. Meneguzzo, and M. Pagliaro, "Hydrogen peroxide: A key chemical for today's sustainable development," ChemSusChem, vol. 9, no. 24, pp. 3374–3381, 2016, doi: 10.1002/cssc.201600895.

[4] S.-A. Theofanidis, A. G. Georgiadis, C. J. W. Hop, X. Yu, V.-L. Yfanti, G. Fayet, C. Villemur, H. Vleeming, E. Delikonstantis, and R. H. Heyn, "Alternative $H_2O_2$ production processes: An outlook on candidate technologies beyond the anthraquinone process," ACS Omega, vol. 10, no. 50, pp. 61076–61095, 2025, doi: 10.1021/acsomega.5c07503.

[5] E. Santacesaria, M. Di Serio, R. Velotti, and U. Leone, "Kinetics, mass transfer, and palladium catalyst deactivation in the hydrogenation step of the hydrogen peroxide synthesis via

anthraquinone," Industrial & Engineering Chemistry Research, vol. 33, no. 2, pp. 277–284, 1994, doi: 10.1021/ie00026a016.
[6] Q. Wang, L. Wang, Y. Wang, F. He, Z. Li, and Z. Mi, "Study on deactivation and regeneration of $Pd/Al_2O_3$ catalyst in hydrogen peroxide production by the anthraquinone process," Reaction Kinetics and Catalysis Letters, vol. 81, no. 2, pp. 297–304, 2004, doi: 10.1023/B:REAC.0000019436.13144.29.
[7] P. Albers, J. Pietsch, and S. F. Parker, "Poisoning and deactivation of palladium catalysts," Journal of Molecular Catalysis A: Chemical, vol. 173, no. 1–2, pp. 275–286, 2001, doi: 10.1016/S1381-1169(01)00154-6.
[8] T. Berglin and N.-H. Schöön, "Selectivity aspects of the hydrogenation stage of the anthraquinone process for hydrogen peroxide production," Industrial & Engineering Chemistry Process Design and Development, vol. 22, no. 1, pp. 150–153, 1983, doi: 10.1021/i200020a024.
[9] E. Santacesaria, M. Di Serio, R. Velotti, and U. Leone, "Hydrogenation of the aromatic rings of 2-ethylanthraquinone on palladium catalyst," Journal of Molecular Catalysis, vol. 94, no. 1, pp. 37–46, 1994, doi: 10.1016/0304-5102(94)87028-4.
[10] A. Drelinkiewicz, "Deep hydrogenation of 2-ethylanthraquinone over $Pd/SiO_2$ catalyst in the liquid phase," Journal of Molecular Catalysis, vol. 75, no. 3, pp. 321–332, 1992, doi: 10.1016/0304-5102(92)80134-3.
[11] E. Yuan, L. Wang, X. Zhang, R. Feng, C. Wu, and G. Li, "Density functional theory analysis of anthraquinone derivative hydrogenation over palladium catalyst," ChemPhysChem, vol. 17, no. 23, pp. 3974–3984, 2016, doi: 10.1002/cphc.201600874.
[12] R. Kosydar, A. Drelinkiewicz, and J. P. Ganhy, "Degradation reactions in anthraquinone process of hydrogen peroxide synthesis," Catalysis Letters, vol. 139, no. 3–4, pp. 105–113, 2010, doi: 10.1007/s10562-010-0413-1.
[13] A. Drelinkiewicz, R. Kangas, R. Laitinen, A. Pukkinen, and J. Pursiainen, "Hydrogenation of 2-ethylanthraquinone on alumina-supported palladium catalysts: The effect of support modification with $Na_2SiO_3$," Applied Catalysis A: General, vol. 263, no. 1, pp. 71–82, 2004, doi: 10.1016/j.apcata.2003.12.010.
[14] A. Drelinkiewicz, M. Hasik, and M. Kloc, "Pd/polyaniline as the catalysts for 2-ethylanthraquinone hydrogenation. The effect of palladium dispersion," Catalysis Letters, vol. 64, no. 1, pp. 41–47, 2000, doi: 10.1023/A:1019078718474.
[15] Y. Zhang, Z. Pan, N. Wang, and L. Wang, "Performance of carbon-modified Pd/SBA-15 catalyst for 2-ethylanthraquinone hydrogenation," Molecular Catalysis, vol. 504, art. no. 111424, 2021, doi: 10.1016/j.mcat.2021.111424.
[16] L. Wang, Y. Zhang, Q. Ma, Z. Pan, and B. Zong, "Hydrogenation of alkyl-anthraquinone over hydrophobically functionalized Pd/SBA-15 catalysts," RSC Advances, vol. 9, no. 59, pp. 34581–34588, 2019, doi: 10.1039/C9RA07351E.
[17] R. Bi, Q. Wang, C. Miao, J. Feng, and D. Li, "Pd/NiO/Al array catalyst for 2-ethylanthraquinone hydrogenation: Synergistic effect between Pd and NiO/Al support," Catalysis Letters, vol. 149, no. 5, pp. 1286–1296, 2019, doi: 10.1007/s10562-019-02712-y.
[18] H. Yao, C. Shen, Y. Wang, and G. Luo, "Catalytic hydrogenation of 2-ethylanthraquinone using an in situ synthesized Pd catalyst," RSC Advances, vol. 6, no. 28, pp. 23942–23948, 2016, doi: 10.1039/C5RA23187F.
[19] Q. Chen, "Development of an anthraquinone process for the production of hydrogen peroxide in a trickle bed reactor—From bench scale to industrial scale," Chemical Engineering and Processing: Process Intensification, vol. 47, no. 5, pp. 787–792, 2008, doi: 10.1016/j.cep.2006.12.012.
[20] Y. Guo, C. Dai, Z. Lei, B. Chen, and X. Fang, "Synthesis of hydrogen peroxide over $Pd/SiO_2$/COR monolith catalysts by anthraquinone method," Catalysis Today, vol. 276, pp. 36–45, 2016, doi: 10.1016/j.cattod.2016.03.023.
[21] R. Halder and A. Lawal, "Experimental studies on hydrogenation of anthraquinone derivative in a microreactor," Catalysis Today, vol. 125, no. 1–2, pp. 48–55, 2007, doi:

10.1016/j.cattod.2007.03.055.
[22] J. Tan, J. S. Zhang, Y. C. Lu, J. H. Xu, and G. S. Luo, "Process intensification of catalytic hydrogenation of ethylanthraquinone with gas–liquid microdispersion," AIChE Journal, vol. 58, no. 5, pp. 1326–1335, 2011, doi: 10.1002/aic.12670.
[23] H. Li, B. Zheng, Z. Pan, B. Zong, and M. Qiao, "Advances in the slurry reactor technology of the anthraquinone process for $H_2O_2$ production," Frontiers of Chemical Science and Engineering, vol. 12, no. 1, pp. 124–131, 2018, doi: 10.1007/s11705-017-1676-5.
[24] A. A. Ingle, S. Z. Ansari, D. Z. Shende, K. L. Wasewar, and A. B. Pandit, "Progress and prospective of heterogeneous catalysts for $H_2O_2$ production via anthraquinone process," Environmental Science and Pollution Research, vol. 29, no. 57, pp. 86468–86484, 2022, doi: 10.1007/s11356-022-21354-z.
[25] A. Drelinkiewicz and A. Waksmundzka-Góra, "Investigation of 2-ethylanthraquinone degradation on palladium catalysts," Journal of Molecular Catalysis A: Chemical, vol. 246, no. 1–2, pp. 167–175, 2006, doi: 10.1016/j.molcata.2005.10.026.
[26] Z. Guo, J. Feng, Y. Feng, D. G. Evans, and D. Li, "In situ synthesis of solid base catalysts for the regeneration of degradation products formed during the anthraquinone process for the manufacture of hydrogen peroxide," Applied Catalysis A: General, vol. 401, no. 1–2, pp. 163–169, 2011, doi: 10.1016/j.apcata.2011.05.013.
[27] H. Bai, X. Fang, and C. Peng, "Novel working solvent for the production of hydrogen peroxide," Industrial & Engineering Chemistry Research, vol. 58, no. 16, pp. 6948–6956, 2019, doi: 10.1021/acs.iecr.9b01130.
[28] E. Santacesaria, R. Ferro, S. Ricci, and S. Carrà, "Kinetic aspects in the oxidation of hydrogenated 2-ethyltetrahydroanthraquinone," Industrial & Engineering Chemistry Research, vol. 26, no. 1, pp. 155–159, 1987, doi: 10.1021/ie00061a029.
[29] T. Nishimi, T. Kamachi, K. Kato, T. Kato, and K. Yoshizawa, "Mechanistic study on the production of hydrogen peroxide in the anthraquinone process," European Journal of Organic Chemistry, vol. 2011, no. 22, pp. 4113–4120, 2011, doi: 10.1002/ejoc.201100300.
[30] H.-G. Korth and P. Mulder, "Phenolic hydrogen transfer by molecular oxygen and hydroperoxyl radicals. Insights into the mechanism of the anthraquinone process," Journal of Organic Chemistry, vol. 85, no. 4, pp. 2560–2574, 2020, doi: 10.1021/acs.joc.9b03286.
[31] M. Á. Gómez García, I. Dobrosz-Gómez, and J. C. Ojeda Toro, "Thermal safety assessment for catalytic decomposition of hydrogen peroxide by dynamic analysis," Process Safety and Environmental Protection, vol. 109, pp. 46–54, 2017, doi: 10.1016/j.psep.2017.03.025.
[32] F. Meng, X. Jia, F. Sun, B. Sun, and Z. Yang, "Systemic risk control in anthraquinone-based hydrogen peroxide synthesis: A technical review," Journal of Loss Prevention in the Process Industries, vol. 97, art. no. 105689, 2025, doi: 10.1016/j.jlp.2025.105689.
[33] I. Eto, M. Akiyoshi, A. Miyake, T. Ogawa, and T. Matsunaga, "Hazard evaluation of runaway reaction of hydrogen peroxide – Influence of contamination of various ions," Journal of Loss Prevention in the Process Industries, vol. 22, no. 1, pp. 15–20, 2009, doi: 10.1016/j.jlp.2008.09.009.
[34] D. Wu and X. Qian, "Experimental study on the thermal runaway of hydrogen peroxide with in-/organic impurities by a batch reactor," Journal of Loss Prevention in the Process Industries, vol. 51, pp. 200–207, 2018, doi: 10.1016/j.jlp.2017.12.012.
[35] X. Jia, F. Sun, Y. Fei, M. Jin, F. Zhang, W. Xu, N. Shi, and Z. Lv, "Explosion characteristics of mixtures containing hydrogen peroxide and working solution in the anthraquinone route to hydrogen peroxide," Process Safety and Environmental Protection, vol. 119, pp. 218–222, 2018, doi: 10.1016/j.psep.2018.08.007.
[36] I. A. Zlochower and G. M. Green, "The limiting oxygen concentration and flammability limits of gases and gas mixtures," Journal of Loss Prevention in the Process Industries, vol. 22, no. 4, pp. 499–505, 2009, doi: 10.1016/j.jlp.2009.03.006.
[37] L. G. Britton, M. P. Clouthier, B. K. Harrison, and S. A. Rodgers, "Limiting oxygen concentrations of gases," Process Safety Progress, vol. 35, no. 1, pp. 107–114, 2016, doi: 10.1002/prs.11806.

[38] P. M. Osterberg, J. K. Niemeier, C. J. Welch, J. M. Hawkins, J. R. Martinelli, T. E. Johnson, T. W. Root, and S. S. Stahl, "Experimental limiting oxygen concentrations for nine organic solvents at temperatures and pressures relevant to aerobic oxidations in the pharmaceutical industry," Organic Process Research & Development, vol. 19, no. 11, pp. 1537–1543, 2015, doi: 10.1021/op500328f.

[39] T. C. Hofelich, M. S. LaBarge, and D. A. Drott, "Prevention of thermal runaways in carbon beds," Journal of Loss Prevention in the Process Industries, vol. 12, no. 6, pp. 517–523, 1999, doi: 10.1016/S0950-4230(99)00025-X.

[40] R. A. Zerbonia, C. M. Brockmann, P. R. Peterson, and D. Housley, "Carbon bed fires and the use of carbon canisters for air emissions control on fixed-roof tanks," Journal of the Air & Waste Management Association, vol. 51, no. 12, pp. 1617–1627, 2001, doi: 10.1080/10473289.2001.10464393.

[41] Y. Jia, Y. Bai, J. Chang, Y. Zhai, T. Zhang, K. Ren, and J. Hong, "Life cycle assessment of hydrogen peroxide produced from mainstream hydrogen sources in China," Journal of Cleaner Production, vol. 352, art. no. 131655, 2022, doi: 10.1016/j.jclepro.2022.131655.

[42] Ş. Sarıoğlan, "Recovery of palladium from spent activated carbon-supported palladium catalysts," Platinum Metals Review, vol. 57, no. 4, pp. 289–296, 2013, doi: 10.1595/147106713X663988.

[43] D. W. Flaherty, "Direct synthesis of $H_2O_2$ from $H_2$ and $O_2$ on Pd catalysts: Current understanding, outstanding questions, and research needs," ACS Catalysis, vol. 8, no. 2, pp. 1520–1527, 2018, doi: 10.1021/acscatal.7b04107.

[44] J. K. Edwards, B. Solsona, E. Ntainjua N, A. F. Carley, A. A. Herzing, C. J. Kiely, and G. J. Hutchings, "Switching off hydrogen peroxide hydrogenation in the direct synthesis process," Science, vol. 323, no. 5917, pp. 1037–1041, 2009, doi: 10.1126/science.1168980.

[45] S. Yang, A. Verdaguer-Casadevall, L. Arnarson, L. Silvioli, V. Čolić, R. Frydendal, J. Rossmeisl, I. Chorkendorff, and I. E. L. Stephens, "Toward the decentralized electrochemical production of $H_2O_2$: A focus on the catalysis," ACS Catalysis, vol. 8, no. 5, pp. 4064–4081, 2018, doi: 10.1021/acscatal.8b00217.

[46] S. C. Perry, D. Pangotra, L. Vieira, L.-I. Csepei, V. Sieber, L. Wang, C. Ponce de León, and F. C. Walsh, "Electrochemical synthesis of hydrogen peroxide from water and oxygen," Nature Reviews Chemistry, vol. 3, pp. 442–458, 2019, doi: 10.1038/s41570-019-0110-6.